Quark Model Calculations of the N to Delta Reaction

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Abstract

The electromagnetic excitation of the nucleon resonances is studied in the framework of Constituent Quark Models. Particular attention is devoted to the transition to the \( \Delta \) resonance and to the issue of a possible deformation of hadronic systems, mainly in connection with the problem of the quadrupole excitation. The analysis of the emerging discrepancies between data and theoretical predictions is discussed and shown to lead to important conclusions concerning the internal dynamical structure of hadrons.

1 Introduction

The study of the electromagnetic excitation of the nucleon resonances is expected to provide a good test for our knowledge concerning the internal structure of baryons. The \( N - \Delta \) transition is one of the most important ones, since both in the pion-nucleon and the electroproduction channels the \( \Delta \) peak is the most evident and lowest one in energy. Moreover, according to the quark model, the \( \Delta \) state is the \( SU(6) \) partner of the nucleon and therefore, apart from a spin-isospin flip, it shares the same internal structure with the nucleon. From a fundamental point of view, the description of the nucleon resonances and their excitation should be performed within a QCD approach, at least in its Lattice formulation. There is considerable progress in this area (see e.g. [1]), however a complete and consistent account of the whole excitation spectrum is not yet available.

In this respect, Constituent Quark Models (CMQs) are particularly useful, since they allow to take into account fundamental aspects of the quark dynamics within a simple scheme, which can on the other hand be used for a systematic and consistent study of various baryon properties.

In the following, some of the more popular CQMs will be briefly reviewed and compared, showing to which extent they have been applied to the study of a large variety of hadron properties. The electromagnetic (e.m.) excitation
of the nucleon resonances will be discussed, with particular attention to the $N - \Delta$ problem. The CQMs permit a systematic comparison between the theoretical predictions and the observed experimental behaviour and are able to describe in a quantitative way many important data. The analysis of the emerging discrepancies allows then to draw reasonable conclusions concerning some fundamental aspects of the quark dynamics, such as meson and/or sea-quark effects, which are presently missing, but expected to play a relevant role in the future of hadron physics.

2 Constituent Quark Models

Various Constituent Quark Models (CQM) have been proposed in the past decades after the pioneering work of Isgur and Karl (IK) [2]. Among them let us quote the relativized Capstick-Isgur model (CI) [3], the algebraic approach (BIL) [4], the hypercentral CQM (hCQM) [5], the chiral Goldstone Boson Exchange model ($\chi$CQM) [6] and the Bonn instanton model (BN) [7]. They are all able to reproduce the baryon spectrum, which is the first test to be performed before applying any model to the description of other physical quantities. The ingredients of the models are quite different, but they have a simple general structure, since the interaction $V_{3q}$ they use can be split into a spin-flavour independent part $V_{inv}$, which is $SU(6)$-invariant and contains the confinement interaction, and a $SU(6)$-dependent part $V_{sf}$, which contains spin and eventually flavour dependent interactions

$$V_{3q} = V_{inv} + V_{sf}$$  \hspace{1cm} (1)

This structure should be compared with the prescription provided by the early Lattice QCD calculations [8], that is an interaction containing a spin-independent long range part and a spin-dependent short range term. The pattern of Eq. (1) is actually in agreement with an important feature of the baryon spectrum. In fact, the various resonances can be grouped into $SU(6)$-multiplets, the energy differences within each multiplet being at most of the order of 15\% (as in the case of $N - \Delta$ mass difference and of the splittings within the $SU(3)$ multiplets). To illustrate this point, we list below the lower $SU(6)$-multiplets accompanied by the non strange baryons they contain:
The notation for the $SU(6)$-multiplets is $(N, L^P)$, where $N$ is the dimension of the $SU(6)$-representation, $L$ is the total orbital angular momentum of the three-quark state describing the baryon and $P$ the corresponding parity. The star in the second line reminds that the states have the same spin-isospin structure as those in the first line but are radially excited. It should be reminded that with three quarks one can obtain the $SU(6)$-representations with dimensions $N = 20, 56, 70$. The spin and flavour content of each $SU(6)$-representation is well defined, since the three $SU(6)$ representations can be decomposed according to the following scheme

\begin{align}
20 &= 41^1 + 28^2 \\
56 &= 28^2 + 410^3 \\
70 &= 21^1 + 28^2 + 48^3 + 210^4
\end{align}

The suffixes in the r.h.s. denote the multiplicity $2S + 1$ of the $3q$ spin states and the underlined numbers are the dimensions of the $SU(3)$ representations. This means for instance that the 56 representation contains a spin-$1/2$ $SU(3)$ octect and a spin-$3/2$ $SU(3)$ decuplet (more details can be found in \cite{9}).

