Executive summary of the workshop: "Hadron Spectroscopy: The Next Big Steps"

[https://indico.mitp.uni-mainz.de/event/246/]

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1 Introduction

Sixty years after the birth of the quark model, the hadron physics community is at a crossroads again to classify composite particles. The discovery of the narrow $\chi_{c1}(3872)$ exotic state by Belle in 2003 opened the floodgates. In fact, a plethora of states that do not fit the conventional potential models for mesons and baryons have been observed. What is the nature of most of these states is still unclear: are they compact bound states, molecules, or dynamically generated objects? In addition, several critical anomalies in the flavor sector have their leading uncertainties deriving from poor control of the QCD part of the Standard Model, especially in the low-medium energy range.

In order to meet these challenges and plan for the coming years, the two-week in-person workshop, *Hadron Spectroscopy: The Next Big Steps* was organized at MITP between 14-25 March, 2022. Due to the pandemic situation, in January 2022 the decision was taken to move it to a fully online event. Four organizers, 165 participants 52 contributions, 17 session chairpersons, 18 moderators in the discussion sessions, and 18 hours of afternoon session discussions, are some of the numbers that testify to the success of the event.

The originality of this workshop lies in the fact that equal weight was given to the morning and afternoon sessions. The morning sessions were dedicated to presentations, and the afternoon sessions were devoted to topical discussions. Eighteen hours of intense afternoon discussions were counted, at the end of the two-week workshop. The feedback received from participants, at the end of the workshop, was extremely positive.

Major international experiments represented in this workshop included ATLAS, BaBar, Belle (II), BESIII, CBELSA/TAPS, COMPASS, CMS, LHCb, GlueX, PANDA, among others. Eleven key speakers were invited to lead the discussions and chair the sessions, from both experimental and theoretical points of view. Care was taken to balance the workshop, introducing theoretical and experimental talks with equally allotted time slots, and weighting the workshop in a way that both young and more senior/renowned researchers in the field were equally represented. Particular attention was given to diversity issues: 30% of the physicists who participated in discussions and morning sessions, in terms of contributions and as chair of the sessions, were women.

2 List of topics

The main topics discussed during the two-week workshop were:

- Conventional baryon and meson spectroscopy
- Exotic states
- Potential models and beyond
- Lineshape studies and re-scattering effects

- Lattice calculations (both light and heavy sectors)
- Amplitude analysis: fitters, methods, new software tools
- Input for muon $(g-2)$
- Baryon-antibaryon interactions
- Future perspectives at colliders

3 Highlights

Summarizing a dense workshop where 52 plenary talks were given followed by hours of afternoon discussions, is an unenviable task. This report focuses on some of the topics that generated the most lively discussions during the afternoon sessions.

Proton radius puzzle The workshop was kicked off by a discussion on the proton radius saga. Before 2010, this was measured by two different methods, *ep* scattering, and hydrogen spectroscopy. The results converged to 0.877 fm, in tension with QCD dispersion-relation-based theory calculations, which predicted a smaller value. In 2010, a third method using muonic-hydrogen spectroscopy also yielded a smaller value ($\sim$ 0.875 fm). Finally, in 2019, updated *ep* scattering and hydrogen spectroscopy measurements also agreed with the muonic-hydrogen results. These discrepancies show that even 100 years after its discovery, the proton is still leading discussions in the hadron physics community.

Understanding di-baryon threshold enhancements In $e^+e^- \to B\overline{B}$, where $B \in \{p, n, \Lambda^0, \Lambda_c^+\}$ represent baryons, the cross-sections show threshold enhancements, leading to the conjecture of di-baryon sub-threshold bound states. The enhancement is also seen in radiative $J/\psi \to \gamma p\bar{p}$ decay, which has been linked to the $X(1835) \to \pi^+\pi^-\eta'$ resonance seen by BESIII in $J/\psi \to \gamma\pi^+\pi^-\eta'$. The phenomenon is not universal: the $B \in \{\Sigma^0, \Xi^0\}$ baryons do not seem to exhibit the enhancements, nor does $\psi(2S) \to \gamma p\bar{p}$ show a $p\bar{p}$ threshold enhancement. A program to look for those was presented by Belle II as well, which will play a leading role in future radiative decay analyses, where slow pions are involved. The somewhat controversial topic of the di-baryon candidate $d^*(2380)$ from WASA at COSY was also discussed.

