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Negative parity hyperons from coupled-channel scattering

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We present ongoing work on the $J^P = 1/2^-$ hyperons from meson–baryon scattering in lattice QCD. The $\Lambda(1405)$ is studied on CLS ensembles with 2+1 flavours and $m_\pi = 285$ MeV, $m_K = 460$ MeV, extending an earlier work where two poles were identified. Single- and two-hadron operators are considered at rest and in moving frames. Preliminary results are also shown for the $\Xi(1/2^-)$ channel, including three open scattering thresholds. The importance of extended operators in the determination of the baryon spectrum is discussed as well.

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1. Introduction

This talk reports our progress on the investigation of meson-baryon scattering in different channels and lattice ensembles. Since the discovery of the $\Delta(1232)$ baryon in the 1950s, meson–baryon scattering has played a primary role in the study of baryon resonances. It is now approachable from first principles on the lattice using the Lüscher method in combination with techniques to improve the signal. We investigate meson-baryon scattering with strangeness $S = -1$ and $S = -2$. We aim to study the s-wave contribution, and therefore the $J^P = 1/2^-$ channel, where there is evidence of the existence of different resonances which are challenging to study experimentally. We consider different CLS ensembles, which cover various quark masses, volumes and lattice spacings. Not only is this done to extrapolate to the physical world, but also for a better coverage of the center-of-mass energies and to extract the quark-mass dependence. The latter is described in the continuum by unitarised Chiral Perturbation Theory (UChPT) computations, which typically track the movement of resonant poles in the complex plane from the SU(3) flavour symmetric point to the physical one. The knowledge of the quark-mass dependence therefore allows one to extract information on the nature of the resonant states as well as to connect with other processes related by SU(3) symmetry. The aforementioned calculations can be used to check the consistency of the results or can incorporate the lattice data themselves. A brief overview of the lowest-lying resonant states expected in these channels is given below.

- $S = -1$, $I = 0$ channel: Here the $\pi\Sigma$ and $\bar{K}N$ thresholds lie significantly lower than the $\eta\Lambda$ one. In this energy region the $\Lambda(1405)$ and $\Lambda(1380)$ are listed with four and two stars respectively by the PDG [1]. These states have received a lot of attention since the first experimental evidence was found in 1961 in Ref. [2]. Given the extent of the literature, we point the interested reader to the review of Ref. [3].

- $S = -1$, $I = 1$ channel: Here three meson-baryon thresholds are relatively close together, $\pi\Lambda$, $\pi\Sigma$, $\bar{K}N$, compared to the next two-body channel, $\eta\Sigma$. This of course complicates the coupled-channel analysis, which in our analysis would consist of three channels. Some UChPT studies, e.g. Ref. [4], predict a lowest-lying state $\Sigma(1430)$ (see Ref. [5] for an analysis that includes lattice data); a $\Sigma(1620)$ state is reported only with one star by the PDG [1] (the first evidence of this has been observed in Ref. [6]).

- $S = -2$, $I = 1/2$ channel: Again, three meson-baryon thresholds lie relatively close together in this channel below the $\eta\Xi$ threshold: $\pi\Xi$, $\bar{K}\Lambda$ and $\bar{K}\Sigma$. The candidate states $\Xi(1620)$ and $\Xi(1690)$ are reported with two and three stars respectively, but no confirmed J^P, by the PDG [1] (a recent review can be found on Ref. [7]). A certain amount of evidence for them being $J^P = 1/2^-$ states dynamically generated by the meson-baryon interaction has been reported in several UChPT studies. See Refs. [8–10] for $\Xi(1620)$ and Refs. [9, 10] for $\Xi(1690)$. This channel has also been a subject of femtoscopic studies in Refs. [11, 12].

As mentioned above, negative parity strange resonances can be studied from first principles using lattice QCD. For instance, several works of Refs. [13–20] have analysed the $\Lambda(1405)$ channel with single-baryon operators on the lattice. In the last decade, it has been shown that multi-hadron operators are crucial in order to compute the hadronic spectrum. In particular, in the meson-baryon

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ensembles	boundary	a	$T \times L^3$	m_π	m_K	$m_\pi L$	N_{cnfg}
D200	open	0.064 fm	128×64^3	200 MeV	480 MeV	4.3	2000
X451	periodic	0.075 fm	128×40^3	287 MeV	462 MeV	4.4	2000
N451	"	"	128×48^3	286 MeV	466 MeV	5.3	1000
E250	"	0.064 fm	192×96^3	131 MeV	493 MeV	4.1	1000

Table 1: CLS ensembles of interest for the computation of meson-baryon scattering amplitudes along the physical TrM trajectory.

case, several works have studied πN scattering with such interpolating fields (Refs. [21–24]). The $\Lambda(1405)$ channel has been studied with single- and two-hadron operators in Refs. [25, 26]. Our work extends this analysis to other ensembles as well as to different channels.

