doi:10.1038/nature18011

# Searching for the rules that govern hadron construction

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**Just as quantum electrodynamics describes how electrons are bound in atoms by the electromagnetic force, mediated by the exchange of photons, quantum chromodynamics (QCD) describes how quarks are bound inside hadrons by the strong force, mediated by the exchange of gluons. QCD seems to allow hadrons constructed from increasingly many quarks to exist, just as atoms with increasing numbers of electrons exist, yet such complex constructions seemed, until recently, not to be present in nature. Here we describe advances in the spectroscopy of mesons that are refining our understanding of the rules for predicting hadron structure from QCD.**

While decades of experimental study support QCD as the underlying theory of quark interactions, a detailed understanding of the way QCD generates protons, neutrons, and other strongly interacting 'hadrons' remains elusive. The majority of observed hadrons fall neatly into only two very limited sets: baryons, which are consistent with being three-quark constructions ($qqq$); and mesons, which are quark–antiquark ($q\bar{q}$) constructions. QCD also appears to allow constructions featuring larger numbers of quarks as well as hadrons built not only from quarks, but also from gluons. This has raised the question of why, until possibly now, there has been no evidence for a spectrum of such hadrons. Have we just been historically unsuccessful in producing these exotic particles in the laboratory, or are there more restrictive rules for building hadrons that are not obvious from the unsolved equations of QCD? Here we choose to focus specifically on the spectrum of mesons, where timely developments in both theory and experiment can be used to illustrate how the field of hadron spectroscopy addresses fundamental questions about QCD, questions that are common to both the meson and baryon sectors.

## Interacting quarks and gluons in QCD

Within QCD, the 'charge' that controls the interactions of quarks is known as 'colour', and it was the study of the empirical spectrum of hadrons that first introduced the concept of quarks and their threefold colour charge. Interactions in QCD are symmetric under changes of colour, that is, no single colour of quark behaves differently from the other two, and imposing this symmetry on the theory uniquely defines the interactions allowed in QCD between the quarks and the force-carrying gluons. Coloured quarks can interact by emitting or absorbing gluons, and because they carry colour charge themselves, gluons can also emit and absorb gluons.

Although observations about the spectrum of hadrons inspired the fundamental theory of quark interactions, calculating the detailed spectrum from this theory has so far been impossible. The difficulties in these calculations stem from the presence of gluon–gluon interactions, which make QCD forces very strong on the distance scale of $10^{-15}$ m that characterizes hadrons. This ultimately results in a property called 'confinement', whereby quarks are permanently trapped inside composite hadrons, making it difficult to isolate the interaction of a single quark and antiquark from the collective behaviour of quarks and gluons in the hadron. The strong coupling means that, unlike for the electromagnetic force, where the exchange of two photons between electrons in an atom is far less probable than the exchange of just one, exchange of any number of gluons between quarks in a hadron is every bit as probable as exchanging one. Because of this, there is no simple method of calculating the net effect of interactions between two quarks, and a QCD calculation of the mass of a hadron, easily measurable by experiment, becomes intractable.

## Understanding QCD via rules for building hadrons

Our inability to solve the equations of QCD is not just a curiosity—it restricts our understanding of the behaviour and structure of hadrons, owing to the lack of any simple relationship between the fundamental quarks and gluons of QCD and the spectrum of hadrons observed experimentally. This has motivated the use of heuristic models, or 'rules', that serve as a bridge between QCD and experiment, capturing the important features of the spectrum while attempting to respect the known properties of QCD. The development of a rulebook for construction of hadrons consistent with both QCD and experimental data would arguably define what it means to understand how QCD generates hadrons. A uniform set of rules may not exist—there may be no simple way to capture the complex behaviour of QCD—but the high degree of regularity in the experimental spectrum of hadrons suggests that this is not a forlorn hope, and the search for this rulebook drives the field of hadron spectroscopy.

An important area of exploration attempts to create previously unobserved classes of hadrons in the laboratory, such as quark–gluon hybrids or tetraquarks. From the pattern of such states, or their absence, we can refine our understanding of the rules of hadron construction. A second area develops techniques for calculating the observable properties of hadrons directly from QCD, which will indicate how the rules follow from the strong interactions of quarks and gluons prescribed by that theory. In what follows we will review the current developments in each of these two areas and discuss the prospects for achieving the goal of determining the rulebook for hadron construction.

## Rules inferred from experimental data

We label hadrons by their mass and their quantum numbers $J$ (spin), $P$ (parity, behaviour under reflection in a mirror), and $C$ (charge-conjugation, behaviour under exchange of particles with antiparticles). These properties are directly observable, but other characteristics, such as their internal composition, must be inferred. As the number of observed hadrons has increased over the last half-century, definite patterns have emerged that have led to an initial set of simple rules for the construction of hadrons from quarks.