An important observation concerns the level ordering displayed by the experimental baryon masses: the $1^-$ states are in average almost degenerate with the first $0^+$ excitation, while for any two body potential the ordering is $0^+, 1^-, 0^+$. Moreover, in the case of the h.o. potential the spacing between two shells is the same over the whole spectrum.

In order to reproduce the spectrum, any CQM should lead to reasonable average energy levels by means of the $SU(6)$-invariant part of the potential $V_{\text{inv}}$ and describe the splittings within each multiplet through the spin-flavour dependent interaction $V_{\text{sf}}$. The latter is relevant for the topic of this workshop, in fact the (spin-dependent) tensor forces, which are present in some models, are
able to generate a deformation of the three quark states. It is therefore useful to analyze the main features of the various models.

CI [3]. The confinement is provided by a three-body term corresponding to a $Y$-shaped configuration. The multiplet splittings are mainly given by an interaction, which is inspired by the One-Gluon-Exchange mechanism and as such it contains a spin-spin term and a tensor force. The three-body equation, with relativistic kinetic energy, is solved by means of a variational approach in a large h.o. basis.

BIL [4]. The $SU(6)$-invariant part of the levels is obtained starting from a $U(7)$-symmetry of the three-quark states and considering a string-like collective model for the mass operator of the baryon states, taking into account rotations and vibrations of a $Y$-shaped configuration. The energy splittings are produced by a Gürsey-Radicati mass formula [10], containing constant spin, isospin and flavour dependent terms, which are proportional to the Casimir operators of the $SU(6)$, $SU(2)$ and $SU(3)$ groups describing the relevant intrinsic quark degrees of freedom.

hCQM [5]. The quark potential is assumed to be hypercentral, that is to depend only on the hyperradius $x$, defined as $x = \sqrt{\vec{\rho}^2 + \vec{\lambda}^2}$, where $\vec{\rho}$ and $\vec{\lambda}$ are the Jacobi coordinates describing the quark internal motion. The hyperradius $x$ assumes the meaning of a collective variable, describing the size of the baryon state. The explicit form of the potential is given by

$$V_{hCQM} = -\frac{\tau}{x} + \alpha x$$  \hspace{1cm} (5)$$

A potential containing a coulomb-like and a linear confinement term has been used since long time in the description of the meson sector (Cornell potential). Such structure has been recently supported by Lattice QCD calculations for static quarks [11, 12, 13]. In this respect the hCQM potential can be considered as the hypercentral approximation of a quark-quark interaction of the Cornell type. The hypercentral approximation has been used both in the nuclear [14, 15] and baryon [16] cases, with good results specially for the lower part of the spectra. Thanks to the $x$-dependence, the hCQM interaction may also include many body contributions, corresponding for instance to the already mentioned $Y$-shaped string configuration. The presence of the coulomb-like term is important for various reasons. Here it is sufficient to remind that the potential $1/x$ leads to an analytical solution, thereby providing an alternative basis to the h.o. one, and moreover the $1^-$ states are perfectly degenerate with the excited $0^+$ states. The linear confinement term slightly modifies this ordering [5], and, in order to obtain the correct position of the resonances, in particular of the Roper $P_{11}(1440)$, it is necessary to add isospin dependent terms to the potential [17]. The multiplet splittings are provided by a hyperfine interaction of the standard form [2]. The description of the spectrum has been extended to the strange resonances by means of a Gürsey-Radicati $V_{sf}$ term [18]. The fit of the spectrum leads to the values $\tau = 4.59, \alpha = 1.61(\text{fm})^{-2}$ [5], which are kept fixed in the subsequent applications of the model to various quantities of interest.
GBE [6]. The confinement interaction, in the more recent version of the model, is given by a linear two-body term. Consistently with the idea that at low energies pseudoscalar mesons are relevant degrees of freedom as Goldstone Bosons, an explicit quark-quark potential due to meson exchange is introduced. The splittings within multiplets are then provided by the spin and isospin dependence of the pseudoscalar meson exchange. The model has been extended to include also scalar and vector meson exchange [19]. Of course, both $\pi$ and $\rho$ exchange lead to tensor forces and therefore to a possible deformation of the nucleon and of the $\Delta$ resonance.

