A Proposal to the Jefferson Lab PAC43

Search for Hybrid Baryons with CLAS12 in Hall B

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I

I. STRATEGIES FOR IDENTIFYING HYBRID- AND THREE-QUARK NEW BARYON STATES

In this section we address the question if and how gluonic hybrid baryons are distinct from ordinary quark excitations. We will also elucidate the additional opportunities offered by the studies of exclusive electroproduction processes at different photon virtualities for the search of new baryon states both hybrid-baryons and regular three-quark so-called "missing" resonances.

A. Spectrum of the lowest hybrid-baryons from QCD

As discussed in section **??**, according to the LQCD evaluation [11] of the baryon spectrum from the QCD Lagrangian, the lowest hybrid baryons should have isospin $I = \frac{1}{2}$ and $J^P = \frac{1}{2}^+$ or $J^P = \frac{3}{2}^+$ (see Fig. **??**). A difference between mass of the ground nucleon and LQCD expectation is ≈ 0.3 GeV for the computation with pion mass 0.396 GeV. However, a difference between physical mass of $N(1440)\frac{1}{2}^+$ resonance and the LQCD expectation [11] is ≈ 0.7 GeV suggesting that physics mass of the excited state can be push down by even more than 0.3 GeV, when the pion mass from LQCD is approaching the physics value. So, the masses of the lightest hybrids mass range should be in the range of 2.10 to 2.50 GeV This mass range must be verified once LQCD calculations with physical pion masses become available. Three states with $I = \frac{1}{2}$ and $J^P = \frac{1}{2}$ are predicted with dominant quark contributions and with masses below the mass of the lowest LQCD hybrid states. Of these three states two are the well known $N(1440)\frac{1}{2}^+$ and $N(1710)\frac{1}{2}^+$, and less well established $N(1880)\frac{1}{2}^+$ with 2* rating. Other states $N(2100)\frac{1}{2}^+$ and $N(2300)$ have 1* and 2* ratings, respectively, and fall right into the lowest hybrid mass band projected by LQCD. The The states $N(2100)\frac{1}{2}^+$ and $N(2300)$, if confirmed, could be the candidates for the predicted lowest LQCD hybrid state of $J^P = \frac{1}{2}$.

In the $J^P = \frac{3}{2}^+$ sector the situation is more involved. There are hybrid states predicted in the mass range 2.2 to 2.4 GeV, with masses above quark model states at same J^P. Of these states, two are well known 4* the $N(1720)\frac{3}{2}^+$ and the 3* state $N(1900)\frac{3}{2}^+$, and one state, the $N(2040)\frac{3}{2}^+$, has a 1* rating. Here we will have to confirm (or refute) the 1* star state and find (if $N(2040)$ does not exist) more quark model state(s) with the same quantum numbers in the mass range 2.1 to 2.5 GeV. Among the states of spin-parity $J^P = \frac{3}{2}^+$, there is one candidate $\frac{3}{2}^+$ state with mass near 1.72 GeV seen in $p\pi^+\pi^-$ electroproduction [25], whose status we will be able to pin down with the expected very high statistics data.

In the computation [11] the lowest $J^P = \frac{3}{2}^+$ gluonic states are nearly mass degenerate with the corresponding $J^P = \frac{1}{2}^+$ gluonic states generating a glue-rich mass range of hybrid nucleons. If these projections hold up with LQCD calculations using near physical pion masses, one should expect a band of the lowest mass hybrid baryon states with spin-parity $\frac{1}{2}^+$ and $\frac{3}{2}^+$ to populate a relatively narrow mass band of $2.1 - 2.5$ GeV. Note, that these states fall into a mass range where no 3-quark nucleon excitations are predicted to exist from these calculations. The corresponding negative parity hybrid states, which are expected to occur at much higher masses, are not included in the Fig. **??**, and are not further considered here; although they may be subject of analysis, should they appear within the kinematic range covered by this proposal.

Therefore, we propose to search for the extra states of spin-parity $J^P = \frac{1}{2}^+$, $J^P = \frac{3}{2}^+$, $I = \frac{1}{2}^+$, isospin in the excited nucleon spectrum in the mass range from 2.1 GeV to 2.5 GeV. In order to conclude on their hybrid nature further studies of their hadronic decays and electrocouplings are needed, since expected spin-parities and isospin of the lowest hybrid states are the same as for three-quark "missing" resonances.