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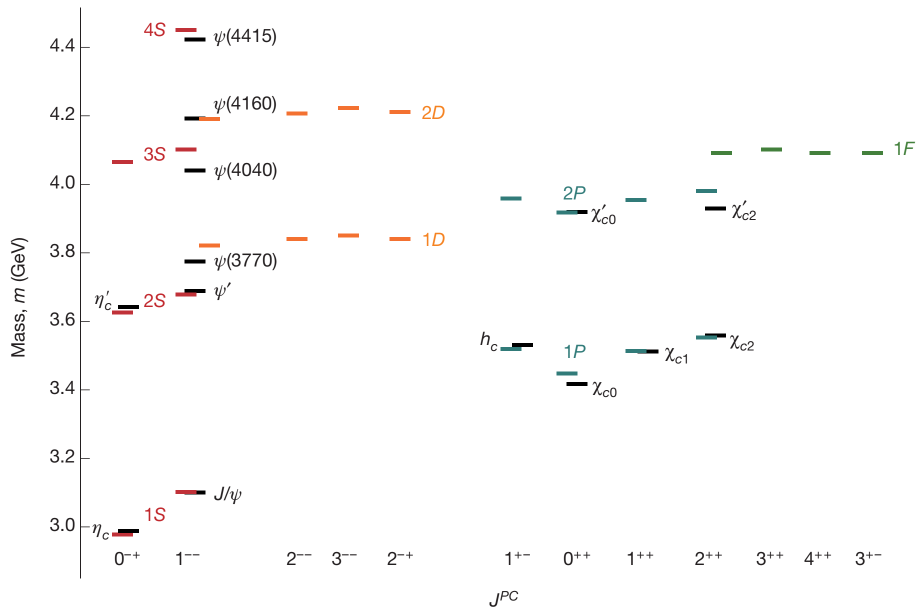


**Figure 1 | The charmonium spectrum.** A $q\bar{q}$ potential model calculation (coloured)[60] of the charmonium spectrum is compared to experiment (black)[61]. Columns indicate states of common $J^{PC}$. Potential model states appear in groups labelled by their radial and orbital angular momentum quantum numbers, $nL$ (coloured text; $n=1, 2, 3...$ $L=$ S, P, D, F...).

## The quark–antiquark rule for constructing mesons

One of the earliest patterns discovered (in the 1960s) was that mesons with the same $J^{PC}$ quantum numbers could be grouped into sets of nine ('nonet') having similar mass. This could be explained by combining a quark $q$ with an antiquark $\bar{q}$ if there were three 'flavours' of quark—these were given the names 'up', 'down' and 'strange'. The lightest nonet of mesons has $J^{PC}=0^{-+}$, and there are heavier nonets with other $J^{PC}$ values. It was suggested that the additional mass-energy of the excited hadrons arises principally from the orbital or radial motion of the quark–antiquark ($q\bar{q}$) pair, in analogy to the excitations of a single-electron atom.

With the discovery of charmonium (in the 1970s)[1,2], this quantum-mechanical picture became more precise—these new mesons with masses much larger than those observed earlier were explained as being bound states featuring a new, heavier quark, which was dubbed 'charm'. Charmonium mesons with a range of $J^{PC}$ values were observed and their spectrum (Fig. 1) resembles that of a pair of particles bound by a potential. The large mass of the charm quark justified such an approach, as many of the complexities of a relativistic system could be neglected. The potential needed to describe the spectrum was novel, featuring a steady rise at large distances that would confine the quarks within the meson[3]. A feature of this model of mesons is that it is not possible for a $q\bar{q}$ pair in any orbitally or radially excited state to have $J^{PC}$ in the set $0^{+-}, 1^{-+}, 2^{+-}, \ldots$. Sets of mesons with these 'exotic' quantum numbers were not convincingly observed experimentally, either in charmonium or for the lighter quarks, supporting the $q\bar{q}$ picture.

Until recently virtually all experimentally observed hadrons could have their presence explained by a simple rule stating that each meson is constructed from a $q\bar{q}$ pair, and each baryon from a three-quark configuration. However, it has never been at all obvious why QCD is so parsimonious—why are there not meson-like states of two quarks and two antiquarks ('tetraquarks'), or baryon-like states of four quarks and an antiquark ('pentaquarks')? Furthermore, since the gluons of QCD strongly interact just as quarks do, could we not have 'hybrid mesons' in which gluons bind to a $q\bar{q}$ pair, and 'glueballs' that do not require quarks at all? Observation of hadrons like these would challenge the simple rule outlined above, and indeed, recent experimental results are casting doubt on how parsimonious QCD really is.