BN [7]. The model is fully relativistic in the sense that it is based on a Bethe-Salpeter approach for the description of the three-body system. The confinement is produced by a three-body term depending linearly on a collective variable corresponding to a $\Delta$-shaped three-quark configuration. The result for the spectrum are only slightly changed if the $\Delta$-shaped three-quark configuration is substituted with the $Y$ or the hypercentral one. The $V_{s\beta}$ part is provided by a two-body ’t Hooft’s residual interaction, based on QCD-instanton effects. It is important to mention that such interaction acts only on antisymmetric two quark spin states and therefore it does not affect the $\Delta$ resonance.

As mentioned above, all models provide a more or less reasonable description of the baryon spectrum; in particular the $N-\Delta$ mass difference is correctly fitted, although this splitting has various origins in the different models: hyperfine interaction (GI, hCQM), pion exchange (GBE), instanton effects (BN), spin-isospin dependent Casimir operators (BIL).

The CQMs have also been applied to the calculation of other physical quantities and it is interesting to see to which extent and how systematically the various CQM have been used; one should however not forget that in many cases the calculations referred to a CQM calculations are actually performed using a simple h.o. wave function for the internal quark motion either in the non relativistic (HO) or relativistic (relHO) framework. In the following a (non exhaustive) list of applications of the various CQM models (HO, relHO, IK, CI, BIL, hCQM, GBE, BN) is reported:

- photocouplings: HO [20], IK [21], CI [22], BIL [4], hCQM [23] (for a comparison among these and other approaches see e.g. [23, 24]);
- the transition form factors for the excitation of the nucleon resonances (helicity amplitudes): HO [20], KI [21], relHO [22], CI [22, 26, 27], hCQM [28, 29, 30], BN [31], in the latter case with particular attention to the strange baryons [32];
- the elastic nucleon form factors: BIL [4, 33], CI [34], hCQM [35, 29, 36, 37], GBE [38, 39], BN [31], again with emphasis on the strange baryons [40];
- the axial nucleon form factors GBE [39, 41], BN [31];
- the strong decay of baryon resonances IK [21], relHO [32], CI [33], BIL [44], GBE [45], hCQM [46].

There also calculations of the nucleon structure functions [47] and of the Generalized Parton Distributions [48, 49], performed using simple CQMs, eventually in a relativized framework.
Here however the attention will be devoted to the $N - \Delta$ transition both in the photon limit and in its full $Q^2$ dependence.

## 3 The electromagnetic transition amplitudes

The attempt of describing the transition amplitudes for the electromagnetic excitation of the baryon resonances implies a more stringent test of the dynamics involved in the various CQMs, since this kind of process is more sensitive to the internal structure of the three quark states.

From the experimental point of view, the transition amplitudes are extracted from measurements of the photo- or electro-production of pions. This leads to a problem concerning the sign of the e.m. amplitude. In fact, one can determine the overall phase of the pion production amplitude, however the sign of the e.m. excitation vertex is strictly correlated to the one of the strong decay. Presently, CQMs are not able to calculate in a consistent way the pion production process and it is therefore important to extract in any case the e.m. amplitude, even if it includes the unknown phase of the strong decay vertex (for a discussion on this point see e.g. [24]).

In order to calculate the e.m. transition amplitudes within a CQM, one considers a direct coupling between the quark current and the e.m. field. The quark current is chosen in the majority of cases as a one-body current in impulse approximation. In this approximation, the transverse photon-quark interaction can be written

$$H_{em}^t = - \sum_{i=1}^{3} \left[ \frac{e_j}{2m_j} (p_j^\gamma \cdot \vec{A}_j + \vec{p}_j \cdot \vec{A}_j) + 2\mu_j \vec{s}_j \cdot (\vec{\nabla} \times \vec{A}_j) \right],$$

in Eq. (6) $m_j$, $e_j$, $s_j$, $p_j$ and $\mu_j = \frac{e_j}{2m_j}$ denote the mass, the electric charge, the spin, the momentum and the magnetic moment of the $j$-th quark, respectively, and $\vec{A}_j = \vec{A}_j(p_j^\gamma)$ is the photon field.

The non relativistic formulation of Eq. (6) can be relativized introducing various higher order spin dependent terms (see e.g. [24] and references quoted therein). There are also formulations which make use of a covariant quark current in the framework of a relativistic dynamics approach [26].