B. Distinctive features of the hybrid hadronic and electrocouplings in exclusive electroproduction.

Expected hadronic decays of hybrid baryons were discussed in the Section **??**. Because of the coupling of the glue admixture to the $q\bar{q}$ pair, the hybrid baryons will manifest in the channels with strange mesons and baryons, as well as in the electroproduction of multi- meson final states with more than single mesons. We included into our proposal those of the aforementioned channels which we already studied in details previously and included into the future N^* studies with the CLAS12 [34, 36], i.e. $K^+\Lambda$, $K^+\Sigma$ and $\pi^+\pi^-p$. Later on these studies may be extended by the exploration of other electroproduction channels such as $\phi(1020)N$, $K^*\Lambda$.

Studies of excited nucleon state electrocouplings in a wide range of photon virtualities is proven to be the effective tools in establishing the active degrees of freedom contributing to the N* structure at different distances [34, 36, 42–44]. The information on the $\gamma_v NN^*$ electrocoupling evolution with Q^2 becomes critical in the search for hybrid baryons. The distinctively different Q^2-evolution of the hybrid-baryon electrocouplings is expected considering the different color-multiplet assignments for the quark-core in a regular versus a hybrid baryon, i.e. a color singlet and octet, respectively.

The electroproduction transition form factors of a Roper state assuming the presence of glue (hybrid Roper) were evaluated in [15]. This studies demonstrated that for hybrid Roper longitudinal electrocouplings should be much smaller than transverse $A_{1/2}$ electrocouplings. Virtually $S_{1/2}$ electrocouplings should be comparable with zero at the scale of the transverse electrocouplings. It also showed that a hybrid Roper transition amplitude $A_{1/2}$ should behave like the $A_{1/2}$ of the ordinary $\Delta(1232)$. The aforementioned predictions should apply to each lowest mass hybrid state with $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$. The suppression of the longitudinal coupling is a property of the γqG vertex and is largely independent of specific, which is purside of the current model assumptions.

Based on quark counting rules [**?**], we expect that electrocouplings of hybrid baryons should decrease with photon virtuality Q^2 more rapidly than for the regular three-quark nucleon resonance because of the extra- constituent. So, the low photon virtualities offer a preferential regime for the studies of hybrid-baryons. In our proposal we are planning to explore the range of $Q^2 < 2.0$ GeV^2 with particular focus for hybrid baryon search at $Q^2 < 1.0$ GeV^2.

In a case of $J^P = \frac{3}{2}^+$ all three electrocouplings $A_{1/2}$, $S_{1/2}$ and $A_{3/2}$ contribute to the state electroexcitations. The prediction on the relations between $A_{1/2}$, $A_{3/2}$, and $S_{1/2}$ hybrid electrocouplings exist only for the area large photon virtuality [9] which is outside of the current study scope. In the future the $A_{1/2}$, $S_{1/2}$ and $A_{3/2}$ hybrid electrocouplings will be evaluated within.... at $Q^2 < 2.0$ GeV^2 as a part of the commitment of....

In order to identify hybrid-baryon we are looking for its electrocouplings behavior which should have distinctively different features in comparison with already established from the CLAS results [36] electrocouplings of three-quark resonances of $J^P = \frac{1}{2}^+$ shown in Fig 2 and of $J^P = \frac{3}{2}^+$ shown in Fig 4

C. Signature of the hybrid-baryon in the experimental data

We propose to search for the new baryon states in the exclusive $K^+\Lambda$ and $K^+\Sigma$ and $p\pi^+\pi^-$ electroproduction at the photon virtualities from 0.05 GeV^2 to 1.0 GeV^2. Possible signatures of the lowest mass hybrid baryons are:

- Almost degenerated pairs of the states with isospin $I = 1/2$, and spin-parities $J^P = \frac{1}{2}^+$ or $J^P = \frac{3}{2}^+$ and the masses in the range 2.0 GeV $\leq W \leq$ 2.5 GeV. The hybrid-states of both spin-parities should belong to the two spin-parity bands with well established lowest $N(1440)1/2^+$ and $N(1720)3/2^+$ resonances and with the regular three-quark resonances of masses above and below the hybrid-baryon mass.
- particular features in Q^2 dependence of hybrid electrocouplings related to the color octet assignment for three constituent quarks including: dominance of the transverse over longitudinal amplitudes, similarity of the transverse helicity amplitudes $A_{1/2}(Q^2)$ for the hybrid-baryon and for the $\Delta(1232)\frac{3}{2}^+$ but dissimilar to the three-quark excited states of same J^P, and
- a strongly suppressed helicity amplitude $S_{1/2}(Q^2) \approx 0$ in comparison to other ordinary 3-quark states.