## Recent results challenge the $q\bar{q}$ rule

A powerful way to study the meson spectrum is to collide high-energy beams of electrons and positrons and to observe the rate at which systems of hadrons are produced. In this process, the $e^+e^-$ pair first annihilates, producing a photon; the photon converts into a quark and antiquark, which then interact, exchanging gluons and perhaps creating more $q\bar{q}$ pairs; finally, these quarks and gluons arrange themselves into a system of hadrons that are observed by the particle detector. If the collision energy is close to the mass of a meson with $J^{PC}=1^{--}$ quantum numbers, the system 'resonates', and the probability of a collision increases. Thus, a plot of the normalized rate of hadron production, the 'cross-section', against the $e^+e^-$ centre-of-mass energy, shows peaks corresponding to the produced meson states, also known as 'resonances' (Fig. 2a). These excited states exist only briefly before decaying into the set of observed lighter hadrons, and the width of the peak is inversely related to the lifetime of the state.

Figure 2a depicts the total rate of hadron production as a function of the $e^+e^-$ centre-of-mass energy. The peaks are interpreted as evidence for a series of excited states—the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$—consistent with expectations from the $q\bar{q}$ picture (see Fig. 1). But recent experimental advances have allowed a closer inspection. If instead of the total rate, we look at the rates for the production of specific systems of hadrons, distinct features appear that have no simple explanation in the $q\bar{q}$ picture.

The production rate of the $\pi^+\pi^-J/\psi$ system, shown in Fig. 2b, provides one such example. (The $J/\psi$ is a hadron that, for historical reasons, has two names associated with it, $J$ and $\psi$.) Here, a prominent peak appears at 4,260 MeV, which, surprisingly, lies between the masses of the $\psi(4160)$ and $\psi(4415)$ states. Unlike the $\psi(4160)$ and $\psi(4415)$, this $Y(4260)$ resonance has no explanation within the $q\bar{q}$ picture. Another example is the production rate of the $\pi^+\pi^-\psi'$ system. The $Y(4260)$ resonance might be expected also to appear here, since $\pi^+\pi^-J/\psi$ and $\pi^+\pi^-\psi'$ are very similar systems, but it does not. Instead, two peaks appear, for $Y(4360)$ and $Y(4660)$ (Fig. 2c), in further disagreement with the spectrum suggested by the total cross-section. These $Y$ states, which appear in addition to those expected within the $q\bar{q}$ picture, may be a signal that QCD does indeed produce mesons with internal structures beyond the simple $q\bar{q}$ rule.

The observation of new states in charmonium, which was previously believed to be well understood, has spurred searches for further exotic candidate states, observations of which are providing still more challenges for the simple $q\bar{q}$ rule. For example, a detailed study of the $\pi^+\pi^-J/\psi$ system produced in $Y(4260)$ decays showed that the $\pi^{\pm}J/\psi$ system (Fig. 3a)