$a_0(890)$-$f_0(980)$ mixing The $a_0(890)$ and $f_0(980)$ states belonging to the lightest scalar nonet, have long been conjectured to be tetraquarks. In the quark model, these should have no strangeness content. However, both states decay to $K\overline{K}$. Isospin violation via f_0-a_0 has also been seen via $\chi_{c_1} \to a_0(\to f_0 \to \pi^+\pi^-)\pi$ at BESIII. Further probes of the $m(K\overline{K})$ lineshapes via both K^+K^- and $K^0\overline{K}^0$ modes will elucidate the isospin violation in this system.

Holography Three different talks were given on this topic. Light-front holography as a novel approach to QCD color confinement and hadron spectroscopy. Fundamental QCD predictions can be performed using this new approach. Examples of calculations performed with this tool were shown to evaluate the bottomonium and charmonium spectrum, glueball predictions, tetraquarks, and other exotics. It seems to be a promising approach.

Overviews on XYZ states. Exotic XYZ states offer a unique possibility to investigate the dynamic properties of strongly correlated systems in QCD (a multi-scale problem). Invited speakers from all experimental collaborations reported on their most recent highlights in this sector. These presentations were always combined with a theoretical contribution specific to the production mechanism of the experiment. Theoretical tools using non-relativistic effective QFT (NREFT) plus lattice QCD exist and describe heavy quarkonia quite well. For $Q\overline{Q}q\bar{q}$ states, the Born-Oppenheimer EFT (BOEFT) potentials can describe hybrids and calculate multiplets, mixing, and decays and is extendable to tetraquarks and pentaquarks (once lattice input on a few relevant correlators will be available). This formalism was shown to give a promising unified description of exotics, with the dynamics deciding which configuration will dominate in a given range.

On the experimental side, a wide spectrum of results were shown from a variety of collider and fixed-target-based experiments. At the LHC, the huge heavy $q\overline{q}$ production cross-sections are advantageous, compared to e^+e^- colliders. On the other side, a cleaner event reconstruction at e^+e^- colliders compensates for the cross-section issue. Between 2011-2018, LHCb collected $9/\text{fb}^{-1}$ data at the energies $\sqrt{s} = 7, 8, 13$ TeV. Conventional heavy-hadron spectroscopy includes observations of new excited heavy mesons and baryons, charmonia and bottomonia states, determination of masses, widths, branching fractions, and lifetimes. Most of these can be performed by LHCb, in a complementary fashion with ATLAS, BaBar, Belle II, BESIII, CBELSA/TAPS, COMPASS, CMS, GlueX, and PANDA. LHCb also has an intensive program in the study of exotic spectroscopy: the queen of these studies will be of course the $\chi_{c_1}(3872)$ (new production and decay modes, lineshape), but also new hidden and open charm tetraquarks, new pentaquarks. Listed below are some of the Run 1/2 highlights presented by LHCb:

- observation of excited $B_c^*(2S)^+$ and evidence for a $B_c(2S)^+$. Consistent but more precise than corresponding CMS observations.
- new excited B_0^{**0} states decaying to B^+K-
- new $D_s(2S)^+ \to D^+K^+\pi^-$ in $B^0 \to D^+D^-K^+\pi^-$
- new Ξ_b^0 1D doublet in $m(\Lambda_b^0 K^-\pi^+)$
- new $X(4630)$, $X(4685)$, $Z_{cs}(4000)$ (BESIII has seen a $Z_{cs}(3985)$ close by, but narrower) and $Z_{cs}(4220)$ in $B^+ \to J/\psi\phi K^+$
- discovery of $X(6900)$ in di-J/ψ mass spectrum. If confirmed, this would be the first observation of an exotic hadron composed of heavy quarks of the same flavor.
- exotic open-charm $X_{0,1}(2900) \to D^-K^+$ in $B^+ \to D^+D^-K^+$.
- discovery of the double-charm $T_{cc}^+ \to D^0D^0\pi^+$, close to $D^{*+}D^0$ threshold
- evidence for a new pentaquark in $B_s^0 \to J/\psi p\overline{p}$
- evidence for new strange pentaquark in $\Xi_b^0 \to J/\psi\Lambda^0 K^-$ (LHCb has observed a $P_{\psi s}^{\Lambda}(4338)$ in $B^- \to J/\psi\Lambda\overline{p}$)