D. Search for the three-quark new baryon states

Advanced studies of the data on exclusive meson photoproduction off protons carried out within the framework of the global multi-channel amplitude analysis developed by the Bonn-Gatchina group [48–50] revealed the signals from many new baryon states in the mass range from 1.7 GeV to 2.5 GeV. These states were included to the PDG [1] with the status from one to three star states. Notably, the most prominent signals from new states come from analyses of the CLAS [51–54], ELSA [55], MAMI [56] and GRAAL [58**?**] data on KY electroproduction. Studies of KY as well as $\pi^+\pi^-p$ exclusive electroproduction channels extend considerably our capability in establishing of the excited nucleon state spectrum, including both regular three-quark and exotic hybrid states.

The new baryon states, if they are excited in s-channel should be seen in exclusive reactions both with the real and virtual photons in the same final states. Furthermore, their masses, total decay widths, partial decay widths to different final states should be Q^2-independent. The values of $\gamma_v pN^*$ electrocouplings obtained independently from analyses of different exclusive channels with completely different non-resonant contributions should be the same. Consistent results on resonance masses, $\gamma_v pN^*$ electrocouplings for all exclusive de- cay channels under study, and

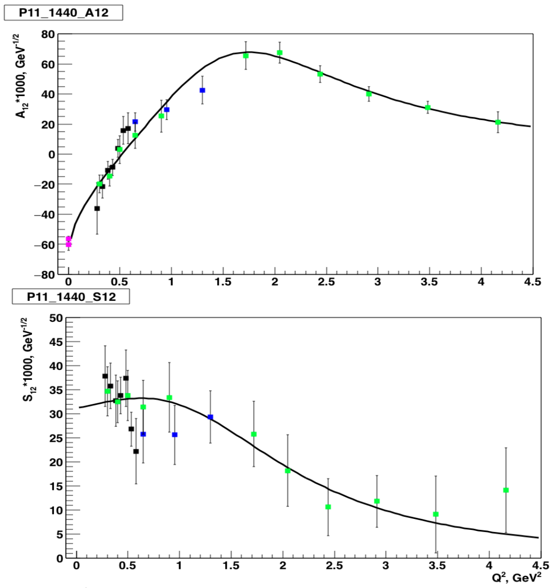

FIG. 1: Interpolation of the $N(1440)1/2^+$ electrocouplings from the CLAS data on $N\pi$ (green circles) [4] and $\pi^+\pi^-p$ [26, 44] (black and blue squares) exclusive electroproduction off protons. The results at the photon point are taken from [1, 45]

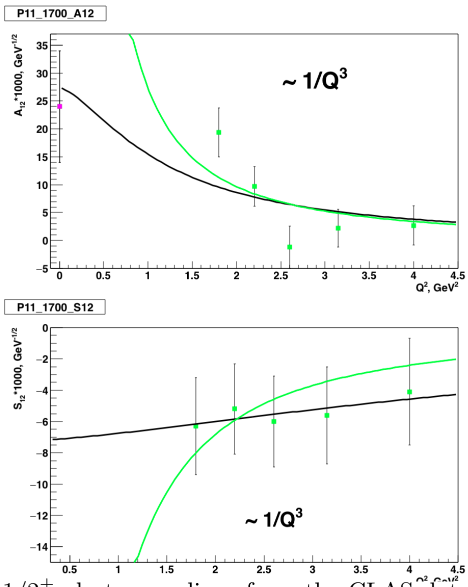

FIG. 2: Interpolation of the $N(1710)1/2^+$ electrocouplings from the CLAS data on $N\pi$ (green circles) [46] exclusive electroproduction off protons. The results at the photon point are taken from [1, 45]

Q^2-independent partial hadronic decay widths, over the full covered Q^2-range, will offer convincing evidence for the existence of new states. These studies offer model independent way to prove not only the existence of new excited nucleon states but also their nature as the s-channel resonances eliminating the alternative interpretations for the structures observed in the kinematics dependencies of the observables as complex coupled channel effects, dynamical singularities for the non-resonant amplitudes, kinematic reflections, etc.