Besides, the construction of operators with spatial structure has been shown to be beneficial to increase the overlap with states of interest. We investigate operators in which the quarks have been displaced in space. To illustrate their benefits, preliminary results for the $\Lambda(1520)$ state are displayed.

2. Lattice details and correlation functions

We are working on the computation of meson-baryon scattering amplitudes on different CLS[1] ensembles along the physical TrM trajectory (see Tab. 1). We employ the stochastic Laplacian-Heaviside method [27, 28] to evaluate large correlation matrices containing single and two-hadron interpolating operators via optimised tensor contractions [29]. Starting with the analysis of the $\Lambda(1405)$ channel of Refs. [25, 26] on the D200 ensemble, we are extending it to the X451 and N451 ensembles, and in the future to E250. These are periodic boxes, which effectively provide higher statistics than lattices with open boundaries, where time slices near the edge are discarded[2]. The X451 and N451 ensembles correspond to a higher pion mass than D200, while E250 has physical masses. The use of different quark masses makes a UChPT analysis with the aforementioned benefits possible. Of course, different volumes allow us to access more momenta. The combination of ensembles will increase the statistics as well as allow for an extrapolation to the physical world. In what follows, the computation of the $\pi\Sigma - \bar{K}N$ scattering in the $\Lambda(1/2^-)$ channel and $\pi\Xi - \bar{K}\Lambda - \bar{K}\Sigma$ in the $\Xi(1/2^-)$ channel on X451 and N451 is discussed, including preliminary results of correlators.

2.1 $\pi\Sigma - \bar{K}N$ in the $\Lambda(1/2^-)$ channel

The lowest-lying free energy levels in the Λ-flavour channel are computed on X451 and N451, for irreducible representations (irreps) corresponding to rest and moving frames (see Fig. 1). The levels are closer together on N451, because this ensemble only differs in volume with X451. We consider the number of free energy levels below the three body $\pi\pi\Lambda$ threshold sufficient to conduct

[1] CLS is the Coordinated Lattice Simulations consortium, which employs a tree-level improved Lüscher-Weisz gauge action and nonperturbatively $O(a)$ improved Wilson fermions.

[2] Our procedure is to employ two randomly selected time-sources per configuration and to compute forward as well as backward correlators. However, for the preliminary results shown here, only one source and direction was used per configuration.

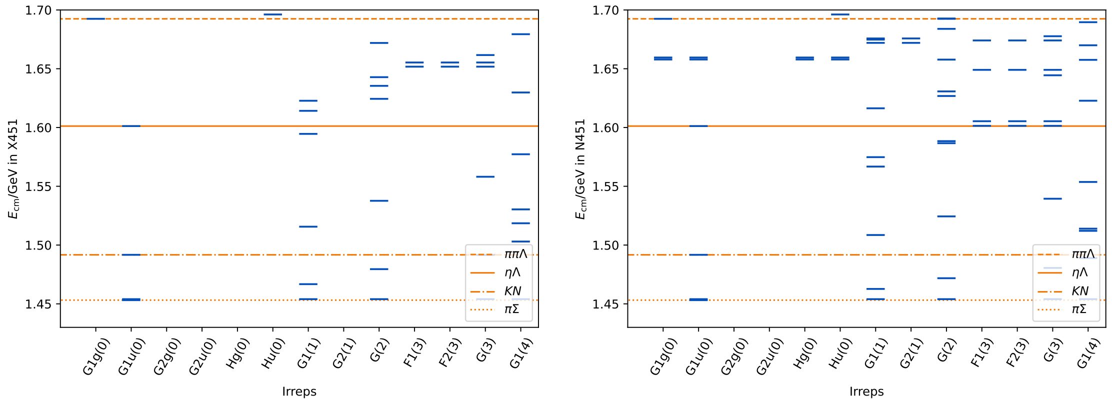

Figure 1: Free energy levels by irrep for the $I = 0$ $S = -1$ meson-baryon channel on X451 (left) and N451 (right) ensembles. The orange lines indicate the corresponding thresholds.