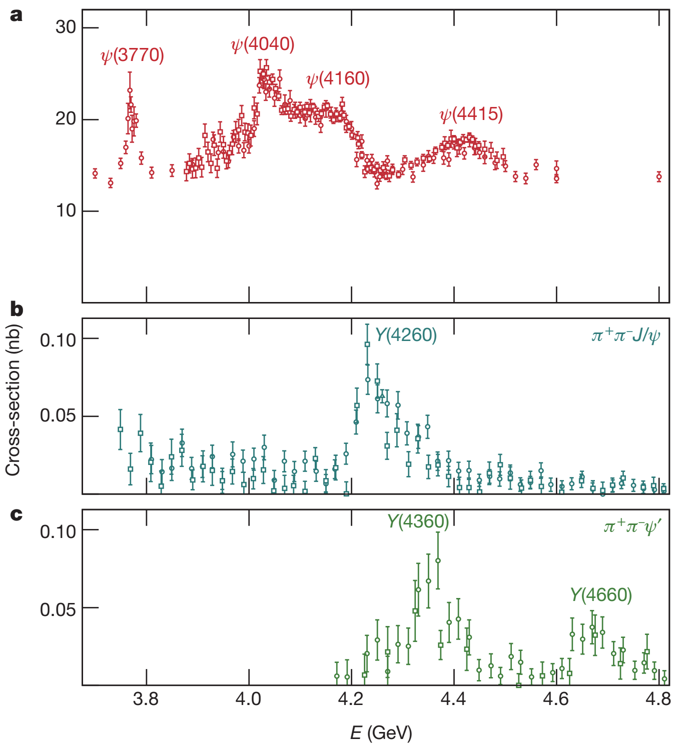


**Figure 2 | Electron–positron annihilation cross-sections. a**, $e^+e^- \rightarrow$ hadrons (refs 62, 63). **b**, $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ (refs 4–6). **c**, $e^+e^- \rightarrow \pi^+\pi^-\psi'$ (refs 65, 66). The $1^{--}$ states $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$, indicated in **a**, can be associated with the $1D$, $3S$, $2D$ and $4S$ states of the potential model of Fig. 1. The error bars represent combined statistical and systematic uncertainties, taken from the appropriate references. The enhancements observed in **b** and **c** do not line up with these states, which may indicate that they correspond to new hadron states that do not appear in the potential model and hence do not obey the $q\bar{q}$ rule. 1 nanobarn (nb) $= 10^{-37}\,\mathrm{m}^2$.

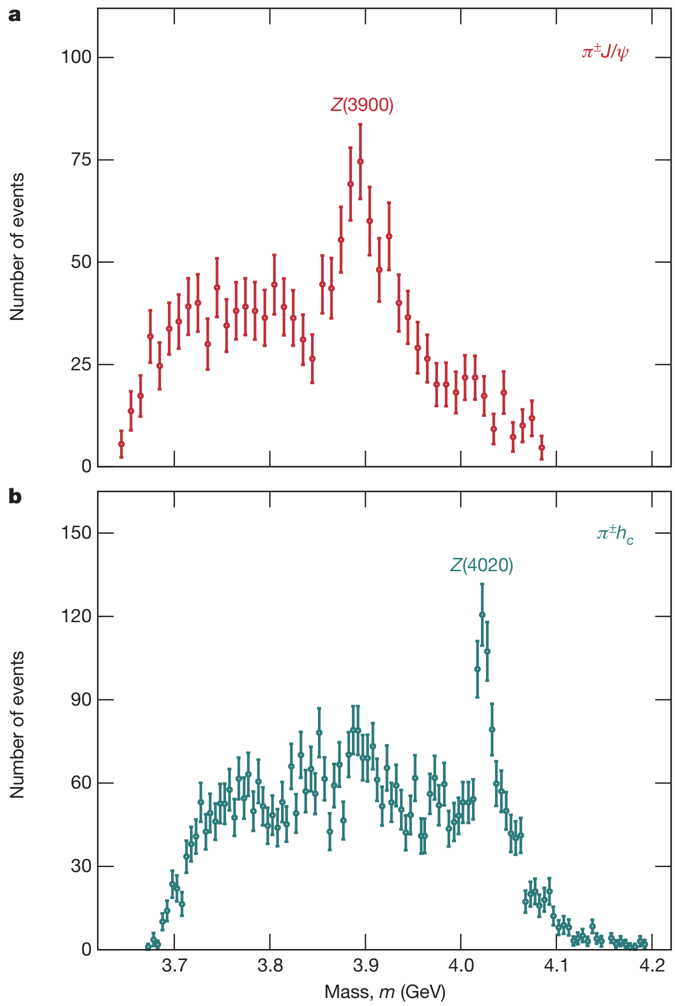


**Figure 3 | Number of events collected as a function of invariant mass. a**, For $\pi^\pm J/\psi$ (ref. 5). **b**, For $\pi^\pm h_c$ (ref. 7). In each case a clear narrow enhancement is observed that may be interpreted as a new hadron state. The error bars represent statistical uncertainty.

appears to resonate at a mass of 3,900 MeV, producing an electrically charged state labelled $Z(3900)$[4–6]. This structure is particularly noteworthy because its large mass and decay featuring $J/\psi$ suggest that it contains a charm quark and an anti-charm quark, while its net electric charge requires further light (up- and down-flavoured) quarks. It is thus a possible tetraquark. A pattern of such states is beginning to emerge around 4 GeV: for example, in the $\pi^+\pi^- h_c$ system, also produced in $e^+e^-$ collisions, another electrically charged structure, $Z(4020)$, appears in the $\pi^\pm h_c$ spectrum[7] (Fig. 3b) with a somewhat larger mass.

These new states can also, in principle, be produced in the weak decay of heavy mesons containing a bottom quark. Strangely, recent experimental data yields no evidence of $Z(3900)$ production in such decays[8]. Instead, signals for still further new states of higher mass are observed[8–11]. A related process is the decay of heavy baryons containing a bottom quark, and here, equally as surprising, we find what appears to be a resonating proton–$J/\psi$ system[12]. This hadron is a possible pentaquark. Although the origin of these new states is not yet firmly established, they present a serious challenge to the simple rules for constructing mesons and baryons that we previously believed were obeyed by QCD.

