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Baryon Masses and Structures Beyond Valence-Quark Configurations⋆

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Abstract. In order to describe baryon resonances realistically it has turned out that three-quark configurations are not sufficient. Rather explicit couplings to decay channels are needed. This means that additional degrees of freedom must be foreseen. We report results from a study of the nucleon ground state and the Delta resonance by including explicit pionic effects.

All current approaches to quantum chromodynamics (QCD) struggle with a proper description of hadron resonances. For baryons one has found that in case of ground states at low energies three-quark configurations can still provide a reasonable picture. For instance, in a relativistic constituent-quark model relying on $\{QQQ\}$ configurations only, the masses of all ground-state baryons as well as their electromagnetic and axial structures can be well reproduced [1]. In this framework, however, the resonant states are afflicted with severe shortcomings. While the characteristics of the mass spectra can still be yielded to some extent, the reaction properties of baryon resonances fall short, especially with respect to their strong decays. Obviously the reason is that with three-quark configurations only the resonances are described as excited bound states with real eigenvalues rather than genuine resonant states with complex eigenvalues. Consequently, the corresponding wave functions or amplitudes show a completely distinct behaviour.

We have started to include beyond $\{QQQ\}$ configurations explicit mesonic degrees of freedom. In the first instance, we have studied pionic effects in the N and the Δ masses. We have done so by considering π-loop effects on the hadronic as well as the microscopic quark levels. Our program aims at developing a coupled-channels relativistic constituent-quark model that can generate consistently the strong vertex form factors, the baryon ground-state and resonant masses as well as their electroweak structures. It will contain mesonic degrees of freedom such as $\{QQQ\pi\}$, $\{QQQ\rho\}$, and eventually $\{QQQ\pi\pi\}$ etc.

Here we discuss results obtained from π-dressing of the N and the Δ on the hadronic level. We have investigated the most important one-π-loop effects and several higher-order diagrams. A first account of this study was given already in Ref. [2], where also the formalism and details of the calculation are explained. In this context one has in the first instance to solve an eigenvalue equation, which

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results from coupling of a bare $\widetilde{N}$ and a bare $\widetilde{\Delta}$ to a single π according to the diagrams in Fig. 1. It yields the bare and dressed masses, where the latter is real for the N ground state and becomes complex for the Δ resonance. The only input into the calculation are the prescriptions for the $\pi\widetilde{N}\widetilde{N}$ and $\pi\widetilde{N}\widetilde{\Delta}$ form factors at the strong-interaction vertices. For that we have employed models existing in the literature [3–5]. Beyond the results already produced in Ref. [2] we give here in addition values for the dressing effects by using the more recent form-factor parametrization by Kamano et al. [6] derived from a coupled-channels meson-nucleon model. The different form factors are parametrized through the formulae

$$F_{\pi\widetilde{N}\widetilde{B}}(\mathbf{k}_\pi^2) = \frac{1}{1 + (\frac{k_\pi}{\lambda_1})^2 + (\frac{k_\pi}{\lambda_2})^4} \qquad \text{or} \qquad F_{\pi\widetilde{N}\widetilde{B}}(\mathbf{k}_\pi^2) = \exp^{-\mathbf{k}_\pi^2/2\lambda^2}$$

$$\text{or} \qquad F_{\pi\widetilde{N}\widetilde{B}}(\mathbf{k}_\pi^2) = \left(\frac{\lambda^2}{\mathbf{k}_\pi^2 + \lambda^2}\right)^2, \tag{1}$$

where $\widetilde{B}$ stands either for $\widetilde{N}$ or $\widetilde{\Delta}$. The values of the various cut-off parameters are given in Tab. 1 together with the corresponding coupling constants.

Table 1. Parameters of the bare $\pi\widetilde{N}\widetilde{N}$ and $\pi\widetilde{N}\widetilde{\Delta}$ vertex form factors. The first three columns correspond to the multipole type as in the first formula of Eq. (1), the fourth column to the Gaussian type as in the second formula of Eq. (1), and the last column to the dipole type as in the third formula of Eq. (1). The corresponding parametrizations are taken from Refs. [3], [5] and [6], respectively. All (bare) coupling constants belong to $\mathbf{k}_\pi^2 = 0$. RCQM refers to the predictions of the relativistic constituent-quark model [7] in Ref. [3], SL to the πN meson-exchange model by Sato and Lee [4], PR to the Nijmegen soft-core model of Polinder and Rijken [5], and KNLS to the coupled-channels meson-nucleon model of Kamano, Nakamura, Lee, and Sato. All cut-off parameters are in GeV.

