

Precise study of triply charmed baryons Ω_{ccc}

Navdeep Singh Dhindsa^{1,2,*} Debsubhra Chakraborty^{2,†} Archana Radhakrishnan^{2,‡}
 Nilmani Mathur^{2,§} and M. Padmanath^{1,3,||}

¹*The Institute of Mathematical Sciences, CIT Campus, Chennai, 600113, India*

²*Department of Theoretical Physics, Tata Institute of Fundamental Research,
 Homi Bhabha Road, Mumbai 400005, India*

³*Homi Bhabha National Institute, Training School Complex, Anushaktinagar, Mumbai 400094, India*



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We present the most precise results for the ground state mass of the triply-charmed spin-3/2 baryon using lattice quantum chromodynamics. The calculations are performed on six $N_f = 2 + 1 + 1$ highly improved staggered quark (HISQ) lattice ensembles generated by the MILC collaboration. Two different lattice setups are employed: in the first one, a fully dynamical calculation with HISQ action is performed, while in the second calculation, an overlap action is utilized for the valence charm quark dynamics. Following the continuum extrapolation of our results, obtained at five different lattice spacings, two different volumes, and two different actions, our prediction for the mass of the lowest triply charmed spin-3/2 baryon, $\Omega_{ccc}(3/2^+)$, is $4793(5)_{-8}^{+11}$ MeV. This is the most precise determination to date, fully addressing the systematic uncertainties. We also predict the $\Omega_{ccc}(3/2^-)$ mass to be $5094(12)_{-17}^{+19}$ MeV.

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The role of single-flavored baryons was paramount in identifying the color degrees of freedom and the subsequent development of quantum chromodynamics (QCD), the theory of strong interactions. The discovery of the $\Omega(sss)(J^P = 3/2^+)$ baryon firmly established the quark model as an effective phenomenological framework for describing subatomic particles, which further led to many key advancements in our understanding of nuclear and particle physics. Although the single-flavored baryons have only been discovered with light and strange flavors (Δ and Ω), the existence of their counterparts with charm and bottom flavors—namely Ω_{ccc} and Ω_{bbb} —is beyond any doubt within QCD. The Ω_{QQQ} ($Q \equiv c, b$) baryons, which are baryon analogs of heavy quarkonia, offer a simplistic system for studying quark-quark interactions and quark confinement without the complexities of valence light quark dynamics [1–3]. As pointed out by Bjorken, such baryons may provide a new window for understanding the internal parton level dynamics within baryons [1]. These

baryons are expected to be discovered as experimental facilities reach the required center-of-momentum energy and luminosity, with Ω_{ccc}^{++} likely being the first to be observed. Precise theoretical predictions using first principles calculations of QCD can guide the experiments in discovering the $\Omega_{ccc}^{++}(3/2^+)$ baryon. In this work, we present the most precise determination of the ground state mass of the $\Omega_{ccc}^{++}(3/2^+)$ baryon using the first-principles lattice QCD methodology, carefully accounting both statistical and all potential systematic uncertainties, which ensures that the final mass prediction is reliable and accurate.

Since the strong decay of the lightest spin-3/2 Ω_{ccc} baryon is forbidden, it should have a relatively long lifetime. Probable decay modes, where they could be searched for, are semileptonic decay processes such as $\Omega_{ccc}^{++} \rightarrow \Omega_{ccs}^+ + \{l\} \rightarrow \Xi_{ccu}^{++} + 2\{l\}$, $\Omega_{ccc}^{++} \rightarrow \Xi_{ccd}^+ + \{l\}$, among others ($\{l\}$ refers to lepton pair involved in the decay). Direct detection of such long lived particles could be difficult, unless the lighter hadrons to which they decay are well understood. However, recent experimental reports on tri- J/ψ production [4], and recent proposals of inclusive search strategies [5,6] and extensions of new sensitive timing based variables [7] to identify signatures for long lived hadrons augment promising prospects for the discovery of Ω_{ccc}^{++} baryons in the near future.

Considering the heavy quark constituents within, it is expected that the phenomenological models would be able to reliably predict the masses of Ω_{ccc} baryons. Indeed, within model calculations, starting with early works of

*Contact author: navdeep@theory.tifr.res.in

†Contact author: debsubhra.chakraborty@tifr.res.in

‡Contact author: archana.radhakrishnan@tifr.res.in

§Contact author: nilmani@theory.tifr.res.in

||Contact author: padmanath@imsc.res.in

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Bjorken [1], these baryons have been studied with non-relativistic [8–14] and relativistic [15,16] quark models, QCD sum rule [17–21], Faddeev equation [22–24], diquark model [25,26], variational method [27,28], bag model [29,30], hypercentral constituent quark model [31–33], Regge theory [34], Bethe-Salpeter equation [35] and renormalization group procedure for an effective particles approach [36]. However, depending on the model parameters, these predictions are spread over 400 MeV uncertainty.

In this context, first principles lattice QCD calculations with controlled systematics can play a vital role in narrowing the possible mass window for these baryons. Most importantly, lattice QCD calculations can rigorously incorporate nonperturbative aspects that may be overlooked by potential models and other phenomenological approaches. Several lattice QCD studies of Ω_{ccc} baryons have also already been performed, starting with studies using pure $SU(3)$ gauge theory [37], dynamical simulations with quenched charm quarks [2,38–46], and those involving dynamical quarks up to charm flavor [47–51]. Most of these calculations were performed at a single lattice spacing, whereas addressing lattice artifacts through continuum extrapolation with several lattice spacings is essential to assess the systematic uncertainties from cutoff effects, particularly considering the presence of three heavy quarks in these baryons. The studies in Refs. [38,40,47,49,51] have performed continuum extrapolation with up to three lattice spacings, leading to mass estimates for $\Omega_{ccc}(3/2^+)$ that are spread over a range of 100 MeV. There are no continuum extrapolated results for the mass of $3/2^-$ ground state, with existing predictions scattered over a 250 MeV energy interval.

It is therefore important to perform a systematic lattice QCD determination of the masses of low lying Ω_{ccc}^{++} baryons, with an accuracy similar to the state-of-the-art lattice determination of other hadrons, such as that in low-lying charmonia and proton. In this work, we present such a study utilizing up to six lattice QCD ensembles, five different lattice spacings, two lattice volumes and $N_f = 2 + 1 + 1$ highly improved staggered quark (HISQ) dynamics [52], generated by the MILC Collaboration [53,54] (see Fig. 1, and Table I in Ref. [55]). In the valence sector, we employ two different approaches. In the first, a fully dynamical evaluation of the Ω_{ccc}^{++} baryon masses is made with HISQ action for the valence charm quark evolution. In the second approach, an overlap action [71,72], which has no $\mathcal{O}(ma)$ error, is employed for the valence charm quark dynamics, similar to many of our previous publications [73–77]. With such a diverse and state-of-the-art setup of multiple lattice spacings, lattice volumes, and two different valence charm quark actions, we predict the ground state mass of $\Omega_{ccc}^{++}(3/2^+)$ baryon to be $4793(5)_{(-8)}^{(+11)}$ MeV. The mass for the lowest $J^P \equiv 3/2^-$ state is also predicted with per mille precision. Below, we detail the methods and procedures employed to obtain these results.