Λ-flavour G_{1u}	Ξ-flavour G_{1u}
$\Lambda[G_{1u}(0)]_0$	$\Xi[G_{1u}(0)]_0$
$\Lambda[G_{1u}(0)]_1$	$\Xi[G_{1u}(0)]_1$
$\Lambda[G_{1u}(0)]_2$	$\Xi[G_{1u}(0)]_2$
$\Lambda[G_{1u}(0)]_3$	$\Xi[G_{1u}(0)]_3$
$\bar{K}[A_{1u}(0)]_0\ N[G_{1g}(0)]_0$	$\pi[A^-_{1u}(0)]_0\ \Xi[G_{1g}(0)]_0$
$\pi[A^-_{1u}(0)]_0\ \Sigma[G_{1g}(0)]_0$	$\bar{K}[A_{1u}(0)]_0\ \Lambda[G_{1g}(0)]_0$
$\bar{K}[A_2(1)]_1\ N[G_1(1)]_0$	$\bar{K}[A_{1u}(0)]_0\ \Sigma[G_{1g}(0)]_0$
$\pi[A^-_2(1)]_1\ \Sigma[G_1(1)]_0$	$\pi[A^-_2(1)]_1\ \Xi[G_1(1)]_0$
-	$\bar{K}[A_2(1)]_1\ \Lambda[G_1(1)]_0$

Table 2: Single- and two-hadron G_{1u} operators of Λ- and Ξ-flavour channels employed on X451 (see Ref. [26] for details).

a Lüscher analysis. The setup of the matrix element computation— including the operator basis and the mixing of continuum eigenstates — is, *mutatis mutandis*, analogous to that of D200; we therefore refer the reader to Ref. [26]. Notice that as shown therein, an extensive basis of single- and two-hadron operators is necessary to resolve the lowest-lying energy levels. We report in Tab. 2 the operators included in the G_{1u} irrep for the X451 ensemble.

Regarding the $\Lambda(1/2^-)$ study, we present now preliminary results only for the ground state single-hadron correlators. See Sect. 2.2 for first results on two-hadron correlators on X451 (in the $\Xi(1/2^-)$ channel). The aforementioned meson and baryon octet correlation functions have been computed on X451 with a reduced set of $N_{\text{prelim}} = 135$ gauge configurations (using a single time-source and direction per configuration). This is to $O(1\%)$ of the target statistics, which is 2000 gauge configurations on two time-sources and two directions each. The effective masses of the ground state correlators corresponding to selected local operators are shown in Fig. 2. The results are consistent with expectations, despite the reduced statistics. Notice that the uncertainty is reduced with increasing strangeness content, yielding a remarkably precise signal for the Ξ ground state given the limited statistics.