This strategy was successfully employed in the recent analysis of the $\pi^+ pi^- p$ preliminary photo- and electroproduction cross sections [25] from the CLAS carried out combined within the framework of meson-baryon reaction model JM [47]. It was found that in order to describe both photo- and electroproduction data at W around 1.7 GeV keeping $\pi\Delta$ and ρp hadronic decay widths of all contributing resonances Q^2-independent, new baryon state $N'(1720)3/2^+$ state is needed with almost the same mass , total widths and the same spin-parity as for the conventional $N(1720)3/2^+$ resonances, but with completely different branching fractions for the hadronic decay to the $\pi\Delta$ and ρp final state and Q^2-evolution of its $\gamma_v p N^*$ electrocouplings.

The studies of exclusive KY, $\pi^+\pi^-p$ electroproduction channels at $Q^2 < 2.0$ GeV^2 with maximal virtual photon flux ever achieved in exclusive electroproduction will allow us to solidify the results on the spectrum of excited nucleon states, confirming or ruling out the signal of "missing" resonances observed in exclusive photoproduction. Furthermore, for the first time the information on $\gamma_v pN^*$ electrocouplings of new baryon states will become available offering an access to the structure of "missing" resonances elucidating their differences from the conventional resonances. Finally we want to note that the studies of two major exclusive $N\pi$ and $\pi^+\pi^-p$ electroproduction channels with CLAS revealed the relative growth of the resonant contributions with Q^2 in both channel. So, use of the high intensity virtual photon flux of the proposed experiment may be even preferential for new baryon state search in comparison with the photoproduction. It still remain to be seen which range of photon virtualities is the most suitable for the discovery of new excited nucleon states.

II. AMPLITUDE ANALYSES OF MEASURED OBSERVABLES IN A SEARCH FOR NEW BARYON STATES.

In the analyses of the future experimental data we will apply the amplitude analyses methods for the resonance search and extraction of the resonance parameters. We will employ the global fit of all exclusive channels studied with the CLAS12 in the kinematics of out interest with a focus on new baryon state search within the framework of coupled channel approaches. We also planning to extract of the resonance parameters from the independent analyses of KY, $\pi^+\pi^-p$ exclusive electroproduction off protons carried our within the framework of the reaction models for description of these exclusive channels. Consistent results on the resonant parameters determined from independent analyses of different exclusive meson electroproduction channels and extracted from the global multi-channel fit of all available data will offer strong and almost the model independent evidences for the new state existence and reliable extraction of their parameters. Note, that in order to apply the coupled channel approaches to the analyses of KY, $\pi^+\pi^-p$ exclusive electroproduction data, the information on $N\pi$ electroproduction off protons is also needed. The $N\pi$ exclusive channels dominate at $W < 1.6$ GeV and remain have much bigger cross sections in comparison with the KY electroproduction in the entire kinematics area of our interest. The events from $N\pi$ exclusive channels will be collected simultaneously with the measurement of KY, $\pi^+\pi^-p$ exclusive electroproduction off protons offering the information on the $N\pi$ channel observables.

Advanced amplitude analysis approach for extraction of the nucleon resonance parameters from the global analysis of the photoproduction data, which include almost all relevant in resonance excitation region exclusive meson photoproduction channels off nucleons, has been developed by Bonn-Gatchina group [48–50]. In this approach production amplitudes are decomposed over the set of partial waves. The partial wave amplitudes are parameterized fully accounting for the restrictions imposed by the general unitarity and analyticity conditions, employing K- and D-matrix approaches for the final state interactions while for the photoproduction amplitudes the P-vector approach is used. In a case of pronounced t-channel contributions, Reggeized t-exchanges are incorporated to the photoproduction amplitudes. The hadronic final state interaction are treated employing phenomenological parameterisation, for the respective amplitudes. The resonance parameters were determined from the global fit of all available exclusive photoproduction data augmented by the fit of hadroproduction channels for the final states under studies. Application of the Bonn-Gatchina approach to the global analysis of the dominant part of exclusive meson photoproduction data measured with the CLAS and worldwide provided information on masses, widths, photocouplings and hadronic decay parameters for most excited nucleon states in the mass range up to 3.0 GeV. This analyses revealed the signal from around ten new baryon states, reported in the PDG [1] with the status from one- to three- stars and shown in Fig. 5. Extension of this approach for description of exclusive electroproduction including KY channels represent the part of the commitment of the Bonn-Gatchina group reported in [59]. Bonn-Gatchina approach extended for analysis of the exclusive electroproduction will be used for extraction of resonance parameters and search for new baryon states in the proposed experiment. The aforementioned extension will be vital in order to check the signals from new baryon states observed in the exclusive meson photoproduction and shown in Fig. 5 independently in the exclusive electroproduction processes confirming or rejecting the candidate-states observed in the photoproduction. It is a critical part of effort in finalizing the long-term program on exploration of the spectrum of excited nucleon states and simultaneously the new avenue extending our knowledge on variety of hadrons in the Nature through the search for hybrid-baryons.