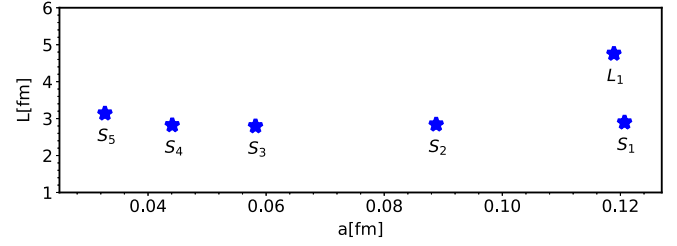


FIG. 1. Six lattice QCD ensembles used in this work and are labeled in the plot as S_5 ($96^3 \times 288$), S_4 ($64^3 \times 192$), S_3 ($48^3 \times 144$), S_2 ($32^3 \times 96$), S_1 ($24^3 \times 64$), and L_1 ($40^3 \times 64$).

We evaluate the hadron masses from the two point correlation functions with a wall source and a point sink smearing, where the correlators are fitted with an exponential form at large source-sink separation. Such a setup was demonstrated to be robust and reliable for extracting single-hadron masses, particularly for their ground states [73,75,78–83]. We also observe that to be the case for the Ω_{ccc} baryon masses studied in this work. The charm quark mass, being heavy, leads to relatively clean and stable signals. Further, to mitigate the excited state effects from the extracted ground state hadron masses, we evaluate correlation matrices that are analyzed variationally following the solutions of a generalized eigenvalue problem [84,85].

Ω_{ccc} baryons with valence overlap fermions. In this setup, we utilize only spatially local interpolators, $(\mathcal{O}_b)$. This is well justified considering the predicted smaller charge radius of Ω_{ccc} [41]. The trivial flavor symmetry and color antisymmetry imply the total spin structure for the Ω_{ccc} baryon interpolator has to be symmetric. With a four component fermion spinor in the Dirac-Pauli representation of Dirac- γ matrices [86] with $\gamma_4 = \text{diag}[1, 1, -1, -1]$ representing the quark fields, one can have two embeddings of finite volume irrep H ($\in \{\Lambda_{O_h}\}$) possessing fully symmetric spin structure and with spin-3/2 being the lowest contributing spin [2,87]. Here, Λ_{O_h} refers to the irrep of the Octahedral group O_h . Correlation matrices are evaluated using the operator basis composed of these two operators and are then analyzed following variational techniques [84,85]. The antisymmetry along the temporal extent in baryon correlators can be utilized to average over the forward and the time-reversed backward propagations thus doubling the statistics for each parity [88–90]. Further details on this are provided in Sec. II of Supplemental Material [55].

Ω_{ccc} baryons with HISQ fermions. The $\Omega_{sss}(3/2^+)$ has been studied with HISQ valence quark previously [91], and following that we use the following interpolating field for $\Omega_{ccc}(3/2^+)$,

$$\mathcal{O}_{\Omega_{ccc}}(t) = \epsilon_{abc} D_1 c^a(\mathbf{x}, t) D_2 c^b(\mathbf{x}, t) D_3 c^c(\mathbf{x}, t), \quad (1)$$

where $c^a(\mathbf{x}, t)$ is the HISQ charm quark field with (a, b, c) as the color indices, and D_i s are the spatial derivative

operators [92]. Note that the operator in Eq. (1) couples with multiple tastes. However, the splittings between finite-volume ground state energy of Ω baryons of different tastes are expected to be small as HISQ action removes all taste-exchange effectively through one-loop order [52], and this has been shown in Ref. [91]. To reduce the effects of oscillating components of staggered correlators, the two-point correlators are first smoothed and the procedure is detailed in the supplement [55]. To determine the ground state masses, we employ two methods. The first one involves the standard large-time fit with a single exponential. We also use two-exponentials particularly for the spin- $3/2^-$ state where the contamination from the excited states may not be insignificant. In the second method, we utilize the generalized eigenvalue problem (GEVP) [84,85], using a matrix constructed from time-shifted correlation functions, as described in Ref. [93], allowing a robust estimation of the ground state.

Mass extraction and results. In Fig. 2, we present two representative effective mass plots ($m_{\text{eff}} = \log[C(\tau + 1)/C(\tau)]$, $C(\tau)$ being the correlation function) for the lowest energy level of the $\Omega_{ccc}(3/2^+)$ state on ensembles with the finest two lattice spacings. Further details are provided in the caption. The horizontal bands represent the fit estimate with 1σ error. Further details of mass fits and results for other lattices and other hadrons studied are shown in Supplemental Material [55].

The large bare quark mass ($m_0 a$) introduces significant discretization effects, which can be a primary source of systematic uncertainties in heavy hadrons, especially in those containing multiple heavy quarks. The leading discretization errors in the valence quark actions that we employ (overlap and HISQ) are at $\mathcal{O}((ma)^2)$. To further mitigate these errors, instead of estimating the masses directly, we follow the practice of studying mass splittings, where the valence heavy quark content is subtracted out as in Refs. [73–77,94]. Here we subtract out the valence charm quark content with the following choice,

$$a\Delta M_{\Omega_{ccc}} = \left[aM_{\Omega_{ccc}}^L - \frac{3}{2} aM_{c\bar{c}}^L \right], \quad (2)$$

where $aM_{\Omega_{ccc}}^L$ and $aM_{c\bar{c}}^L$ are the finite lattice estimates for the mass of Ω_{ccc} baryon and the reference charmonia energy ($c\bar{c}$), respectively. Two different choices for $c\bar{c}$ are considered in our analysis: J/ψ and the spin averaged $\overline{1S}$ state, $\frac{1}{4}(\eta_c + 3J/\psi)$. These choices are made considering that we tune the charm quark mass using $\overline{1S}$, while J/ψ masses on the lattice are found to be closer to its physical mass on each lattice. We perform the continuum extrapolation on these mass splittings, owing to the expectations of reduced cutoff effects on them. Here we prefer the reference energy with respect to the J/ψ meson mass as the estimation of the J/ψ mass on lattice is more accurate compared to the spin-averaged $\overline{1S}$ energy, potentially