The quark-photon interaction of Eq. (6) (or its relativistic version) is used to calculate the helicity amplitudes for the excitation of the baryon non strange resonances

$$A_{1/2}(Q^2) = \langle B, J', J_z' = \frac{1}{2} | H_{em}^t | N, J = \frac{1}{2}, J_z = -\frac{1}{2} \rangle$$

$$A_{3/2}(Q^2) = \langle B, J', J_z' = \frac{3}{2} | H_{em}^t | N, J = \frac{1}{2}, J_z = \frac{1}{2} \rangle$$

There are two important aspects in connection with the phenomenological e.m. helicity amplitudes: the strength at $Q^2 = 0$ (photocouplings) and the $Q^2$ behaviour (transition form factors).
As for the photocouplings, the calculations in general describe the overall trend, in the sense that they reproduce the oscillatory behaviour displayed by data if increasing masses of the $N$ or $\Delta$ resonance states are considered. This means in particular that the locations of zero or very small strength are accounted for. However, there is also an equally general underestimate of the strength, quite independently of the model which is used; the inclusion of relativistic corrections with spin dependent terms does not improve the fit (for a discussion see e.g. [23, 24]). The fundamental reason of this common failure is probably due to the fact that all CQMs have the same spin-isospin structure and, as it will be discussed later, also because meson or quark pair effects are lacking.

The behaviour of the theoretical transition form factors at low $Q^2$ is affected by the lack of strength mentioned above. For higher $Q^2$, the results are strictly dependent on the quality of the three-quark wave function, that is on the dynamics which is chosen. For instance, for wave functions dominated by pure h.o., the resulting transition form factors are too strongly damped for increasing $Q^2$ and therefore are not able to reproduce the phenomenological trend. In the case of the negative parity non strange resonances, the experimental behaviour is fairly well reproduced by the parameter-free calculations made with the hCQM [28], specially for the $S_{11}$, whose trend has been predicted before the recent Jlab data [50]. The softer $Q^2$ dependence displayed by the theoretical form factors is due, in the hCQM calculation, to the presence of the Coulomb-like term in the interaction. In fact, very similar results are obtained in the analytical version of the model [29], in which the linear confinement is treated as a perturbation and the (analytical) $Q^2$ dependence is completely determined by the $1/x$ potential [29].

Coming to the $N-\Delta$ excitation, the main $M1$ transition can be evaluated in all models, but the theoretical amplitudes underestimate the phenomenological one by a factor of the order of 30%; this feature was present also in the early quark model calculations, which gave the result [51, 52]

$$G_{M1} = \frac{2M_\Delta}{M + M_\Delta} \frac{2}{\sqrt{3}} \mu_P = 3.7$$

where $M$ and $M_\Delta$ are the nucleon and $\Delta$ mass, respectively and $\mu_P$ is the proton magnetic moment; the value in Eq. (8) should be compared with the measured one, which is of the order of 5. The situation has not been modified by the more recent and refined models.

The $E2$ transition is important because it is connected with the issue of a possible deformation of hadrons. If the quarks in the Nucleon and the $\Delta$ are in a pure $S$-wave state there is obviously no $E2$ excitation [52]. Therefore a deformation can be produced only if the interaction contains a tensor force: this happens in models with a hyperfine interaction inspired by QCD [53, 3, 5, 23] or with a pion exchange potential [6] (however in the latter case no $E2$ transition calculation is available). At the photon point, the results on the quadrupole $N-\Delta$ transition are given in terms of the ratio
where $G_{E2}$ and $G_{M1}$ are the transverse electric and magnetic transition strengths, respectively. The PDG value is $R = -0.02 \pm 0.005$. A number not far from this was obtained with the CQM including a hyperfine interaction [21, 53]. In particular, taking care of the higher shells and of the Siegert’s theorem for a more accurate and reliable calculation, the value $R = 0.02$ was obtained [55]. However one should not forget that the $M1$ transition is underestimated and then, even if the ratio is correctly reproduced, the quadrupole strength still remains too low. An estimate of the total quadrupole excitation strength for the nucleon can be obtained from an energy weighted sum rule approach to the excitation of the quark degrees of freedom [56]; the $F_{15}(1680)$ resonance, which is mainly a D-state, saturates only 30% of the sum rule, showing that the missing strength is expected to be spread over the whole spectrum.