		RCQM	SL	PR multipole	PR Gaussian	KNLS
	$f^2_{\pi\widetilde{N}\widetilde{N}}/4\pi$	0.0691	0.08	0.013	0.013	0.08
	λ_1	0.451	0.453	0.940		
$\pi\widetilde{N}\widetilde{N}$	λ_2	0.931	0.641	1.102		
	λ				0.665	0.656
	$f^2_{\pi\widetilde{N}\widetilde{\Delta}}/4\pi$	0.188	0.334	0.167	0.167	0.126
	λ_1	0.594	0.458	0.853		
$\pi\widetilde{N}\widetilde{\Delta}$	λ_2	0.998	0.648	1.014		
	λ				0.603	0.709

For the $\pi\widetilde{N}\widetilde{N}$ vertex the momentum dependences of the form factors from the five different models are shown in Fig. 2. With these ingredients the π-dressing effects in the N mass are yielded as in Tab. 2. The mass shifts are basically of the same order of magnitude for all form-factor models employed, even though

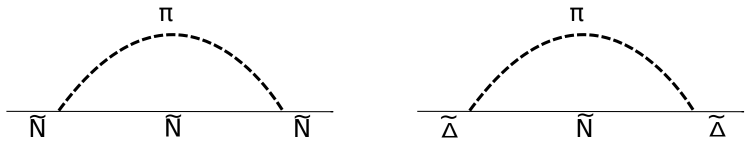

Fig. 1. π-loop diagrams considered for the dressing of a bare $\widetilde{\mathrm{N}}$ and a bare $\widetilde{\Delta}$.

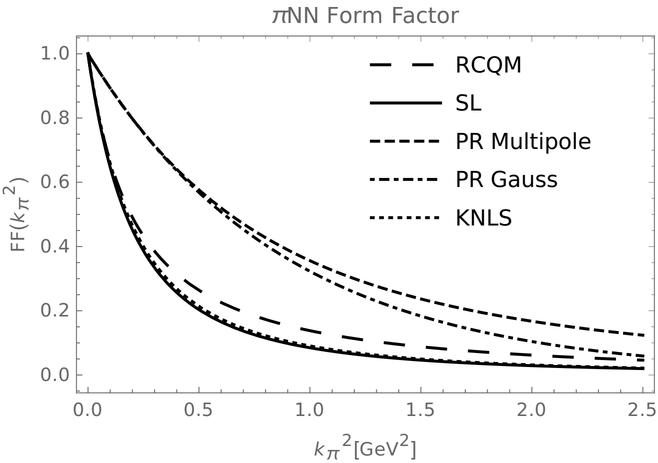

Fig. 2. Dependences on the π three-momentum squared $\mathbf{k}_\pi^2$ of the different (bare) form-factor models for the $\pi\widetilde{\mathrm{N}}\widetilde{\mathrm{N}}$ system.

the momentum dependences are quite different as seen from Fig. 2. However, the net effect is gained from an interplay of the momentum dependence of each form factor and the corresponding $\pi\widetilde{\mathrm{N}}\widetilde{\mathrm{N}}$ coupling constant (cf. Tab. 1). The largest dressing effect is obtained in case of the RCQM.

Table 2. π-loop effects in the N mass $m_\mathrm{N} = 0.939$ GeV according to the l.h.s. diagram of Fig. 1.

		RCQM	SL	PR multipole	PR Gaussian	KNLS
$m_{\widetilde{\mathrm{N}}}$	[GeV]	1.067	1.031	1.051	1.025	1.037
$m_{\widetilde{\mathrm{N}}} - m_\mathrm{N}$	[GeV]	0.128	0.092	0.112	0.086	0.098

For the $\pi\widetilde{\mathrm{N}}\widetilde{\Delta}$ vertex the momentum dependences of the form factors from the five different models are shown in Fig. 3. With these ingredients the π-dressing effects in the Δ mass are yielded as in Tab. 3. It is immediately evident that the Δ mass gets complex. The real part corresponds to resonance position in the πN channel and the complex part to (half) the hadronic Δ decay width. While the π-dressing effects in the real part are of about the same magnitudes as in the N, in all cases the decay widths are much too small as compared to the empirical value of about 0.117 GeV.