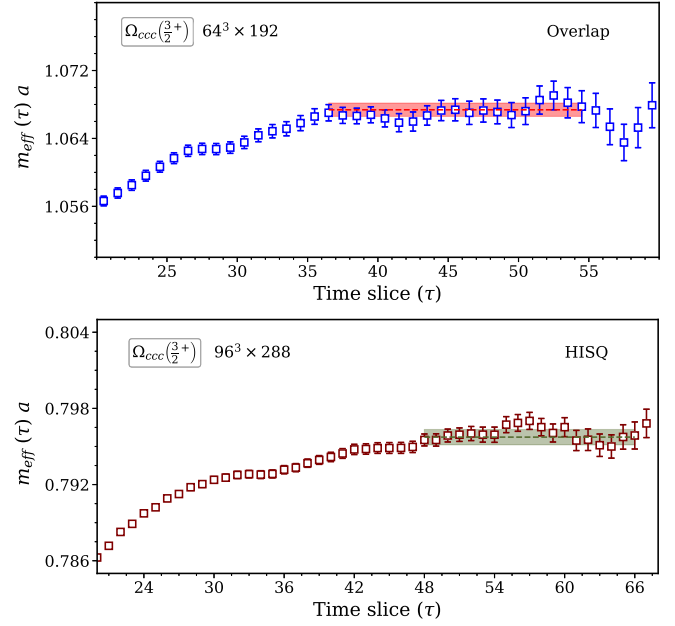


FIG. 2. Representative effective mass plots for the lowest energy state of $\Omega_{cc}(3/2^+)$ baryon. Top: overlap action, lattice size: $64^3 \times 192$, Bottom: HISQ action, lattice size $96^3 \times 288$.

related to the dominant charm self-annihilation effects expected and also observed in η_c meson mass [95].

In Fig. 3 we show the continuum extrapolation of the mass splittings $\Delta M_{\Omega_{ccc}(3/2^+)}$ in physical units, with the top two panes using $c\bar{c} \equiv J/\psi$ (top figure) and $c\bar{c} \equiv \overline{1S}$ (second from the top). We consider two possible cutoff dependences: (i) $\Delta M(a) = c_1 + c_2 a^2$, (ii) $\Delta M(a) = c_1 + c_2 a^2 + c_3 a^4$. The marker and coloring convention used are explained in the figure and its caption. The bottom two figures, with the same color-coding and fit forms, represent the continuum extrapolation for the $\Omega_{ccc}(3/2^-)$ baryon. Once the continuum extrapolated value of $\Delta M_{\Omega_{ccc}}^{\text{cont}}$ is obtained, we add that to the physical value of $\frac{3}{2} M_{c\bar{c}}^{\text{exp}}$ to obtain the physical estimates for baryon mass, as in,

$$M_{\Omega_{ccc}}^{\text{phys}} = \left[\Delta M_{\Omega_{ccc}}^{\text{cont}} + \frac{3}{2} M_{c\bar{c}}^{\text{exp}} \right]. \quad (3)$$

A clear agreement can be observed between the $\Omega_{ccc}(3/2^+)$ estimates using the overlap as well as the HISQ action across finer lattices leading to a consistent continuum extrapolated value. Our final result, represented by the red square at the continuum point, is a symmetrized average of the HISQ (green star) and overlap (blue star) results obtained from linear fits to the finest lattice points (starting at $a = 0.0888$ fm), with the magenta and blue bands representing the fitted results for the HISQ and overlap actions, respectively. The associated fit error, indicated by the thick red line, encompasses the fit errors for both the overlap and HISQ actions and is quoted as the

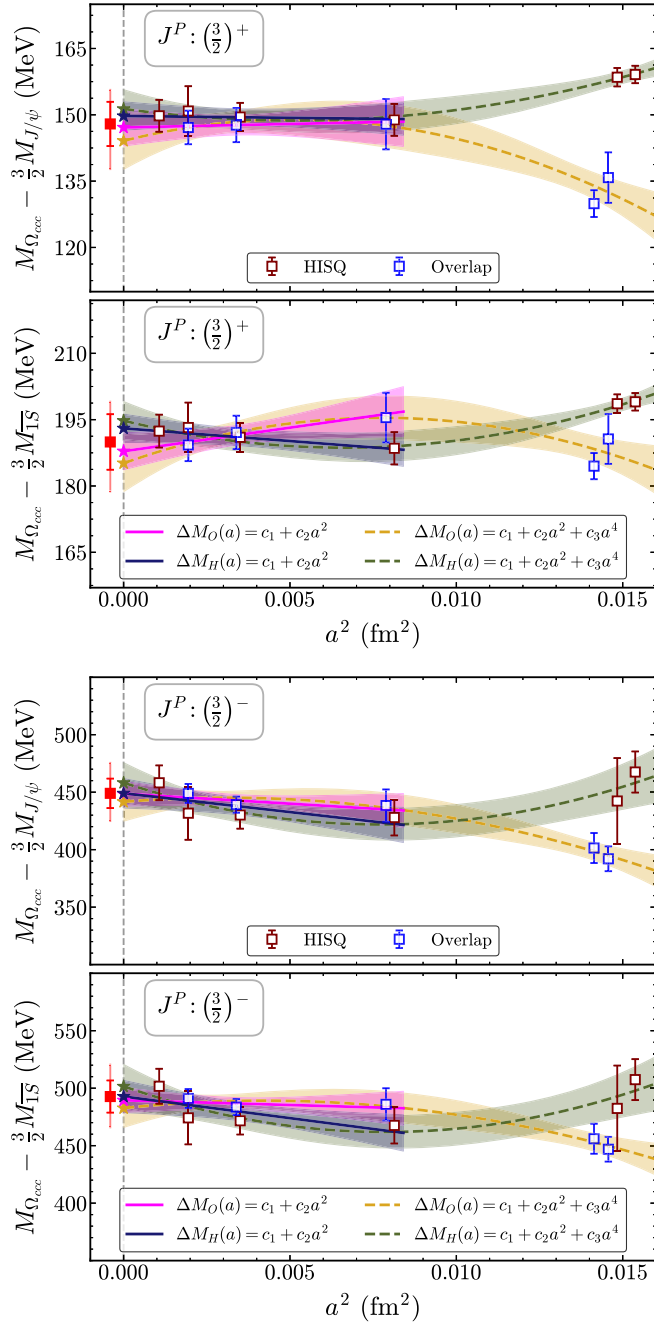


FIG. 3. Continuum extrapolations of the subtracted ground state masses $\Delta M_{\Omega_{ccc}}^{\text{sub}}(a)$ [Eq. (2)]. Top two: $\Omega_{ccc}(3/2^+)$ and bottom two: $\Omega_{ccc}(3/2^-)$. Subtraction of charm quark content is done with both $c\bar{c} \equiv J/\psi$ and 175 . Various fit forms with their respective color schemes are shown in the legends and more details on fits are provided in Supplemental Material [55]. The shaded bands represent 1σ uncertainties, estimated via the bootstrap method. Symbol star: continuum extrapolated values. Red solid square: final value by symmetrized averaging the linear fit results of overlap and HISQ quarks, while the extended errors include other fits results.