The inadequacy of CQMs to reproduce the quadrupole photon excitation is visible also when one studies the $Q^2$ behaviour of the transition form factors. In this case also the longitudinal amplitude $S_{1/2}$ must be considered. The situation is illustrated in Fig. 1 [57], where the longitudinal form factor for the $N \rightarrow \Delta$ transition, calculated with the hCQM, is reported in comparison with a global fit performed by the Mainz group [58]. The theoretical $S_{1/2}$ is very small in comparison with data.

A similar underestimate occurs also for the transverse helicity amplitudes $A_{1/2}, A_{3/2}$ (see Figs. 2 and 3) and therefore also for the the transverse electric
$G_{E2}$ and the magnetic $G_{M1}$ from factors, since by definition they are proportional to linear combinations of the transverse helicity amplitudes:

\begin{align}
G_{E2} &\propto A_{3/2} - \sqrt{3}A_{1/2} \\
G_{M1} &\propto \sqrt{3}A_{3/2} + A_{1/2}
\end{align}

Figure 2: The same as in Fig. 1 but for the transverse helicity amplitude $A_{1/2}$. At $Q^2 = 0$ the photon coupling from PDG is shown [54].

The seriousness of this discrepancy is enhanced by the expectation that, on the basis of helicity conservation in the virtual photon-quark interaction, the ratio

$$A = \frac{|A_{1/2}|^2 - |A_{3/2}|^2}{|A_{1/2}|^2 + |A_{3/2}|^2}$$

is expected to reach the value 1 [67] if $Q^2$ goes to infinity. It is easy to show that

$$A = -\frac{1}{2} + \frac{3G_{E2}(G_{E2} - G_{M1})}{G_{M1}^2 + 3G_{E2}^2}$$

which implies that the value $A = 1$ is reached for $G_{E2} = -G_{M1}$.

A possible reason of this discrepancy can be envisaged looking again at Figs. 1, 2 and 3, where the contributions of the meson cloud [60] to the $\Delta$ helicity amplitudes are reported. But this point will be discussed in the next section.

## 4 Meson and Quark pair effects

As quoted in the last section, the various models reproduce the overall trend of the photocouplings, in particular the cases where the excitation strength is vanishing. It should be reminded that in the earlier h.o. calculations [20] the vanishing of the $A_{1/2}$ helicity amplitude for the excitation of the proton to the
Figure 3: The same as in Fig. 1 but for the transverse helicity amplitudes $A_{3/2}$. At $Q^2 = 0$ the photon coupling from PDG is shown \[54\].

$F_{15}(1680)$ resonance was obtained imposing the proton radius to be of the order of 0.5 fm. In this way also the $A_{1/2}$ helicity amplitude for the proton transition to the $D_{13}(1520)$ turns out to be small. It is worthwhile noting that the calculated proton radius in the hCQM is actually about 0.35 fm; this fact is one of the reasons why the hCQM predictions for the helicity amplitudes of the negative parity resonances are in reasonable agreement with data \[28\].

The smallness of the proton radius required for the description of the e.m. excitation together with the lack of strength in the low $Q^2$ region, suggest an interesting picture for the proton \[68, 23, 28\] (and consequently for hadrons), namely that of a small core, with radius of about 0.5 fm, surrounded by an external cloud made of mesons and/or quark-antiquark pairs. The contributions coming from this external cloud have been pointed out as a possible origin of the missing strength \[68, 23, 28\] and are obviously lacking in the available CQMs; their effect is expected to decrease for medium-high $Q^2$ and therefore it is not a surprise that the hCQM fails to reproduce the strength at the photon point but give reasonable results for medium $Q^2$. These considerations are supported by the inspection of Fig. 1, 2 and 3, where the pion cloud contributions, evaluated by means of a dynamical model \[60\], are reported. Their importance decreases with increasing $Q^2$, going rapidly to zero, as expected. This feature is quite general, since it happens systematically also for the excitation of higher resonances, such as $P_{11}(1440), S_{11}(1535), D_{13}(1520), F_{15}(1680)$ \[57\]. It is important to note that the pion contributions tend to fill the gap between the pure valence quark calculations and the data. In particular, the quadrupole strength observed in the $N - \Delta$ excitation seems to be substantially due to meson effects or, stated in another way, to sea quark effects. Therefore the shape of baryons is determined not only by the quark core but also by the meson or quark-antiquark pair cloud.