An advanced dynamical coupled-channel model (DCC) has been developed by the Argonne-Osaka collaboration for combined analysis of the world data for $\pi N, \gamma N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$ $N\pi\pi$ photo-electro and hadroproduction with a goal of extracting resonance parameters [60, 61]. The DCC approach incorporates three level diagrams derived from effective Lagrangian for the resonant and non-resonant contributions in the photo-/electroproduction as well as in the final state hadronic interactions. The amplitudes for all exclusive channels are fully consistent with the restrictions imposed by the general unitarity and analyticity conditions. This is the only coupled channel approach capable of describing the $N\pi\pi$ photo-/electro-/hadro- production in accord with a general unitarity condition. In order to fulfill the unitarity restrictions, the meson-baryon interactions from the non-resonant amplitudes of all included exclusive processes, the so-called meson-baryon cloud, are incorporated to the electromagnetic and hadronic vertices of nucleon resonances together with direct resonance decays to the $\gamma_{r,v}p$ and meson-baryon final states (bare verticies). Analysis of the observables within the framework of the DCC approach allows us not only to extract the full dressed resonance electromagnetic and hadronic decay amplitudes, but also to disentangle between the contributions from the meson-baryon cloud and bare vertices associated to the quark core part in the nucleon resonance structure. The DCC approach is capable of providing valuable insight to the structure of excited nucleon states. The DCC-model currently is the only available worldwide coupled channel approach that provides the results on $N \to \Delta(1232)3/2^+$ transition form factors at Q^2 up to 7. GeV^2 [36] and $N(1440)1/2^+$ electrocouplings at Q^2 up to 3 GeV^2 [62]. Argonne-Osaka DCC-model will be employed in analyses of the data of the proposed experiment with a goal to observe manifestation of new excited nucleon state and to extract $\gamma_v pN^*$ electrocouplings of the established and new baryon states. This model will allow us to fully account in extraction of $\gamma_v pN^*$ electrocouplings from KY channels for the impact of the final state interaction with the open channels for which the electroproduction cross sections are much larger, i.e. $N\pi$, and $N\pi\pi$. Furthermore, it is the only available worldwide approach capable to account for the complexity of the final state interactions in the $\pi^+\pi^-p$ final state in a way consistent with the unitarity.

So far, most of the results on $\gamma_v pN^*$ electrocouplings have been extracted from independent analyses of π^+n, π^0p, and $\pi^+\pi^-p$ exclusive electroproduction data off the protons.

The $N\pi$ data have been analyzed within the framework of two conceptually different approaches: a unitary isobar model (UIM) and dispersion relations (DR) [4, 46]. The UIM describes the $N\pi$ electroproduction amplitudes as a superposition of N^* electroexcitations in the s-channel, non-resonant Born terms and ρ- and ω- t-channel contributions. The latter are reggeized, which allows for a better description of the data in the second- and third-resonance regions. The final-state interactions are treated as πN rescattering in the K-matrix approximation [**?**]. In the DR approach, dispersion relations relate the real to the imaginary parts of the invariant amplitudes that describe the $N\pi$ electroproduction. Both approaches provide good and consistent description of the $N\pi$ data in the range of $W < 1.7$ GeV and $Q^2 < 5.0$ GeV^2, resulting in χ^2/d.p. < 2.9. In the proposed this approach will be used for evaluation of the $N\pi$ electroproduction amplitudes needed as the input for the aforementioned global multi-channel analyses of the KY and $\pi^+\pi^-p$ exclusive electroproduction data.