The pattern of conventional mesons nicely replicates itself for each flavour of quark: many structures that appear in the spectrum of light quarks (up, down, strange) reappear for charm quarks at the 3-GeV scale, and again for bottom quarks at the 10-GeV scale. One might also expect that any spectrum of hybrids, tetraquarks or other novel constructions should have recurrent patterns for different quark flavours. In fact, bottom-quark analogues of the charged tetraquark candidates in charmonium have been reported[13]. Historically, these observations preceded those in charmonium.

Like tetraquarks and pentaquarks, another class of hadrons that appear to be allowed by the fundamental interactions of QCD are quark–gluon hybrids, in which gluons and quarks have a role in setting the quantum numbers of the hadron. A subset of possible hybrid mesons have a unique experimental signature: exotic $J^{PC}$ not accessible to a $q\bar{q}$ pair. While there are experimental indications of exotic hybrid candidates[14–18], no firmly established spectrum of hybrid mesons has been discovered.

In parallel to the experimental work discussed above, theoretical efforts are underway to understand whether QCD predicts the existence of hadrons which go beyond the $q\bar{q}$ meson and three-quark baryon rule, or whether the collective behaviour of quarks and gluons excludes the construction of more exotic combinations. It is to such calculations that our attention now turns.

## Rules derived from QCD

Much of our understanding of hadrons is informed by models, which may be motivated by features of QCD, by empirical observations, or both. A goal is to develop an understanding that is based on rigorous calculations of the interaction of quarks and gluons through the equations of QCD. However, the strongly coupled nature of QCD makes techniques that are practical for calculating weak and electromagnetic interactions ineffective for predicting properties of hadrons that emerge from QCD. We need a different approach, one that utilizes the fact that all fundamental particles, including quarks and gluons in QCD, are more correctly thought of as fluctuating quantum fields. The quantum aspect of the theory is embodied in the fact that observable consequences follow from a sum over all possible configurations in space and time that these fields can

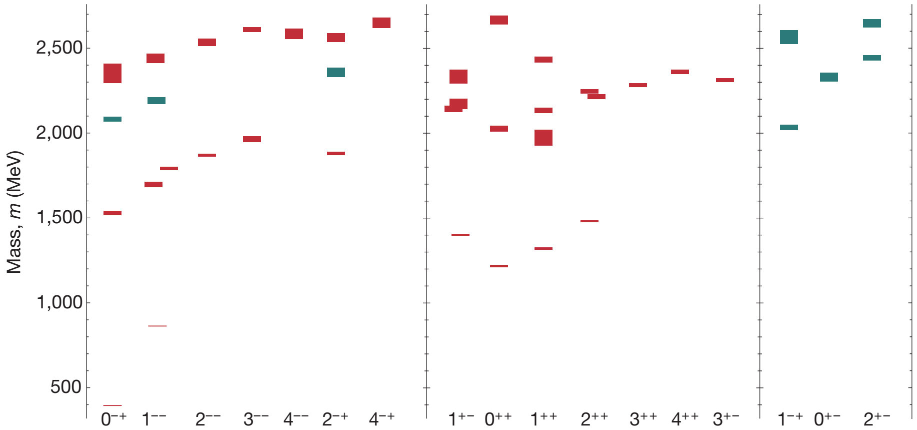


**Figure 4 | Lattice QCD computation of the meson spectrum.** The spectrum is computed with light-quark masses such that $m_\pi = 392$ MeV (ref. 67). The spectrum features sets of states compatible with the $nL$ assignments of a $q\bar{q}$ model (see Fig. 1), but also (shown in blue) states that do not have a place in such a model. These states can be interpreted as hybrid mesons in which a $q\bar{q}$ pair is partnered with an excitation of the gluon field[38]—their presence suggests a new rule of hadron construction that includes gluons. (The height of each box represents the estimated uncertainty in the calculation.)

take. The method known as lattice QCD makes the approximation of considering these fields on a discrete grid of points describing a restricted region of space-time. A finite, but large, number of possible configurations of the fields on this grid can be generated using random sampling on a computer, and a good approximation for observable hadron properties obtained. The volume of the grid and number of field configurations required to achieve useful precision demands substantial computational resources. Total computational times of several teraflop-years are not unusual for contemporary calculations, with such efforts making use of 'leadership-class' supercomputing facilities—future precision lattice QCD calculations of increased sophistication will require petaflop-scale machines.