ATLAS/CMS also have significant programs in hadron spectroscopy, with some limitations from the triggers and particle identification aspects, compared to LHCb, but with higher luminosities. Several new results in conventional heavy-hadron spectroscopy were shown from these two experiments:

- excited $B_c^{(*)+}(2S)$ in $B_c^+\pi^+\pi^-$
- resolved $\chi_{b_1}(3P)$ and $\chi_{b_2}(3P)$ states in $m(\Upsilon(3S)\gamma)$ and converted photon
- several excited Λ_b^{**} in $m(\Lambda_b^0\pi^+\pi^-)$, including a broad state of mass around 6073 MeV, confirmed by LHCb
- excited $\Xi_b^{**}(6100)^-$ in $m(\Xi_b^-\pi^+\pi^-)$
- p_T dependence of production cross-section rations between $\chi_{c_1}(3872)$ and $\psi(2S)$. First observation of the $\chi_{c_1}(3872)$ in Pb-Pb collisions.

Belle II started collecting data only in 2018, with an incomplete detector setup (one PXD layer is still missing). However, an extensive program was presented during the workshop, including the latest results obtained with full Belle data sets, showcasing the potential and physics thrusts in exotic spectroscopy at Belle II. Combined analyses with Belle and Belle II data are planned for the upcoming years. Bottomonium physics and search for exotics in ISR, for example, will be unique physics cases for this experiment. For exotics in B decays, Belle II will have complimentary in studies concerning those at the LHC, using different production and decay mechanisms. The new run is supposed to start in 2023. So far, Belle II has collected almost the same luminosity as the BaBar experiment, which is a bit more than half that collected by the Belle experiment. Preliminary results with 62 fb^{-1} at Belle

II have been shown, re-discovering channels of former Belle analysis up to now.

From Jefferson Lab, GlueX showed intriguing results in searches for pentaquarks via photoproduction. The full Gluex-I run has ~ 2000 J/ψ events. GlueX-II is expected to provide an additional 6000 J/ψ events, with results on other charmonium ($\psi(2S)$ and χ_{c_1}) also expected.

In the light meson sector, the BESIII observation of the exotic 1^{-+} isoscalar $\eta_1(1855) \to \eta\eta'$ (in $J/\psi \to \gamma\eta\eta'$) state with a significance of $> 19\sigma$ was shown for the first time at this workshop. An overview from COMPASS and CB/TAPS and ELSA completed the picture: light mesons and baryons are the main interests of the latter two experiments. The thrust on complicated $\pi p \to pX$ (X decays to ≥ 5 hadrons) multibody partial wave analyses to uncover the light meson spectrum at COMPASS was emphasized.

Threshold lineshapes as key to internal dynamics. Significant and lively discussions during the workshop centered around lineshape fits to the $\chi_{c_1}(3872)$ and the $T_{cc}^{+}(3875)$ states that lie very close to the $D^0\overline{D}^{*0}$ and D^0D^{*+} thresholds, respectively. Close to the threshold, the amplitude scales like $f^{-1} \sim 1/a + r_0k^2/2 - ik$, where k is the breakup momentum, the scattering length $-Re(a)$ is positive for bound states and r_0 is the effective range. The Weinberg compositeness criterion, $Z = 1 - 1/\sqrt{1 + |2r_0/a|}$, asserts the values $Z = 1$ (compact) and $Z \to 0$ (molecular); $r_0 < 0$ (compact) and $r_0 > 0$ (molecular). Significant debates centered around the exact interpretation of Z as an admixture of compact and molecular states. For example, if $Z \neq 0$, some compact component exists. Several groups presented sometimes contradictory extracted values of r_0, thereby leading to different conclusions about the compact or molecular nature of these states. The experimental mass resolutions for these states are also of great importance. The PANDA experiment at FAIR plans to reach a very precise ~ 50 keV resolution for the $\chi_{c_1}(3872)$ width measurement (the resolution at LHCb is so far ~ 2 MeV).