The $\pi^+\pi^-p$ electroproduction data from CLAS [21, 27] provide for the first time information on nine independent single-differential and fully-integrated cross sections binned in W and Q^2 in the mass range $W < 2.0$ GeV and at photon virtualities of 0.25 GeV$^2 < Q^2 < 1.5$ GeV^2. The analysis of the data allowed us to develop the JM reaction model [24, 26, 44] with the goal of extracting resonance electrocouplings as well as $\pi\Delta$ and ρp hadronic decay widths. This model incorporates all relevant reaction mechanisms in the $\pi^+\pi^-p$ final-state channel that contribute significantly to the measured electroproduction cross sections off protons in the resonance region, including the $\pi^-\Delta^{++}$, $\pi^+\Delta^0$, ρ^0p, $\pi^+N(1520)\frac{3}{2}^-$, $\pi^+N(1685)\frac{5}{2}^+$, and $\pi^-\Delta(1620)\frac{3}{2}^+$ meson-baryon channels as well as the direct production of the $\pi^+\pi^-p$ final state without formation of intermediate unstable hadrons. In collaboration with the JPAC [**?**] the special approach has been developed allowing us to remove the contributions from the s-channel resonances to the reggeized t-channel non-resonant terms in $\pi^-\Delta^{++}$, $\pi^+\Delta^0$, ρ^0p electroproduction amplitudes. The contributions from well established N* states in the mass range up to 2.0 GeV were included into the amplitudes of $\pi\Delta$ and ρp meson-baryon channels by employing a unitarized version of the Breit-Wigner ansatz [26]. The JM model provides a good description of $\pi^+\pi^-p$ differential cross sections at $W < 1.8$ GeV and 0.2 GeV$^2 < Q^2 < 1.5$ GeV^2 with χ^2/d.p. < 3.0. The achieved quality of the CLAS data description suggest the unambiguous and credible separation between the resonant/non-resonant contributions achieved fitting the CLAS data [44]. The credible isolation of the resonant contributions makes it possible to determine the resonance electrocouplings and $\pi\Delta$, and ρN decay widths from the resonant contributions employing for their description the amplitudes of the unitarized Breit-Wigner ansatz [26] that fully accounts for the unitarity restrictions on the resonant amplitudes. This model will be used in the proposed experiment for analyses of exclusive $\pi^+\pi^-p$ electroproduction allowing us to determine electrocouplings of most excited nucleon since almost all nucleon resonances have substantial hadronic decays to the $N\pi\pi$ final states. Capability of the JM model to pin down new baryon states was demonstrated in the combined studies of exclusive $\pi^+\pi^-p$ photo- and electroproduction [47] which provided convincing evidence for new baryon state $N(1720)3/2^+$

The model for description of the KY exclusive photo- and electroproduction channels "regge-plus-resonance" (RPR) has been developed by the Ghent group [17, 18]. In this model full production amplitude is described by the superposition of eight resonances and the non-resonant contribution. The non-resonant amplitudes represent the sum of t-channel exchanges by K- and K^*-Regge trajectories. The model provided a good description of KY photoproduction data. It reproduces the gross features in Q^2-evolution for the exclusive unpolarized structure functions. We are planning to use this model for extraction of the resonance electrocouplings from exclusive KY electroproduction data after the model upgrade allowing improved description of the structure functions. The development in this direction was presented in [63].

Contribution from JPAC on Regge for KY, and......

III. MODELING THE HYBRID BARYON CONTRIBUTION TO EXCLUSIVE KY AND $\pi^+\pi^-p$ ELECTROPRODUCTION OFF PROTONS.

IV. MAGNITUDES OF THE ELECTROEXCITATION AMPLITUDES NEEDED FOR THE HYBRID-BARYON OBSERVATION

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V. SEARCH FOR THE HYBRID-BARYON SIGNAL EMPLOYING THE LEGENDRE MOMENT EXPANSION

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VI. TESTING THE PROCEDURES FOR THE HYBRID-BARYON IDENTIFICATION IN THE MONTE-CARLO STUDIES WITH THE QUASI-DATA

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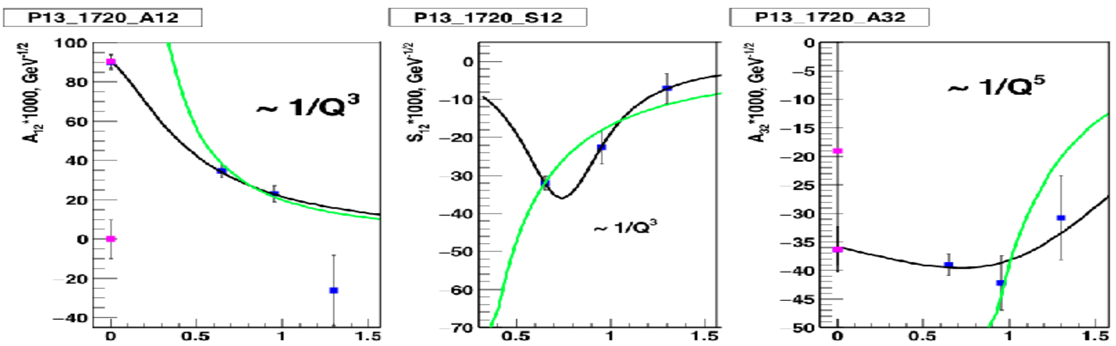