Lattice QCD has been applied with substantial success to a broad range of processes involving hadrons[19], including the spectrum and internal structure of the lightest hadrons[20], the behaviour of hadrons at non-zero temperature, relevant in collisions of heavy ions[21], and heavy flavour decays, in which a heavy quark confined inside a meson decays through the weak interaction[22].

## Lattice QCD as a tool for hadron spectroscopy

Our interest is in the determination of properties of excited hadrons, where obtaining a high degree of numerical precision is an issue that is secondary to the more basic question of whether certain states exist or do not. In the past few years we have seen excellent progress in overcoming the challenges posed by these calculations. Exploration of the excited hadron spectrum is possible using an approach in which each state in the spectrum is produced by a different combination of quark and gluon field constructions, and for this method to be successful, a large set of possible constructions is required. The dynamics of QCD, implemented by the sum over possible field configurations, determines which combination of constructions is present in each state in the spectrum. A scheme outlined in refs 23 and 24 includes many constructions resembling $q\bar{q}$ pairs with various orbital motions and radial wavefunctions, motivated by the success of the $q\bar{q}$ rule in describing the experimental hadron spectrum. More elaborate structures are possible, though, and refs 23 and 24 included several that feature the gluon field in a non-trivial way, inspired by the possibility that hybrid mesons may be allowed by QCD.

This large set of constructions, coupled with advances in computational techniques[25], and the application of state-of-the-art computing hardware[26,27], led to the pioneering results presented in Fig. 4 for the spectrum of mesons constructed from light up and down quarks. The computational challenges of these calculations currently require the utilization of masses for the lightest quarks that are heavier than the physical up and down quark masses, which leads to a systematic shift in the computed meson masses. However, since the immediate goal is to understand the underlying QCD dynamics by studying the pattern of states, rather than precisely to predict the mass of each meson, the computed spectrum allows us to develop intuitive rules for constructing hadrons that generally apply for quarks of any mass.

The spectrum presented in Fig. 4 qualitatively reproduces many of the features of the experimental light meson spectrum, and further it reflects the simple picture of $q\bar{q}$ mesons, with the bulk of the states fitting into the pattern expected for states excited with increasing amounts of orbital angular momentum and/or excitations in the radial quantum number. There are some notable exceptions to this pattern, however, in particular the $0^{-+}$, $1^{--}$ and $2^{-+}$ states between 2.1 GeV and 2.4 GeV do not have an obvious explanation, and most strikingly there is a clear spectrum of states with exotic $J^{PC} = 1^{-+}$, $0^{+-}$ and $2^{+-}$, which cannot be constructed from a $q\bar{q}$ pair alone.

These additional mesons, which go beyond the set predicted by the $q\bar{q}$ rule, have a natural explanation as quark–gluon hybrid mesons. Previously, estimates for the spectrum of hybrid mesons came only from models, which made educated guesses for the behaviour of the strongly coupled gluons inside a hadron. Different guesses led to very different predictions for the number and mass of hybrid states[28–34]. Using the lattice QCD technique, we are now able to predict a definitive pattern of states directly from the fundamental interactions as prescribed by QCD. Further calculations[35–37], performed with larger values of the quark mass, up as high as the charm quark mass, show the same pattern of hybrid mesons, and they are found to be consistently 1.3 GeV heavier than the lightest $J^{PC} = 1^{--}$ meson. The particular pattern of states and the simple mass gap leads to a new rule of hadron construction for hybrid mesons, namely: combine $q\bar{q}$ constructions with a gluonic field that has $J^{PC} = 1^{+-}$ and a mass of about 1.3 GeV to form the spectrum of hybrid mesons in QCD. This is the first example of a rule following from a QCD calculation rather than being inferred from experimental observations[38].

Of course this rule must be verified by producing and studying hybrid mesons in the laboratory, and many current and near-future experiments include searches for these states in their programmes. Some hybrid meson candidates have already been observed experimentally in both the light meson sector[14–18] and in the charm region. For example, the $Y(4260)$ discussed in the previous section has $J^{PC} = 1^{--}$, approximately the right mass relative to the $J/\psi$, and it seems to appear in addition to the expected $q\bar{q}$ excitations. The new rule of hybrid meson construction would have this meson partnered with states of $J^{PC} = (0, 1, 2)^{-+}$ at a similar mass. Searches for these states are underway.

## Calculating how hadrons decay

These calculations of the excited meson spectrum within QCD represent a major step forward in our understanding of hadron spectroscopy, but they still make approximations that fail to capture an important feature of excited hadrons—that they are resonances, decaying rapidly to lighter hadrons. As can be seen in Figs 2 and 3, in simple cases, excited states appear as characteristic peaks in the rate of observation of certain final-state mesons, and lattice QCD calculations should be capable of reproducing this behaviour.