Cross sections and muon $(g-2)$. Overviews from BESIII and BaBar were given on their recent results from studies of transition form factors. Measuring the hadronic corrections to the anomalous magnetic moment of the muon is an important topic in hadron physics. The Hadron Vacuum Polarization (HVP) uncertainty, and therefore the SM prediction of $(g-2)_\mu$ are still largely limited by data from KLOE and BaBar. Existing BESIII and SND measurements (0.9%, 0.8% uncertainties) are not yet precise enough to rule out either KLOE or BaBar measurements. New ISR measurements are expected by BaBar, BESIII, BELLE II. This is a sector covered only by electron-positron colliders. It emerged from the discussion that a new energy scan is planned from VEPP-2000/Novosibirsk (CMD-3, SND), with an accuracy competitive with the other experiments. BESIII measurements can help to solve the puzzle. Concerning Light-by-light (Hlbl) determinations, BESIII measurements will be relevant for a better understanding.

Two-photon physics. Two-photon physics was treated as a key topic. It is interesting for both cross-section calculations and searches for exotics. As for the ISR and bottomonium physics, this is a major physics thrust at Belle II (in general, for e^+e^- colliders). For the first time the $\chi_{c1}(3872)$ is seen in $\gamma\gamma$ interactions, as recently announced by Belle. More data are needed for further studies, as planned by Belle II, once at least 5 ab^{-1} data will be available.

Naming convention. The final day of the workshop included a talk, followed by a lively discussion, on a new naming scheme for exotic hadrons. The proposal was made by Tim Gershon (LHCb) and has been discussed further with the PDG and non-LHCb experts.

4 Conclusion

Hadron spectroscopy as a tool to test understanding medium- and short-range QCD dynamics, remains a vital and highly active field of research today. Since the discovery of the narrow $\chi_{c1}(3872)$ state by Belle in 2003, QCD modeling of the hadron spectrum has gone through enormous challenges, driven by experimental discoveries. Building on the groundwork done at the e^+e^- heavy flavor factories, the (partial) Run 1/2 data from LHCb have been instrumental in unfolding new vistas with the discovery of potential pentaquarks, fully heavy tetraquarks, and open charm tetraquarks. On the theory side, the primary approaches have been molecular, hadrocharmonium, di(tri)quark models, and kinematic effects, but the general consensus has been that "no one size fits all".

A plethora of new important results was presented at this workshop, focusing on a precise understanding of the spectrum below open-charm and bottom thresholds. The case of the $\chi_{c1}(3872)$ has been widely discussed: quantum numbers are now known (LHCb); the absolute branching fraction has been evaluated, albeit with a large error (BaBar); the lower limit on the natural width has been set up (LHCb); the mass value is determined with increased precision but still compatible with $\bar{D}\bar{D}^0$ threshold; large prompt production has been observed at pp and $p\bar{p}$ collisions (CMS, D0); a new method to measure the width down 189 keV has been shown at e^+e^- collisions (Belle II) when 50 ab^{-1} data will be available. Future facilities (*e.g.* PANDA) also presented their plan to measure the width of this state. Yet, we are far from understanding its nature. Recent results showing the evidence for the $\chi_{c1}(3872)$ in $\gamma\gamma$ interactions at Belle have been shown. More data are needed and cross-checking results in different production mechanisms, and different experiments, are compulsory.

With the increasing size of experimental data samples, conventional Breit-Wigner lineshapes no longer appear adequate for studying these exotic states. More input from a theoretical point of view is required. The Joint Physics Analysis Center (JPAC) at Jefferson Lab is an excellent initiative in this direction. This was one of the messages raised during the afternoon discussions.

Based on 52 plenary talks, many results were shown. The charmonium. and bottomonium spectra seem to grow up more and more. The talks and discussions revealed that the crucial quantities to understand the role of molecules in the spectrum are the effective range (from lattice or experiment) and the lineshape. What is needed then is to combine analysis of various channels, and high-resolution analysis. After a two-week workshop, we understood that Breit Wigner analyses are to be taken with care because they violate unitarity and the parameters that can be extracted by experimental analysis are reaction dependent.

From the theoretical point of view, it emerged that currently, the most pressing issue is understanding lattice systematics. There is not much freedom on the phenomenological dispersion and theoretical side of the calculation.