FIG. 3: Interpolation of the $N(1720)3/2^+$ electrocouplings from the CLAS data on $\pi^+\pi^-p$ [47] exclusive electroproduction off protons [21]. The results at the photon point are taken from [45, 47]

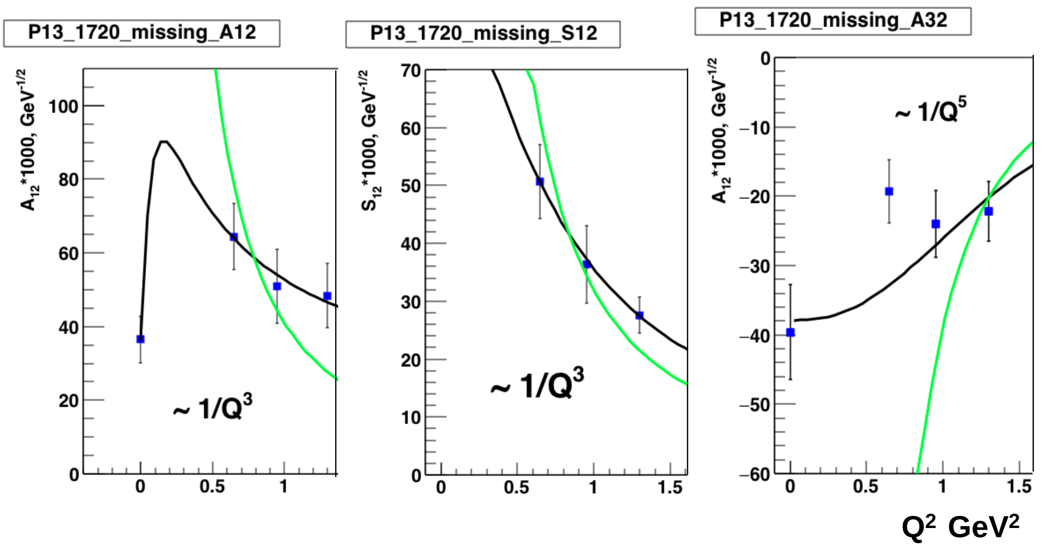

FIG. 4: Interpolation of the $N'(1720)3/2^+$ electrocouplings from the CLAS data on $\pi^+\pi^-p$ [47] exclusive electroproduction off protons [21]. The results at the photon point are taken from [45, 47]

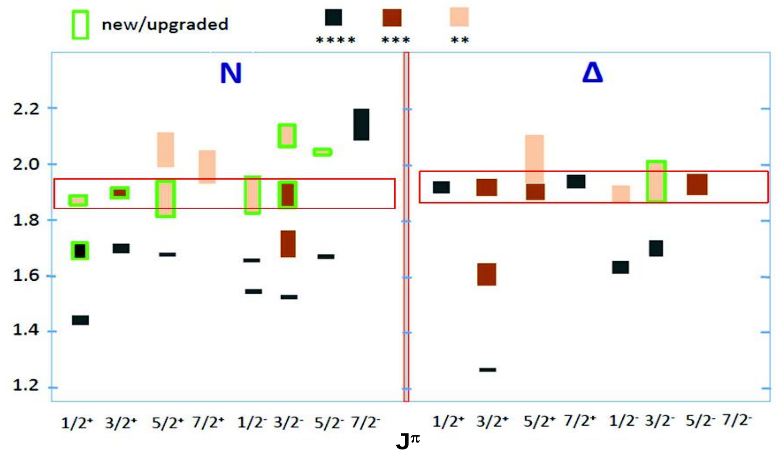

FIG. 5: Recent results on the spectrum of excited nucleon states [1]. Signals from the states shown in green boxes were observed in global multi-channel analysis of exclusive meson electroproduction data carried out within the framework of Bonn-Gatchina approach[48–50].