statistical error. The thin red line illustrates the range of fit errors (bootstrap) arising from variations in lattice spacing

dependence and differences in actions (as shown in Table III of Supplemental Material [55]). The deviations of the thin red line from the thick red line are included in our systematic errors. As previously discussed, using $c\bar{c} \equiv J/\psi$ provides a more reliable basis for continuum extrapolation, and our final values are quoted accordingly. Our final estimates are $M_{\Omega_{ccc}}(3/2^+) = 4793(5)^{(+11)}_{(-8)}$ MeV, and $M_{\Omega_{ccc}}(3/2^-) = 5094(12)^{(+19)}_{(-17)}$ MeV, where the first error is statistical and the second one accounts for all other possible systematic errors, which we will discuss next. We also estimate the mass splitting between these two baryons to be: $\Delta_{\Omega_{ccc}}(3/2^+ - 3/2^-) = 301(13)(14)$ MeV. Note that for reliable estimation of $\Omega_{ccc}(3/2^-)$ mass, one needs to consider the presence of a nearby three hadron final state $\Omega_{ccc}(3/2^+)\pi\pi$ in P wave in the chiral limit [96–103]. However, investigating such contamination is beyond the scope of this work. If the three quark Fock component of the negative parity state were dominant and its coupling with the three hadron state negligible, we anticipate our estimate would be reliable.

A thorough estimation of systematic uncertainties is crucial in any precision investigation. Below, we provide a detailed account on systematics involved in this investigation covering several possible sources of errors.

Statistical. In this, we include bootstrap fit error, including various possible choices of fit-windows, and the final value includes the fit-error covering both overlap and HISQ results.

Discretization. Here, we include the difference in fit values obtained using different fit forms with two different discretized lattice actions.

Scale setting. Measurements of scale with Wilson flow and r_1 parameter are found to be consistent for these lattice ensembles. Including the scale setting errors we find the uncertainty in mass difference [Eq. (2)] for Ω to be ~ 3 MeV.

Charm quark mass tuning. After tuning the charm quark mass on each lattice (as detailed in Supplemental Material [55]), we calculate the mass splittings [Eq. (2)], at its central value and at its variations. The effect on mass splittings was found to be, at most, 2 MeV.

Unphysical sea quarks. The light sea-quark masses are heavier than their physical values in the set of ensembles that we utilize in this work (see Table 1 of Supplemental Material [55]). Although it is naively expected to have only small effects from unphysical light sea quarks to the mass of an all charmed baryon [104–106], it is better to have an estimate on it. In Sec. V of Supplemental Material [55] we provide a detailed account of the associated systematics estimation and we find this uncertainty to be about 5 MeV.

Taste splitting (HISQ). For HISQ valence quarks this effect leads to a difference in masses at finite lattice spacing with a $\mathcal{O}(\alpha_s(1/a)(m_c a)^2)$ mixing between two tastes of Ω_{ccc} baryons. We account for that in the continuum extrapolation, which leads to an error of 2 MeV.

Mixed action effect (Overlap). In the overlap setup, unitarity violations arise for two reasons [107–109]. One is

related to the difference in action used in the sea and valence sectors, which is expected to die out in the continuum limit [110]. In the same lattice setup (with $a = 0.0582$ fm), we found this effect to be small [110]. The second one is related to the sea and valence charm quark mass difference, which could survive in the continuum [109]. The difference in estimates from the HISQ valence action and the overlap valence action already reflects these systematics. Based on the disagreement between the numbers from these two scenarios in the common finest lattice, we assign a conservative estimate of 2 MeV to account for this systematic.

TABLE I. Error budget in the calculation of the ground state mass of $\Omega_{ccc}^{++}(3/2^+)$ baryon.

Source	Error (MeV)
Statistical	5
Discretization	4
Scale setting	3
m_c tuning	2
Unphysical sea-quark	5
Taste-splitting (HISQ)	2
Mixed action (Overlap)	2
Finite size	1
Electromagnetism	+7.8 +0.0
Total	5 (stat) and $^{+11}_{-8}$ (syst)

Finite volume. The elastic strong decay threshold in the $\Omega_{ccc}(3/2^\pm)$ corresponds to the three particle decay mode $\Omega_{ccc}\pi\pi$. Assuming a nonrelativistic scenario, the leading finite-volume correction in binding energy estimates was found to scale $\sim e^{-\kappa L}/L$, where $\kappa = \sqrt{M B_\infty}$ is the binding momentum [111,112]. Choosing M to be the mass of the pion (lightest hadron involved in the $\Omega_{ccc}\pi\pi$ final state) and the binding B_∞ to be the same order of magnitude as the binding B_{FV} determined from the largest volume utilized, one observes the corrections on the $\Omega_{ccc}^{++}(3/2^+)$ mass to be less than 1 MeV. A similar naïve estimate on the binding energy of $\Omega_{ccc}^{++}(3/2^-)$ mass turns out to be of the order of 15 MeV, which is included in the associated systematics. We iterate that the naïve finite volume systematics quoted above for the positive parity is justified as it is significantly below the elastic strong decay threshold; however the uncertainty in the negative parity state should be addressed with more involved finite-volume analysis in the future.

Electromagnetism. The presence of two units of charge is expected to influence the mass of a Ω_{ccc}^{++} baryon. A leading perturbative estimate, as shown in Supplemental Material [55], yields a correction term <5 MeV. In Ref. [44] the Coulomb repulsion in a dibaryon, made with six charm quarks and having four units of charge, was found to be about 5 MeV. Given the constituent composition of Ω_{ccc}^{++} relative to that system, we anticipate that the mass correction from Coulomb effects could be comparatively smaller.