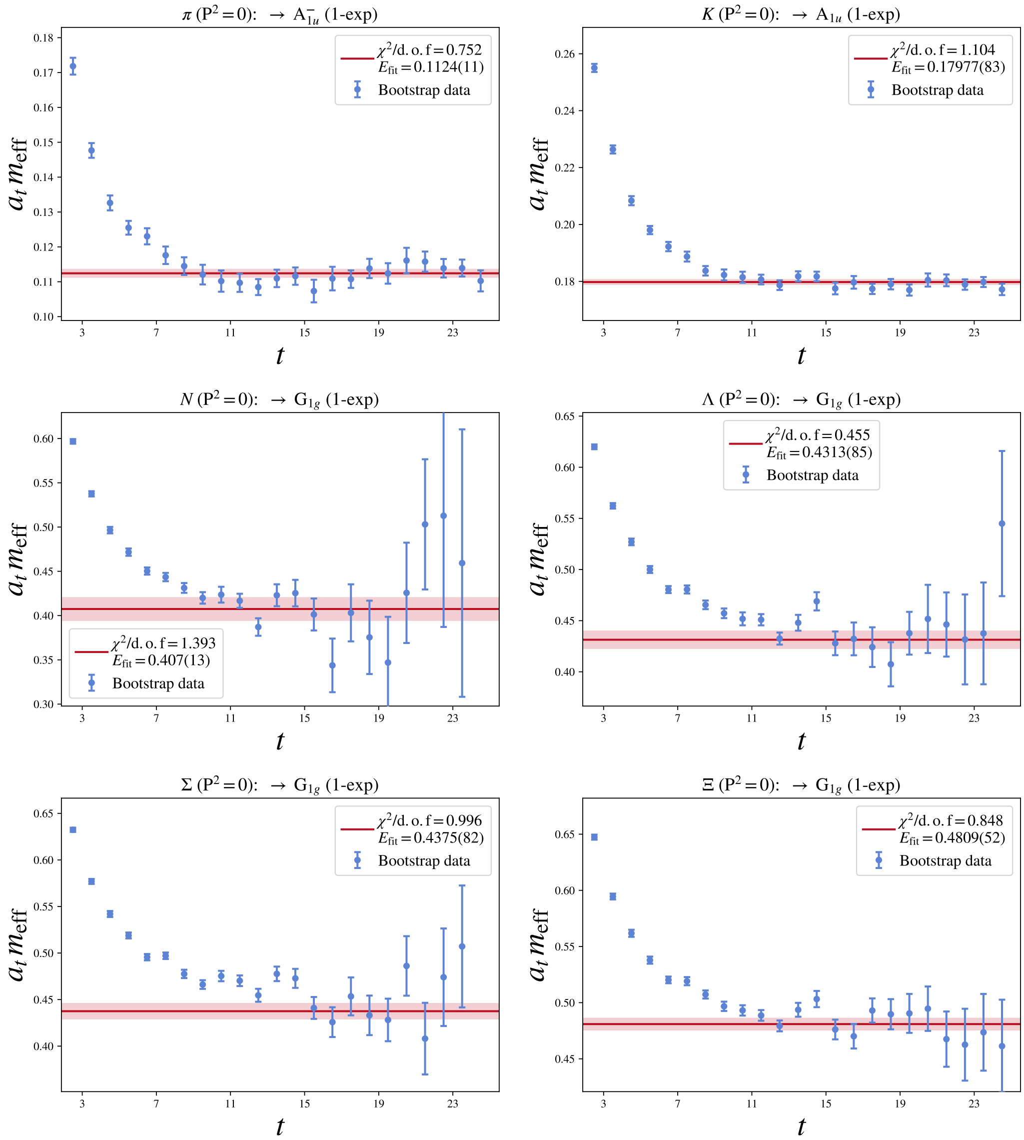

Figure 2: [Preliminary results]: Effective masses of ground state correlators corresponding to selected local operators, measured on $N_{\mathrm{prelim}} = 135$ gauge configurations of the X451 ensemble. The uncertainties are the result of bootstrapping. The corresponding hadron and irrep are reported on top of the figures. The reduced χ^2 and corresponding extracted energy in lattice units are displayed on the boxes.

2.2 $\pi\Xi - \bar{K}\Lambda - \bar{K}\Sigma$ in the $\Xi(1/2^-)$ channel

The $\Xi(1/2^-)$ channel presents the challenge of being a three coupled-channel system: $\pi\Xi - \bar{K}\Lambda - \bar{K}\Sigma$. Moreover, the quantum number mixing intrinsic to the lattice, particularly in moving frames, has to be taken into account. The lightest baryon states in the physical world and the irreps to which they contribute are given for reference in Tab. 3. The lowest-lying free energy levels in the Ξ-flavour channel are computed on X451 and N451 (see Fig. 3). The number of free levels below the $\eta\Xi$ threshold suggests that a Lüscher analysis is feasible, although describing the three open channels constitutes a challenge. Given the two units of strangeness, the states that contribute are

J^P	[000]	[00n]	[0nn]	[nnn]	states
$1/2^+$	G_{1g}	G_1	G	G	Ξ
$1/2^-$	G_{1u}	G_1	G	G	$\Xi(1620), \Xi(1690)$
$3/2^+$	H_g	G_1, G_2	$2G$	F_1, F_2, G	$\Xi(1530)$
$3/2^-$	H_u	G_1, G_2	$2G$	F_1, F_2, G	$\Xi(1820)$

Table 3: Expected lowest-lying Ξ-flavour states in the physical world and the irreps to which they contribute on the lattice.

