# Physical Baryon Resonance Spectroscopy from Lattice QCD

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We complement recent advances in the calculation of the masses of excited baryons in quenched lattice QCD with finite-range regulated chiral effective field theory enabling contact with the physical quark mass region. We examine the *P*-wave contributions to the low-lying nucleon and delta resonances.

# 1. INTRODUCTION

There has been enormous progress in the calculation of the masses of excited baryons in quenched lattice QCD [1]-[9] as a consequence of improved computing resources and the development of spin and parity projection methods. At present, established fitting techniques have successfully extracted resonance masses for quark masses or (equivalently, through the Goldberger-Treiman relation) pion masses in the range  $m_{\pi}^2 > 0.3 \text{ GeV}^2$ . The difficulty lies in maintaining a clear signal for the effective mass of the baryon resonance as the quarks become light. In this region the masses of the first negative and positive parity excited states obtained from standard interpolating fields follow the expectations of the naive harmonic oscillator based quark model with roughly equal spacing between the ground state nucleon, the first  $1/2^-$  and the first  $1/2^+$  excited states.

Quite apart from the ordering of excited states, the chiral extrapolation of hadron masses is a topic of current interest because of the well known non-analytic behaviour with quark mass and the need to incorporate the consequent, model independent constraints of chiral symmetry. For the octet and decuplet baryons as well as the  $\rho$ -meson this problem has been studied extensively and the technique for extracting physical masses with small systematic uncertainties is well understood [10]-[14]. Our aim is to generalise those results to the baryon excited states currently accessible on the lattice.

### 2. CHIRAL PERTURBATION THEORY AND CHIRAL EXPANSION

In the context of the extrapolation of lattice data, chiral perturbation theory provides a functional form applicable as the quark mass vanishes or, equivalently  $m_{\pi}^2 \rightarrow 0$ . Goldstone boson loops play an important role in the theory as they give rise to non-analytic behavior as a function of quark mass. All hadron properties receive contributions involving these loops. For  $m_{\pi} < 400$ -500 MeV, Goldstone loops lead to rapid, non-analytic variation with  $m_q$ . This non-analyticity must therefore be incorporated in any extrapolation scheme.

Chiral effective field theory gives a formal expansion of a baryon mass about the chiral limit

$$M_B = a_0 + a_2 m_\pi^2 + a_4 m_\pi^4 + \sum_{B'} \sigma_{BB'\pi}(m_\pi, \Lambda) + \dots$$
(1)

where  $a_i$  are the coefficients of the analytic terms,  $\Lambda$  is a parameter associated with the regularisation, and  $\sigma_{BB'\pi}$  are pion-induced self-energy contributions. Here we consider *P*-wave pion-baryon contributions, focusing on the most important baryon states as determined by the strength of the meson-baryon coupling constants (see Ref. [15] for details).

Figure 1 shows the extrapolation of CSSM Lattice collaboration [8, 9, 16] data for ground-state and low-lying excited baryon states. Dashed lines represent naive linear extrapolations while solid lines incorporate the non-analytic variation with  $m_q$ . Experimental masses are shown as filled ellipses.

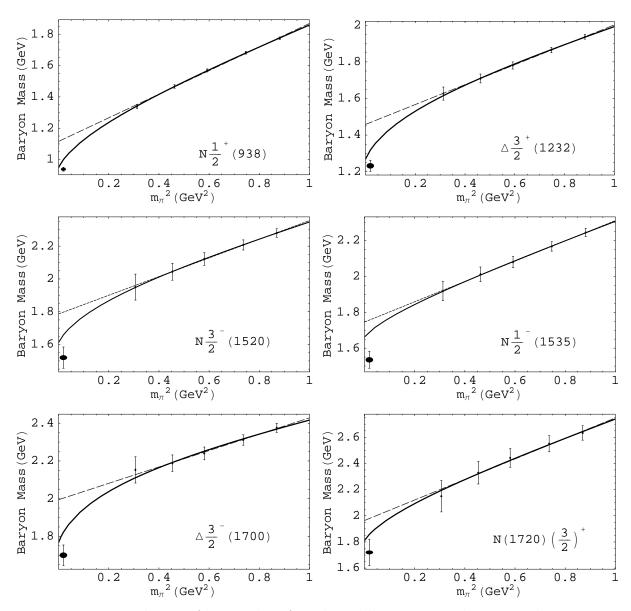


Figure 1. Extrapolation of lattice data for selected baryon ground states and resonances. Symbols are explained in the text.

#### 3. CONCLUSION & OUTLOOK

We have presented the first quantitative analysis of the baryon resonance spectrum from lattice QCD in which the chiral non-analytic behavior of QCD is incorporated. It is interesting to note that a small downward shift in the lattice results upon unquenching (as suggested in Ref. [16]) would provide remarkable agreement with experiment. The incorporation of chiral non-analytic behavior inverts the  $N\frac{1}{2}^{-}(1535)$  and  $N\frac{3}{2}^{-}(1520)$ ordering when compared to the naive linear extrapolation, in accord with experiment.

Encouraged by these early successes, work is now in progress to include additional self-energy contributions. S-wave contributions are of particular interest due to the non-analytic structure of their contributions. Ultimately, quenched chiral perturbation theory will be formulated providing the opportunity to quantitatively estimate the predictions of full QCD.

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