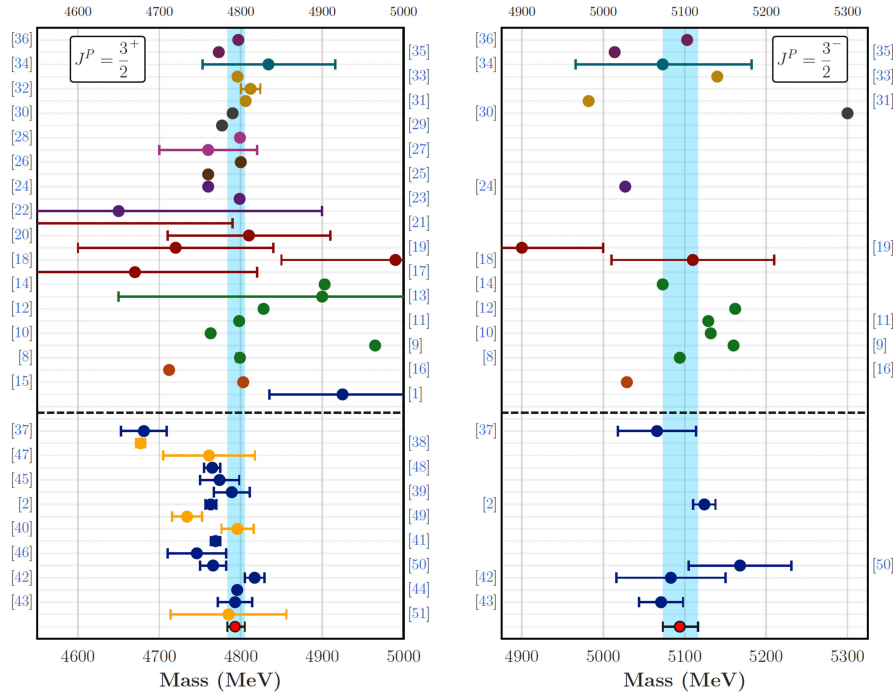


FIG. 4. Summary of results on the ground state mass of $\Omega_{ccc}(3/2^+)$ (left) and $\Omega_{ccc}(3/2^-)$ (right) baryons as obtained in various calculations (references on the side panels can be tracked through the faint horizontal lines). The results below the thick horizontal dashed line are from lattice calculations and above that are obtained using various models. Among the lattice results, those with orange circles are obtained with continuum extrapolations, while others (blue circles) are obtained at a single lattice spacing. The deviation of the results obtained in Refs. [38,49] are most possibly due to their errors in the charm quark mass tuning. Our results at the physical point are shown by the red circles (at the bottom).

Additionally, the magnetic moment of Ω_{ccc}^{++} has been predicted to be about $1 \mu_N$ [113] suggesting no large effect on its mass. Since our estimation of Ω_{ccc}^{++} mass is based on the subtracted mass, $M_{\Omega_{ccc}^{++}} - 3/2 M_{J/\psi}$, we also estimate the electromagnetic corrections to $M_{J/\psi}$, and find it to be 2.4 MeV (details are in Supplemental Material [55]). After accounting the electromagnetic mass corrections to both Ω_{ccc}^{++} and J/ψ , we assign a uncertainty of $(^{+7.8}_{+0.0})$ MeV to the mass of Ω_{ccc}^{++} . However, a direct calculation with Coulomb term within the gauge action would be necessary for a more rigorous assessment of these effects, but that lies beyond the scope of the present work.

Based on the above estimation, we summarize the error budget in Table I below.

In Fig. 4, we summarize the results on the ground state mass of $\Omega_{ccc}(3/2)$ baryons showing our results (red circles at the bottom/vertical blue band) and compare it with previous results, using the blue band as reference. A horizontal dashed line is placed to separate lattice and nonlattice results (see caption). Lattice results are also color coded to distinguish those that include continuum extrapolation from those that do not (cf. see Table X in Supplemental Material [55] for more details). It is evident this work clearly narrows down the broad range of estimates from previous calculations, providing the most precise lattice results to date while properly addressing the associated systematic uncertainties. Note a few of the earlier calculations deviate from the most recent ones. In particular, estimations in Refs. [38,49] differ, despite

continuum and chiral extrapolations. We believe this is due to charm quark mistuning, which was also reflected in their estimation of Ξ_{cc} mass, when compared with other lattice results and the experimental number from LHCb [114]. Deviation in Ref. [2] is also potentially due to charm quark mistuning and uncontrolled discretization errors. It is also worth noting that some model results align closely with the vertical line, suggesting it may be interesting to explore possible commonalities in their interaction potentials that lead to results near our lattice estimation.

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N. S. D., D. C., and A. R. have contributed equally and are credited as co-first authors.

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- [1] J. D. Bjorken, Is the ccc a new deal for baryon spectroscopy?, *AIP Conf. Proc.* **132**, 390 (1985).
 - [2] M. Padmanath, R. G. Edwards, N. Mathur, and M. Peardon, Spectroscopy of triply-charmed baryons from lattice QCD, *Phys. Rev. D* **90**, 074504 (2014).
 - [3] S. Meinel, Excited-state spectroscopy of triply-bottom baryons from lattice QCD, *Phys. Rev. D* **85**, 114510 (2012).
 - [4] A. Tumasyan *et al.* (CMS Collaboration), Observation of triple J/ψ meson production in proton-proton collisions, *Nat. Phys.* **19**, 338 (2023); **19**, 461(E) (2023).
 - [5] T. Gershon and A. Poluektov, Displaced B_c^- mesons as an inclusive signature of weakly decaying double beauty hadrons, *J. High Energy Phys.* **01** (2019) 019.
 - [6] Q. Qin, Y.-J. Shi, W. Wang, G.-H. Yang, F.-S. Yu, and R. Zhu, Inclusive approach to hunt for the beauty-charmed baryons Ξ_{bc} , *Phys. Rev. D* **105**, L031902 (2022).
 - [7] B. Bhattacharjee, T. Ghosh, R. Sengupta, and P. Solanki, Dedicated triggers for displaced jets using timing information from electromagnetic calorimeter at HL-LHC, *J. High Energy Phys.* **08** (2022) 254.
 - [8] B. Silvestre-Brac, Spectrum and static properties of heavy baryons, *Few Body Syst.* **20**, 1 (1996).
 - [9] W. Roberts and M. Pervin, Heavy baryons in a quark model, *Int. J. Mod. Phys. A* **23**, 2817 (2008).
 - [10] J. Vijande, A. Valcarce, and H. Garcilazo, Constituent-quark model description of triply heavy baryon nonperturbative lattice QCD data, *Phys. Rev. D* **91**, 054011 (2015).
 - [11] G. Yang, J. Ping, P. G. Ortega, and J. Segovia, Triply heavy baryons in the constituent quark model, *Chin. Phys. C* **44**, 023102 (2020).
 - [12] M.-S. Liu, Q.-F. Lü, and X.-H. Zhong, Triply charmed and bottom baryons in a constituent quark model, *Phys. Rev. D* **101**, 074031 (2020).
 - [13] F. J. Llanes-Estrada, O. I. Pavlova, and R. Williams, A first estimate of triply heavy baryon masses from the pNRQCD perturbative static potential, *Eur. Phys. J. C* **72**, 2019 (2012).
 - [14] E. Ortiz-Pacheco and R. Bijker, Masses and radiative decay widths of s - and p -wave singly, doubly, and triply heavy charm and bottom baryons, *Phys. Rev. D* **108**, 054014 (2023).
 - [15] A. P. Martynenko, Ground-state triply and doubly heavy baryons in a relativistic three-quark model, *Phys. Lett. B* **663**, 317 (2008).