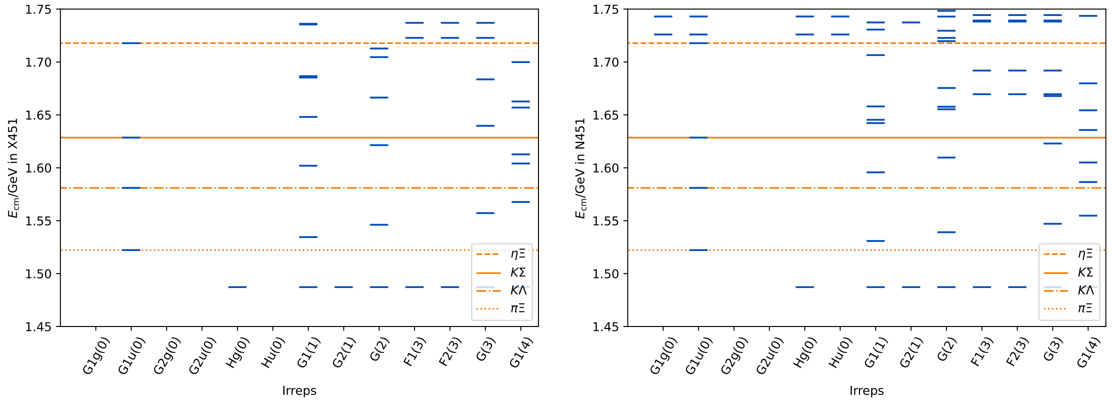

Figure 3: Free energy levels by irrep for the $I = 1/2$ $S = -2$ meson-baryon channel on X451 (left) and N451 (right) ensembles (same notation as Fig. 1).

different from those in the Λ-flavour channel. Here Ξ states are present and nucleons are absent, which reduces the noise associated to baryon operators.

As part of our preliminary results, we discuss the $S = -2$ $I = 1/2$ $J^P = 1/2^-$ (G_{1u} irrep) correlators on the $N_{\text{prelim}} = 135$ configurations of X451. The operators included (in the case of the G_{1u} irrep) are given in Tab. 2. The effective masses of the correlators corresponding to the three multi-hadron operators at threshold are shown in Fig. 4. They are consistent with the expectations from the noninteracting theory, which yields three channels at an $O(50\text{ MeV})$ distance from each other.

As shown in the operator table (Tab. 2), four single-hadron (SH) operators with different Dirac structures and the quantum numbers of the $\Xi(1/2^-)$ are included in the G_{1u} irrep. On the left panel of Fig. 5 the effective masses of the corresponding correlators are displayed. The right panel of Fig. 5 shows the result of a GEVP on such operator basis. One can see that this has a significant effect, isolating excited state contamination, even on limited statistics. This illustrates the importance of a comprehensive basis. As mentioned above, two-hadron operators play a key role and in the final study the GEVP will be performed including both single- and multi-hadron operators. The full analysis will consider an extensive basis of operators at rest and in moving frames up to total momentum $P^2 = 3$.

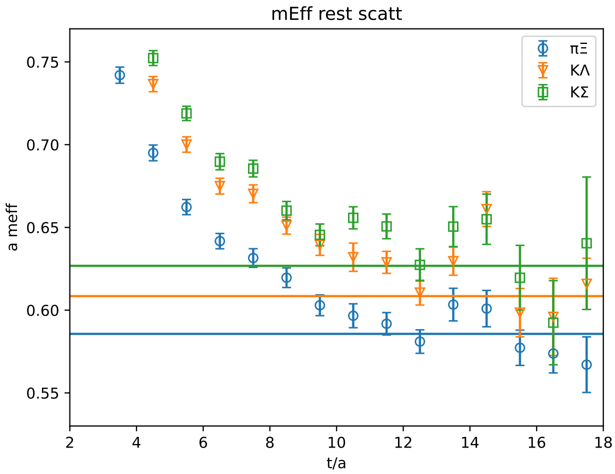

Figure 4: [Preliminary results]: Effective masses of $\pi\Xi$, $\bar{K}\Lambda$ and $\bar{K}\Sigma$ threshold correlators of the $S = -2$ $I = 1/2$ $J^P = 1/2^-$ (G_{1u} irrep) channel, measured on $N_{\text{prelim}} = 135$ gauge configurations of the X451 ensemble. The uncertainties are the result of bootstrap. The lines correspond to the noninteracting thresholds.