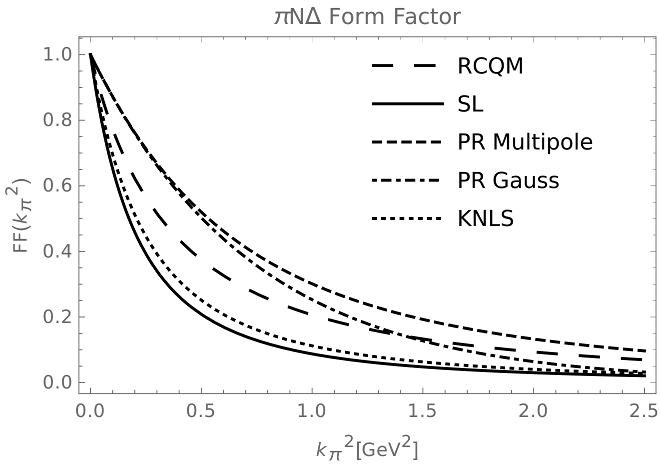

Fig. 3. Dependences on the π three-momentum squared k_π^2 of the different (bare) form-factor models for the $\pi\tilde{N}\tilde{\Delta}$ system.

Table 3. π-loop effects in the Δ mass $\mathrm{Re}\,(m_\Delta)$= 1.232 GeV and in the π-decay width Γ according to the r.h.s. diagram of Fig. 1, where the bare $\tilde{N}$ masses $m_{\tilde{N}}$ in the intermediate states are the same as in Table 2.

		RCQM	SL	PR multipole	PR Gaussian	KNLS
$m_{\tilde{\Delta}}$	[GeV]	1.300	1.290	1.335	1.321	1.259
$m_{\tilde{\Delta}} - \mathrm{Re}\,(m_\Delta)$	[GeV]	0.068	0.058	0.103	0.089	0.027
$\Gamma = 2\,\mathrm{Im}\,(m_\Delta)$	[GeV]	0.004	0.023	0.008	0.016	0.007

An improvement in the $\Delta \to \pi N$ decay width Γ is achieved by replacing the bare $\tilde{N}$ in the intermediate state by the dressed N like in Fig. 4. Thereby the phase space for the strong decay is enlarged, and the situation may be closer to the realistic one. The π-dressing effect in the real part is slightly raised in all cases, as compared to the values in Tab. 3, however, the changes achieved for the decay width Γ are respectable. Now, they reach about 50% of the phenomenological value, except for the KNLS form-factor model. Still, the results appear to be unsatisfactory.

Therefore we have investigated higher-order effects, i.e. two-π loops, where the ones with π-π interactions in the intermediate state can be effectively described by σ and ρ mesons. The corresponding dressing effects turned to be marginal. Their inclusions do not help much to improve the Δ decay width.

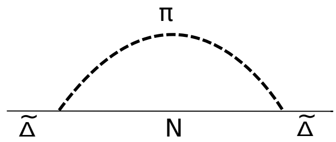

Fig. 4. π-loop diagram considered for the dressing of a bare $\widetilde{\Delta}$, where in the intermediate state a physical N with mass m_N=0.939 GeV is employed.

Table 4. π-loop effects in the Δ mass $\mathrm{Re}\,(m_\Delta)$= 1.232 GeV and in the π-decay width Γ according to the diagram in Fig. 4, where in the intermediate state always m_N = 0.939 GeV.

		RCQM	SL	PR multipole	PR Gaussian	KNLS
$m_{\widetilde{\Delta}}$	[GeV]	1.309	1.288	1.347	1.328	1261
$m_{\widetilde{\Delta}} - \mathrm{Re}\,(m_\Delta)$	[GeV]	0.077	0.056	0.114	0.096	0.029
$\Gamma = 2\,\mathrm{Im}\,(m_\Delta)$	[GeV]	0.047	0.064	0.052	0.051	0.027

We are now in the course of investigating explicit pionic effects on the microscopic level, i.e. along a relativistic coupled-channels constituent-quark model. This will also help us to get rid of inputs of vertex form factors foreign to the quark model, because in such an approach one can determine within the same framework both the mass dressings as well as the vertex form factors consistently.

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