- [16] R. N. Faustov and V. O. Galkin, Triply heavy baryon spectroscopy in the relativistic quark model, *Phys. Rev. D* **105**, 014013 (2022).
- [17] J.-R. Zhang and M.-Q. Huang, Deciphering triply heavy baryons in terms of QCD sum rules, *Phys. Lett. B* **674**, 28 (2009).
- [18] Z.-G. Wang, Analysis of the triply-heavy baryon states with the QCD sum rules, *AAPPS Bull.* **31**, 5 (2021).
- [19] T. M. Aliev, K. Azizi, and M. Savcı, Properties of triply heavy spin-3/2 baryons, *J. Phys. G* **41**, 065003 (2014).
- [20] Z.-G. Wang, Analysis of the $\frac{3}{2}^+$ heavy and doubly heavy baryon states with QCD sum rules, *Eur. Phys. J. C* **68**, 459 (2010).
- [21] R.-H. Wu, Y.-S. Zuo, C. Meng, Y.-Q. Ma, and K.-T. Chao, NLO effects for Ω QQQ baryons in QCD sum rules, *Chin. Phys. C* **45**, 093103 (2021).
- [22] H. Sanchis-Alepuz, R. Alkofer, G. Eichmann, and R. Williams, Model comparison of Delta and Omega masses in a covariant Faddeev approach, *Proc. Sci. QCD-TNT-II2011* (2011) 041.
- [23] M. Radin, S. Babaghodrat, and M. Monemzadeh, Estimation of heavy baryon masses Ω_{ccc}^{++} and Ω_{bbb}^- by solving the Faddeev equation in a three-dimensional approach, *Phys. Rev. D* **90**, 047701 (2014).
- [24] S.-x. Qin, C. D. Roberts, and S. M. Schmidt, Spectrum of light- and heavy-baryons, *Few Body Syst.* **60**, 26 (2019).
- [25] K. Thakkar, A. Majethiya, and P. C. Vinodkumar, Magnetic moments of baryons containing all heavy quarks in the quark-diquark model, *Eur. Phys. J. Plus* **131**, 339 (2016).
- [26] P.-L. Yin, C. Chen, G. a. Krein, C. D. Roberts, J. Segovia, and S.-S. Xu, Masses of ground-state mesons and baryons, including those with heavy quarks, *Phys. Rev. D* **100**, 034008 (2019).
- [27] Y. Jia, Variational study of weakly coupled triply heavy baryons, *J. High Energy Phys.* **10** (2006) 073.
- [28] J. M. Flynn, E. Hernandez, and J. Nieves, Triply heavy baryons and heavy quark spin symmetry, *Phys. Rev. D* **85**, 014012 (2012).
- [29] A. Bernotas and V. Simonis, Heavy hadron spectroscopy and the bag model, *Lith. J. Phys.* **49**, 19 (2009).
- [30] P. Hasenfratz, R. R. Horgan, J. Kuti, and J. M. Richard, Heavy baryon spectroscopy in the QCD bag model, *Phys. Lett.* **94B**, 401 (1980).
- [31] Z. Shah and A. K. Rai, Masses and Regge trajectories of triply heavy Ω_{ccc} and Ω_{bbb} baryons, *Eur. Phys. J. A* **53**, 195 (2017).
- [32] B. Patel, A. Majethiya, and P. C. Vinodkumar, Masses and magnetic moments of triply heavy flavour baryons in hypercentral model, *Pramana* **72**, 679 (2009).
- [33] N. Tazimi and A. Ghasempour, Mass spectrum of triply heavy baryon in the hypercentral quark model, *Mod. Phys. Lett. A* **36**, 2150270 (2021).
- [34] K.-W. Wei, B. Chen, and X.-H. Guo, Masses of doubly and triply charmed baryons, *Phys. Rev. D* **92**, 076008 (2015).
- [35] S. Migura, D. Merten, B. Metsch, and H.-R. Petry, Charmed baryons in a relativistic quark model, *Eur. Phys. J. A* **28**, 41 (2006).
- [36] K. Serafin, M. Gómez-Rocha, J. More, and S. D. Glazek, Approximate Hamiltonian for baryons in heavy-flavor QCD, *Eur. Phys. J. C* **78**, 964 (2018).
- [37] T.-W. Chiu and T.-H. Hsieh, Baryon masses in lattice QCD with exact chiral symmetry, *Nucl. Phys.* **A755**, 471 (2005).
- [38] C. Alexandrou, J. Carbonell, D. Christaras, V. Drach, M. Gravina, and M. Papinutto, Strange and charm baryon masses with two flavors of dynamical twisted mass fermions, *Phys. Rev. D* **86**, 114501 (2012).
- [39] Y. Namekawa *et al.* (PACS-CS Collaboration), Charmed baryons at the physical point in $2 + 1$ flavor lattice QCD, *Phys. Rev. D* **87**, 094512 (2013).
- [40] Z. S. Brown, W. Detmold, S. Meinel, and K. Orginos, Charmed bottom baryon spectroscopy from lattice QCD, *Phys. Rev. D* **90**, 094507 (2014).
- [41] K. U. Can, G. Erkol, M. Oka, and T. T. Takahashi, Look inside charmed-strange baryons from lattice QCD, *Phys. Rev. D* **92**, 114515 (2015).
- [42] H. Bahtiyar, K. U. Can, G. Erkol, P. Gubler, M. Oka, and T. T. Takahashi, Charmed baryon spectrum from lattice QCD near the physical point, *Phys. Rev. D* **102**, 054513 (2020).
- [43] J.-B. Li, L.-C. Gui, W. Sun, J. Liang, and W. Qin, Triply charmed baryons mass decomposition from lattice QCD, *Chin. Phys. C* **49**, 063103 (2025).
- [44] Y. Lyu, H. Tong, T. Sugiura, S. Aoki, T. Doi, T. Hatsuda, J. Meng, and T. Miyamoto, Dibaryon with highest charm number near unitarity from Lattice QCD, *Phys. Rev. Lett.* **127**, 072003 (2021).
- [45] S. Durr, G. Koutsou, and T. Lippert, Meson and Baryon dispersion relations with Brillouin fermions, *Phys. Rev. D* **86**, 114514 (2012).
- [46] C. Alexandrou and C. Kallidonis, Low-lying baryon masses using $N_f = 2$ twisted mass clover-improved fermions directly at the physical pion mass, *Phys. Rev. D* **96**, 034511 (2017).
- [47] R. A. Briceño, H.-W. Lin, and D. R. Bolton, Charmed-baryon spectroscopy from Lattice QCD with $N_f = 2 + 1 + 1$ flavors, *Phys. Rev. D* **86**, 094504 (2012).
- [48] S. Basak, S. Datta, M. Padmanath, P. Majumdar, and N. Mathur, Charm and strange hadron spectra from overlap fermions on HISQ gauge configurations, *Proc. Sci. LAT-TICE2012* (2012) 141.
- [49] C. Alexandrou, V. Drach, K. Jansen, C. Kallidonis, and G. Koutsou, Baryon spectrum with $N_f = 2 + 1 + 1$ twisted mass fermions, *Phys. Rev. D* **90**, 074501 (2014).
- [50] Y.-C. Chen and T.-W. Chiu (TWQCD Collaboration), Lattice QCD with $N_f = 2 + 1 + 1$ domain-wall quarks, *Phys. Lett. B* **767**, 193 (2017).
- [51] C. Alexandrou, S. Bacchio, G. Christou, and J. Finkenrath, Low-lying baryon masses using twisted mass fermions ensembles at the physical pion mass, *Phys. Rev. D* **108**, 094510 (2023).
- [52] E. Follana, Q. Mason, C. Davies, K. Hornbostel, G. P. Lepage, J. Shigemitsu, H. Trotter, and K. Wong (HPQCD Collaboration and UKQCD Collaboration), Highly improved staggered quarks on the lattice, with applications to charm physics, *Phys. Rev. D* **75**, 054502 (2007).
- [53] A. Bazavov *et al.* (MILC Collaboration), Lattice QCD ensembles with four flavors of highly improved staggered quarks, *Phys. Rev. D* **87**, 054505 (2013).
- [54] A. Bazavov, C. Bernard, N. Brown, C. DeTar, A. X. El-Khadra, E. Gámiz, S. Gottlieb, U. M. Heller, J. Komijani,