Experimentally, resonances are often observed to decay preferentially into certain sets of mesons and not others, and these patterns can be used

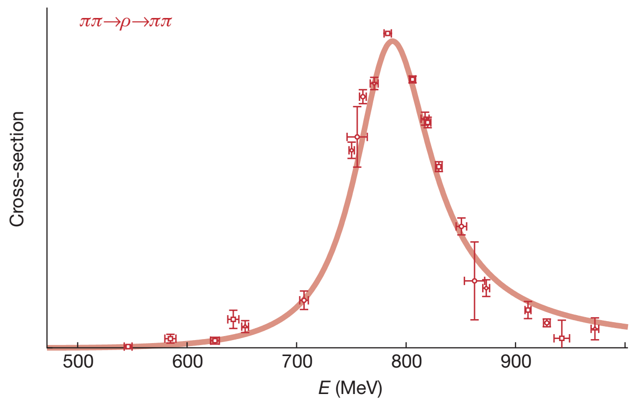


**Figure 5 | Calculation of the $\rho$ resonance.** The cross-section (in arbitrary units) is shown for $\pi\pi \rightarrow \pi\pi$ with $1^{--}$ quantum numbers, calculated using lattice QCD with light-quark masses such that $m_\pi = 236$ MeV (ref. 68). The $\rho$ resonance is clearly observed as a peak, and from its position and width the mass and decay rate of this excited state can be extracted. The errors represent the uncertainty in the calculation.

to infer details of the resonant state's internal structure. To be able to calculate the decay properties of the excited hadrons directly from QCD would provide a powerful tool for interpreting experimental data. In the case of predictions of previously unobserved excitations, it may also provide suggested decay channels to be examined in experimental searches.

Extending the calculations described above to account correctly for the decay of excited states is possible[39–46] but challenging, and serious efforts have only recently begun[47–54]. As an example of what can be achieved, in Fig. 5 we present the cross-section for two pions forming the lightest $1^{--}$ resonance, known as the $\rho$, and then decaying back into two pions. A clear peak is observed, whose position and width provide the mass and decay rate of the $\rho$.

These rapidly maturing theoretical techniques will be required to study the new charmonium mesons, discussed earlier, within QCD. The observed enhancements are seen only in specific final states, which implies that the ability to predict how hadrons decay directly from QCD will be an essential component in interpreting experimental data in the quest to develop the rules for constructing hadrons.

## Towards a unified set of rules

Much of what we know about what emerges from strongly coupled QCD has come from studying patterns of hadrons organized by mass and quantum numbers like $J$, $P$ and $C$. These patterns suggest quarks of several flavours which may be combined with a single antiquark to form mesons—a rather simple rule of hadron construction. The theory of QCD is not limited to such simple constructions, however, and making a definitive statement about the existence of mesons with four-quark or quark–gluon hybrid structure will require observing a spectrum of additional mesons that cannot be explained by the $q\bar{q}$ rule. In particular, we will need to observe a set of states with unusual flavour and/or $J^{PC}$ values.

## Finding a pattern of hadrons is essential

Contemporary technology has enabled experimental investigations at an unprecedented level of statistical precision, which provides the capability to discover more rare and interesting phenomena. However, we must exercise great care when we attempt to interpret experimental data. For example, one needs to be certain that the same logic that allows one to deduce the presence of conventional charmonium mesons in the total hadronic cross-section also applies when one is examining the cross-section for a single exclusive process that is two orders of magnitude smaller (see, for example, Fig. 2). Such precise experimental data make one susceptible to effects that can mimic the experimental signature of a new hadron, but which in fact may have a more prosaic origin[55–59]. This underscores the importance of experimentally establishing a pattern of hadrons: the interpretation of any single state as a new and exotic construction will certainly be questioned. However, the experimental observation of an ordered spectrum of states is harder to dismiss as a misinterpreted experimental artefact.

Likewise, theoretical efforts in lattice QCD must continue in their attempts to compute the complete set of possible hadrons allowed by QCD, and to identify patterns of states within that spectrum. Recent advances have enabled us to develop a simple rule, stated in subsection 'Lattice QCD as a tool for hadron spectroscopy', that describes how QCD constructs hybrid mesons and baryons, in an extension of what we had already for conventional mesons and baryons—this new rule must be verified by observing an experimental spectrum of hybrids. Lattice QCD can also be used to calculate decay properties of hadrons, and identifying particular characteristic decays of hybrid mesons will guide experimental searches and aid in interpretations of data. As has been done with hybrids, lattice QCD needs to determine whether QCD predicts a spectrum of tetraquark and pentaquark states. A particular priority is in the heavy quark sectors, where, as we have discussed above, there is recent experimental evidence for such objects. The ability within lattice QCD to vary arbitrarily the mass of the quarks allows us to identify how the rules of hadron construction vary, and to identify possible common behaviours between the heavy charmonium system and the lighter mesons.