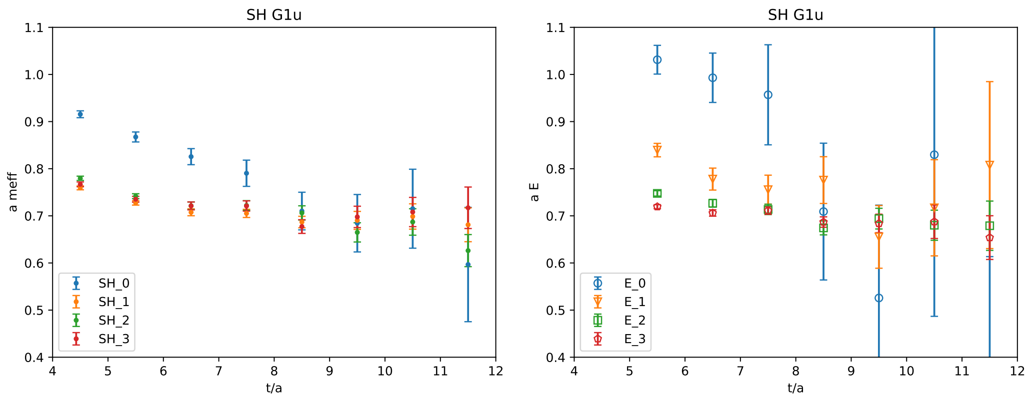

Figure 5: [Preliminary results] Left panel: Effective masses of the single-hadron (SH) $\Xi[G_{1u}(0)]_\mu$ operators of Tab. 2 on $N_{\text{prelim}} = 135$ configurations of X451. Right panel: Energy levels extracted from the left panel correlators by solving a GEVP.

3. Extended baryon operators and the $\Lambda(1520)$

In order to better describe hadron states of interest, we investigate the use of operators extended in space. In particular, we follow the method of Ref. [30] to construct such baryon operators, where one or more quark fields are displaced. We aim to apply this to spectroscopy analyses in the Laplacian-Heaviside scheme to improve the baryon signal. To illustrate the benefits of these constructions, we report our preliminary results on 100 configurations on the X451 ensemble for the $\Lambda(1520)$, $J^P = 3/2^-$ state. We reproduce on X451 the observation made in Ref. [31] about the effective mass of an extended $\Lambda(1520)$ operator being lower than that of the local one. Quark models [32] suggest that the $\Lambda(1520)$ state is dominated by $L = 1$, $S = 1/2$ and SU(3)-flavour singlet structure. This is achieved by an operator containing derivatives (single quark displacements on the lattice) given in Ref. [31]. In Fig. 6, the effective mass of such an interpolating operator

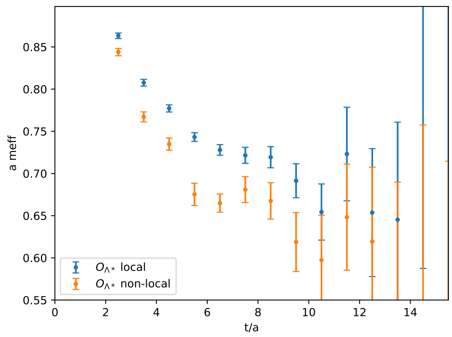

Figure 6: [Preliminary results]: Effective masses corresponding to the $\Lambda(1520)$ local ($\Lambda[H_u(0)]_0$) operator and the extended operator defined in Ref. [31], measured on $N_{\text{prelim}} = 135$ configurations on X451.

is compared to the local one, $\Lambda[H_u(0)]_0$, yielding a significantly lower plateau despite the limited statistics.

4. Conclusions and outlook

Our progress on the study of $J^P = 1/2^-$ hyperons on CLS ensembles has been reported. We are extending the analysis of the $\Lambda(1405)$ state to ensembles with $m_\pi \simeq 287$ MeV, $m_K = 464$ MeV in order to investigate the quark-mass dependence among other aspects. Ultimately, this will allow us to obtain a robust amplitude parameterization and extrapolate to the physical world, as well as to connect with UChPT calculations. Preliminary results for the $\Xi(1/2^-)$ channel on the same ensembles have also been discussed. This is a challenging three coupled-channel problem; however, the double strangeness content has been shown to significantly reduce statistical uncertainties. Finally, the role of extended operators has been discussed, displaying a confirmation of their beneficial effect on the description of the $\Lambda(1520)$ state [31].

Acknowledgements

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