- A. S. Kronfeld, J. Laiho, P. B. Mackenzie, E. T. Neil, J. N. Simone, R. L. Sugar, D. Toussaint, and R. S. Van de Water (Fermilab Lattice Collaboration and MILC Collaboration), *b*- and *d*-meson leptonic decay constants from four-flavor lattice QCD, *Phys. Rev. D* **98**, 074512 (2018).
- [55] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/9phq-k8pv> for further information pertaining to the lattice QCD ensembles and mass extraction procedures in this study of triply charmed baryons (Ω_{ccc}), along with a compilation of our results on mass splittings and continuum extrapolation. This supplemental material also contains citations to Refs. [56–70].
- [56] D. Hatton, C. T. H. Davies, B. Galloway, J. Koponen, G. P. Lepage, and A. T. Lytle (HPQCD Collaboration), Charmonium properties from lattice QCD + QED: Hyperfine splitting, J/ψ leptonic width, charm quark mass, and a_μ^c , *Phys. Rev. D* **102**, 054511 (2020).
- [57] A. Bazavov *et al.* (MILC Collaboration), Gradient flow and scale setting on MILC HISQ ensembles, *Phys. Rev. D* **93**, 094510 (2016).
- [58] S. Basak, S. Datta, A. T. Lytle, M. Padmanath, P. Majumdar, and N. Mathur, Hadron spectra from overlap fermions on HISQ gauge configurations, *Proc. Sci. LATTICE2013* (2014) 243.
- [59] R. C. Johnson, Angular momentum on a lattice, *Phys. Lett.* **114B**, 147 (1982).
- [60] A. Bazavov *et al.* (MILC Collaboration), Scaling studies of QCD with the dynamical HISQ action, *Phys. Rev. D* **82**, 074501 (2010).
- [61] A. Bazavov *et al.* (MILC Collaboration), Nonperturbative QCD simulations with 2 + 1 flavors of improved staggered quarks, *Rev. Mod. Phys.* **82**, 1349 (2010).
- [62] M. F. L. Golterman and J. Smit, Lattice baryons with staggered fermions, *Nucl. Phys.* **B255**, 328 (1985).
- [63] J. A. Bailey, Staggered baryon operators with flavor SU(3) quantum numbers, *Phys. Rev. D* **75**, 114505 (2007).
- [64] C. DeTar and S.-H. Lee, Variational method with staggered fermions, *Phys. Rev. D* **91**, 034504 (2015).
- [65] J. Balog, F. Niedermayer, and P. Weisz, Logarithmic corrections to $O(a^2)$ lattice artifacts, *Phys. Lett. B* **676**, 188 (2009).
- [66] N. Husung, Logarithmic corrections to $O(a)$ and $O(a^2)$ effects in lattice QCD with Wilson or Ginsparg–Wilson quarks, *Eur. Phys. J. C* **83**, 142 (2023); **83**, 144(E) (2023).
- [67] N. Husung, Lattice artifacts of local fermion bilinears up to $O(a^2)$, *Eur. Phys. J. C* **85**, 427 (2025).
- [68] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [69] T. Barnes, S. Godfrey, and E. S. Swanson, Higher charmonia, *Phys. Rev. D* **72**, 054026 (2005).
- [70] R. J. Hudspith, B. Colquhoun, A. Francis, R. Lewis, and K. Maltman, A lattice investigation of exotic tetraquark channels, *Phys. Rev. D* **102**, 114506 (2020).
- [71] H. Neuberger, Exactly massless quarks on the lattice, *Phys. Lett. B* **417**, 141 (1998).
- [72] H. Neuberger, More about exactly massless quarks on the lattice, *Phys. Lett. B* **427**, 353 (1998).
- [73] N. Mathur, M. Padmanath, and S. Mondal, Precise predictions of charmed-bottom hadrons from lattice QCD, *Phys. Rev. Lett.* **121**, 202002 (2018).
- [74] P. Junnarkar, N. Mathur, and M. Padmanath, Study of doubly heavy tetraquarks in lattice QCD, *Phys. Rev. D* **99**, 034507 (2019).
- [75] N. Mathur and M. Padmanath, Lattice QCD study of doubly charmed strange baryons, *Phys. Rev. D* **99**, 031501 (R) (2019).
- [76] M. Padmanath, A. Radhakrishnan, and N. Mathur, Bound Isoscalar Axial-vector bcu^-d^- tetraquark T_{bc} from Lattice QCD using two-meson and diquark-antidiquark variational basis, *Phys. Rev. Lett.* **132**, 201902 (2024).
- [77] A. Radhakrishnan, M. Padmanath, and N. Mathur, Study of the isoscalar scalar bcu^-d^- tetraquark T_{bc} with lattice QCD, *Phys. Rev. D* **110**, 034506 (2024).
- [78] M. Padmanath and N. Mathur, Quantum numbers of recently discovered Ω_c^0 baryons from lattice QCD, *Phys. Rev. Lett.* **119**, 042001 (2017).
- [79] Y. Lyu, S. Aoki, T. Doi, T. Hatsuda, Y. Ikeda, and J. Meng, Doubly Charmed tetraquark T_{cc}^+ from Lattice QCD near physical point, *Phys. Rev. Lett.* **131**, 161901 (2023).
- [80] S. Aoki, T. Doi, T. Hatsuda, Y. Ikeda, T. Inoue, N. Ishii, K. Murano, H. Nemura, and K. Sasaki (HAL QCD Collaboration), Lattice quantum chromodynamical approach to nuclear physics, *Prog. Theor. Exp. Phys.* **2012**, 01A105 (2012).
- [81] X. Feng, L. Jin, and M. J. Riberdy, Lattice QCD calculation of the pion mass splitting, *Phys. Rev. Lett.* **128**, 052003 (2022).
- [82] A. Bazavov *et al.* (Fermilab Lattice Collaboration and MILC Collaboration), Charmed and light pseudoscalar meson decay constants from four-flavor lattice QCD with physical light quarks, *Phys. Rev. D* **90**, 074509 (2014).
- [83] R. J. Hudspith, M. F. M. Lutz, and D. Mohler, Precise Omega baryons from lattice QCD, [arXiv:2404.02769](https://arxiv.org/abs/2404.02769).
- [84] C. Michael, Adjoint sources in lattice gauge theory, *Nucl. Phys.* **B259**, 58 (1985).
- [85] M. Luscher and U. Wolff, How to calculate the elastic scattering matrix in two-dimensional quantum field theories by numerical simulation, *Nucl. Phys.* **B339**, 222 (1990).
- [86] J. Sakurai, *Advanced Quantum Mechanics*, Always learning (Pearson Education, Incorporated, London, 1967).
- [87] S. Basak, R. Edwards, G. T. Fleming, U. M. Heller, C. Morningstar, D. Richards, I. Sato, and S. J. Wallace (Lattice Hadron Physics (LHPC) Collaboration), Clebsch-Gordan construction of lattice interpolating fields for excited baryons, *Phys. Rev. D* **72**, 074501 (2005).
- [88] S. Datta, S. Gupta, M. Padmanath, J. Maiti, and N. Mathur, Nucleons near the QCD deconfinement transition, *J. High Energy Phys.* **02** (2013) 145.
- [89] M. Padmanath, Baryons from lattice QCD, Ph.D. thesis, TIFR Mumbai, 2014.
- [90] I. Montvay and G. Munster, *Quantum Fields on a Lattice*, Cambridge Monographs on Mathematical Physics (Cambridge University Press, Cambridge, England, 1997).
- [91] S. Borsanyi *et al.*, High precision scale setting on the lattice, *Proc. Sci. LATTICE2021* (2022) 371.
- [92] M. F. L. Golterman, Staggered mesons, *Nucl. Phys.* **B273**, 663 (1986).
- [93] C. Aubin and K. Orginos, A new approach for Delta form factors, *AIP Conf. Proc.* **1374**, 621 (2011).