## A global experimental programme

Establishing a spectrum of hadrons beyond those described by the simple $q\bar{q}$ and $qqq$ rules will require the combined efforts of multiple present and future experiments. There is a spectroscopy programme within nearly every particle physics collaboration worldwide. We list the details of a selection of several past, present, and future experiments, primarily those whose work is referenced in this article, in Box 1, as an illustration of the breadth of the worldwide effort.

**BOX 1**

### Hadron spectroscopy experiments

A selection of experiments and their hadron spectroscopy programmes, which typically represent only a fraction of each collaboration's research efforts.

**BaBar** (Menlo Park, California, USA): $e^+e^-$ collisions at bottomonium energies; discoveries of the $Y(4260)$ and $Y(4360)$; finished collecting data in 2008.

**Belle** (Tsukuba, Japan): $e^+e^-$ collisions at bottomonium energies; discovery of the $X(3872)$, $Z(3900)$, $Z(4430)$, and $Z_b$ states; finished collecting data in 2010.

**Belle II** (Tsukuba, Japan): an upcoming continuation of the Belle experiment that will provide much higher intensity $e^+e^-$ collisions than achieved at Belle.

**BESIII** (Beijing, China): $e^+e^-$ collisions at charmonium energies; direct production of the $Y(4260)$; discovery of the $Z(3900)$ and $Z(4020)$; ongoing.

**COMPASS** (Geneva, Switzerland): high-intensity meson beams on nuclear targets; searches for unusual light-quark mesons; discovery of the $a_1(1420)$; ongoing.

**GlueX** (Newport News, Virginia, USA): polarized photon beam on a nuclear target; searches for light-quark hybrid mesons; data collection is beginning now.

**LHCb** (Geneva, Switzerland): high-energy, high-intensity proton–proton collisions, specializing in $B$-meson decays; measurement of resonant nature of the $Z(4430)$; discovery of pentaquark candidates; ongoing.

**$\bar{\text{P}}$ANDA** (Darmstadt, Germany): proton–antiproton collisions at charmonium energies; exploration of charmonium and light-quark mesons; upcoming.

Most of the recently observed new hadrons have so far been observed in only a single production or decay process. Observation of the same state in multiple production and decay modes almost certainly rules out a misinterpretation of experimental data due to some process-dependent phenomenon and solidifies the evidence for a new hadron. Therefore the best current routes to explore new states in the charm sector are by comparing results from $e^+e^-$ collisions (BESIII, Belle, Belle II) and production in $B$-meson decay (LHCb, Belle, Belle II). Supplementing these with results from novel production mechanisms, such as proton–antiproton annihilation ($\overline{\text{P}}$ANDA), would be extremely valuable.

Experiments aimed at exploring different energy regimes and quark flavours are essential for a complete understanding of the meson spectrum, as we expect the underlying patterns of states to be independent of quark mass. A variety of present and future experiments will allow access to both the charmonium system (BESIII, Belle, Belle II, LHCb), and the analogous system of bottom quarks, bottomonium (Belle, Belle II). Mesons constructed from light quarks can be produced in decays of heavier mesons and therefore can be studied at all of the previously mentioned facilities; they can also be produced at experiments dedicated to the study of lighter systems (COMPASS, GlueX). Discovery of light-quark hybrids would suggest the existence of heavy-quark hybrids and further motivate dedicated searches for these states.

With continued coordinated experimental and theoretical investigations we hope to define a complete set of rules for building hadrons that both describes what is observed in nature and can be derived directly from QCD. In doing so, we aim to understand how what seems to be a simple spectrum of hadrons emerges from the complex interactions of quarks and gluons in QCD.

**Received 13 July 2015; accepted 31 March 2016.**


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**Acknowledgements** J.J.D. acknowledges support provided by US Department of Energy contract DE-AC05-06OR23177, under which Jefferson Science Associates manages Jefferson Laboratory and the Early Career Award contract DE-SC0006765. M.R.S. and R.E.M. are supported by US Department of Energy contract DE-FG02-05ER41374. M.R.S. acknowledges the Jefferson Science Associates Sabbatical Leave Support Program. We thank L. Weinstein for comments on the initial draft of this manuscript.

**Author Contributions** All authors contributed equally to this manuscript.

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