The quark-antiquark pair and/or meson cloud effects are relevant in many
properties of hadrons. One important case is the width of resonances, coming from the decay of baryons in the meson nucleon channel. This implies a coupling with the continuum, which is not taken into account in the present CQMs; a quark-meson vertex is in some models introduced in order to describe the strong decay [21, 42, 43, 44, 45], but the theoretical baryon states are all with zero width. The spectrum itself presents some features which might be a manifestation of quark pair effects, namely the isospin dependence which is necessary to describe the position of some states such as the Roper. This is clear in the GBE model [6], where a pion is explicitly exchanged, but also in other models [4, 17] the isospin dependence may be a remnant of quark-antiquark effects. However, an explicit manifestation of quark pair and/or meson effects should be looked for in the baryon widths. A work on these lines has been done some time ago: the IK model has been extended introducing a direct quark-meson coupling by means of appropriate interaction lagrangians and used for the description of both masses and widths of baryons [69].

The elastic nucleon form factors provide another example of physical quantities for which such effects are expected to be relevant. Because of the smallness of the quark core radius, the non relativistic calculations are not able to reproduce the nucleon form factor data. The inclusion of first order relativistic corrections generated by Lorentz boosts gives rise to a substantial improvement [35] and, moreover, it has been shown to lead to a decrease of the ratio $G_E/G_M$ between the electric and magnetic proton form factors [36], in qualitative agreement with the recent Jlab measurements [70].

For a good description of the nucleon elastic form factors a completely relativistic approach is needed. The internal quark motion is usually described in the baryon rest frame, but the elastic form factors are evaluated in the Breit frame, in motion with respect to both the initial and final nucleon rest frame with a velocity which increases with the virtual photon momentum transfer $Q^2$. Therefore, the theory should be formulated in a covariant way, transforming correctly the three quark states by means of Lorentz boosts and making use of a covariant quark current. Various relativistic calculations of the elastic nucleon form factors are now available [34, 38, 39, 31, 37], obtaining a good description of data. However, in order to achieve a detailed account of the experimental behaviour [37], in particular of the decrease of the $G_E/G_M$ ratio and of the small $Q^2$ wiggles in the proton form factors, one has to introduce intrinsic quark form factors. Actually constituent quarks are effective degrees of freedom, which take implicitly into account complicated quark-gluon interactions, which of course contain also quark pair effects. (For a review concerning the elastic nucleon form factors the reader is referred to [71]).

The inclusion of meson effects in hadron properties is now receiving considerable attention and in this Workshop there are numerous examples. Concerning the electromagnetic excitation of nucleon resonances we can quote the Mainz dynamical model [60], the coupled channel approach [72] and the inclusion of explicit $3q$-pion components in the nucleon state [73].
5 Conclusion

The study of the electromagnetic excitation of the nucleon resonances offers the opportunity for a sensitive test of the CQMs. The Nucleon-Δ case is particularly interesting because the Δ resonance is easily and strongly excited and its internal structure is very similar to that of the nucleon. Moreover, some models, namely those which consider a tensor-like force between quarks, predict a deformation of both the nucleon and the Δ, a deformation which can manifests itself in a longitudinal and transverse quadrupole excitation strength. CQM calculations, performed consistently with other baryon properties, in particular the spectrum, predict strengths which are very low in comparison with the observed ones. On the other hand, the pion contributions, evaluated by means of a dynamical model, have been shown to be able to fill at least partially, the gap between data and theoretical predictions, supporting a view of the nucleon as a small quark core surrounded by an external meson (or quark pair) cloud. This means in particular that the shape of hadrons is to a large extent determined by such meson cloud effects, which will be certainly object of intense studies in the near future.

An important issue connected with the study of the internal baryon structure is provided by relativity. This means first of all the necessity of introducing the relativistic kinetic energy in order to describe correctly the internal quark motion, also in case of small constituent quark masses. More relevant is the formulation of the model within a consistent relativistic framework, which means a relativistic hamiltonian in any of the allowed forms (light front, instant or point) or a Bethe-Salpeter approach. The inclusion of relativity, specially in the sense of considering a covariant quark current, is crucial for the description of the elastic form factors. However, for the electromagnetic transition form factors, the relativistic corrections, at least at the first order level, are meaningful but not determinant [30]. On the other hand, the spectrum seems to be not sensitive to relativity, provided that the quark masses are not too low.

The analysis of the theoretical predictions concerning the $Q^2$ behaviour of the helicity amplitudes in general, but in particular in the case of the $N - Δ$ transition, shows that some fundamental mechanism is lacking and there are indications that meson cloud and/or quark-antiquark pair effects should be included in the CQM description of hadron properties.

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