- [94] N. Mathur, M. Padmanath, and D. Chakraborty, Strongly bound dibaryon with maximal beauty flavor from Lattice QCD, *Phys. Rev. Lett.* **130**, 111901 (2023).
- [95] Z. Renqiang, S. Wei, C. Feiyu, C. Ying, G. Ming, J. Xiangyu, and L. Zhaofeng, Annihilation diagram contribution to charmonium masses *, *Chin. Phys. C* **46**, 043102 (2022).
- [96] Z. T. Draper, M. T. Hansen, F. Romero-López, and S. R. Sharpe, Three relativistic neutrons in a finite volume, *J. High Energy Phys.* **07** (2023) 226.
- [97] F. Romero-López, Three-particle scattering amplitudes from lattice QCD, *Rev. Mex. Fis. Suppl.* **3**, 0308003 (2022).
- [98] M. T. Hansen and S. R. Sharpe, Lattice QCD and three-particle decays of resonances, *Annu. Rev. Nucl. Part. Sci.* **69**, 65 (2019).
- [99] M. Mai and M. Döring, Three-body unitarity in the finite volume, *Eur. Phys. J. A* **53**, 240 (2017).
- [100] M. T. Hansen, F. Romero-López, and S. R. Sharpe, Decay amplitudes to three hadrons from finite-volume matrix elements, *J. High Energy Phys.* **04** (2021) 113.
- [101] T. D. Blanton, A. D. Hanlon, B. Hörz, C. Morningstar, F. Romero-López, and S. R. Sharpe, Interactions of two and three mesons including higher partial waves from lattice QCD, *J. High Energy Phys.* **10** (2021) 023.
- [102] Z. T. Draper, A. D. Hanlon, B. Hörz, C. Morningstar, F. Romero-López, and S. R. Sharpe, Interactions of πK , $\pi\pi K$ and $KK\pi$ systems at maximal isospin from lattice QCD, *J. High Energy Phys.* **05** (2023) 137.
- [103] H. Yan, M. Mai, M. Garofalo, U.-G. Meißner, C. Liu, L. Liu, and C. Urbach, ω Meson from Lattice QCD, *Phys. Rev. Lett.* **133**, 211906 (2024).
- [104] C. McNeile, C. T. H. Davies, E. Follana, K. Hornbostel, and G. P. Lepage, Heavy meson masses and decay constants from relativistic heavy quarks in full lattice QCD, *Phys. Rev. D* **86**, 074503 (2012).
- [105] R. J. Dowdall, C. T. H. Davies, T. C. Hammant, and R. R. Horgan, Precise heavy-light meson masses and hyperfine splittings from Lattice QCD including charm quarks in the sea, *Phys. Rev. D* **86**, 094510 (2012).
- [106] B. Chakraborty, C. T. H. Davies, B. Galloway, P. Knecht, J. Koponen, G. C. Donald, R. J. Dowdall, G. P. Lepage, and C. McNeile, High-precision quark masses and QCD coupling from $n_f = 4$ lattice QCD, *Phys. Rev. D* **91**, 054508 (2015).
- [107] O. Bar, C. Bernard, G. Rupak, and N. Shore, Chiral perturbation theory for staggered sea quarks and Ginsparg-Wilson valence quarks, *Phys. Rev. D* **72**, 054502 (2005).
- [108] J.-W. Chen, D. O'Connell, and A. Walker-Loud, Universality of mixed action extrapolation formula, *J. High Energy Phys.* **04** (2009) 090.
- [109] M. Lujan, A. Alexandru, Y. Chen, T. Draper, W. Freeman, M. Gong, F. X. Lee, A. Li, K. F. Liu, and N. Mathur (QCD Collaboration), Δ_{mix} parameter in the overlap on domain-wall mixed action, *Phys. Rev. D* **86**, 014501 (2012).
- [110] S. Basak, S. Datta, N. Mathur, A. T. Lytle, P. Majumdar, and M. Padmanath (ILGTI Collaboration), Hadron spectra and Δ_{mix} from overlap quarks on a HISQ sea, *Proc. Sci. LATTICE2014* (2015) 083.
- [111] S. R. Beane, P. F. Bedaque, A. Parreno, and M. J. Savage, Two nucleons on a lattice, *Phys. Lett. B* **585**, 106 (2004).
- [112] R. A. Briceño, Z. Davoudi, T. Luu, and M. J. Savage, Two-nucleon systems in a finite volume. II. $^3S_1 - ^3D_1$ coupled channels and the deuteron, *Phys. Rev. D* **88**, 114507 (2013).
- [113] B. Mohan, T. Mary S., A. Hazra, and R. Dhir, Screening of the quark charge and mixing effects on transition moments and m_1 decay widths of baryons, *Phys. Rev. D* **106**, 113007 (2022).
- [114] R. Aaij *et al.* (LHCb Collaboration), Observation of the doubly charmed baryon Ξ_{cc}^{++} , *Phys. Rev. Lett.* **119**, 112001 (2017).