Suplemento de la Revista Mexicana de Física **3** 0308004 (2022) 1–7

News from the light and strange meson sector

S. Wallner
Physics Department, Technical University of Munich, Garching, Germany.

Received 18 December 2021; accepted 19 January 2022

Recent high-quality data sets from various experiments grant new insights into the excitation spectrum of light mesons, which are composed of up, down, and strange quarks. In the non-strange light-meson sector, many recent experimental and theory efforts are focused on the search for so-called exotic states, which are states beyond the naïve constituent quark-model. To this end, various potential decay modes of exotic states are studied at experiments such as GlueX or COMPASS. In addition, there is recent progress in the understanding of so-called non-resonant processes, which act as background in searches for light mesons, as well as in the prediction of light mesons from lattice QCD. While the non-strange light-meson spectrum is already mapped out rather well, many predicted strange mesons have not yet been observed experimentally or need further confirmation. Recent high-precision data from experiments such as LHCb and BESIII allow us to study strange mesons in heavy-meson decays. Alternatively, strange mesons are studied in diffractive scattering of high-energy kaon beams. The so far world's largest data set on the diffractively produced $K^-\pi^-\pi^+$ final state was measured by the COMPASS experiment. A recent analysis of this data covers a large variety of strange mesons over a wide mass range in a single, self-consistent analysis

Keywords: hadron spectroscopy; GlueX; COMPASS; LHCb; BESIII; JPAC; HadSpec; partial-wave analysis; non-resonant processes; lattice QCD; light mesons; strange mesons; exotics.

DOI: https://doi.org/10.31349/SuplRevMexFis.3.0308004

1. Introduction

In the naïve quark-model picture, mesons are states build up from a constituent quark and antiquark pair. Non-strange light mesons are build up from up or down (anti)quarks, while strange light mesons are build up from a strange (anti)quark and an up or down (anti)quark, *i.e.* they have strangeness of ± 1. Light mesons are characterized by their isospin I, their total spin J, and their parity P. The latter two are often written as J^P. For non-strange mesons, also the charge-parity quantum number C is defined, such that their quantum numbers are often written as J^{PC}.

Non-strange and strange light mesons are produced, for example, in the inelastic scattering of high-energy pion, kaon, or photon beams and can be studied in their decays to various final states. These processes are employed at experiments such as GlueX, VES, or COMPASS. Light mesons also appear as intermediate states in the decays of heavy mesons or τ leptons to hadronic multi-body final states. Such processes are used to study light mesons at experiments such as Belle(II), BESIII, or LHCb.

In principle, QCD allows for more than just quark-model $q\bar{q}'$ states. For example, there could be so-called hybrid states, which have an excited gluon-field that contributes to their quantum numbers. Also, states with four constituent quarks, so-called molecules or tetraquarks, are possible. Historically, such states are called exotics. They appear as supernumerary states in addition to the quark-model states and are in the focus of many experimental searches. In searches for exotic states, the non-strange light-meson sector plays a special role, because only for non-strange light mesons certain J^{PC} combinations exist that are not possible for a pure quark-model state. Hence, a state with such quantum numbers is manifestly exotic. Such J^{PC} combinations are called spin-exotic quantum numbers.

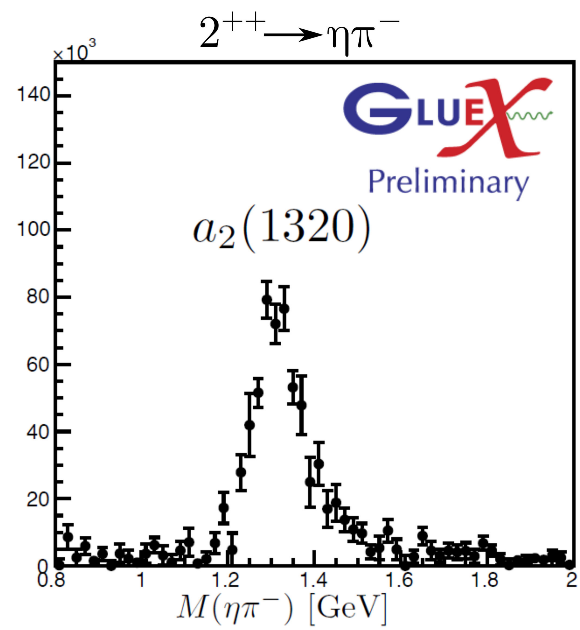

FIGURE 1. Intensity distribution of the $J^{PC} = 2^{++}$ partial wave in the $\eta\pi^-$ final state as measured by GlueX. Taken from Ref. [3]. Some labels were modified for consistency.

2. Light non-strange mesons

2.1. Searching for spin-exotic states

Examples for states with spin-exotic quantum numbers are π_1 states, which have $J^{PC} = 1^{-+}$. Lattice QCD predicts that the lightest hybrid state has $J^{PC} = 1^{-+}$ quantum numbers [2]. Experimentally, the $\eta\pi$ and $\eta'\pi$ final states are considered to be golden channels to search for exotic π_1 states. The GlueX experiment at Jefferson Lab measured a large data

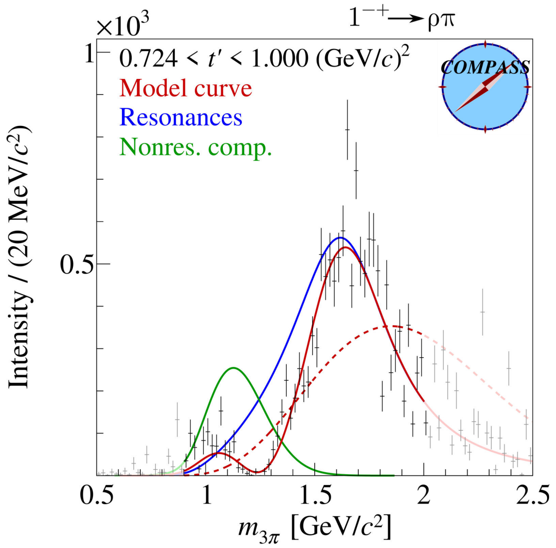

FIGURE 2. Intensity distribution of the spin-exotic $J^{PC} = 1^{-+}$ wave decaying via $\rho(770)\pi$ to the $\pi^-\pi^-\pi^+$ final state as measured by COMPASS [5]. The solid red curve represents the result of a fit of a resonance model that consists of the coherent sum of a resonance component (blue curve) and a non-resonant component (green curve). The dashed red curve represents the result of a fit without a resonance in this wave. Some labels were modified for consistency.

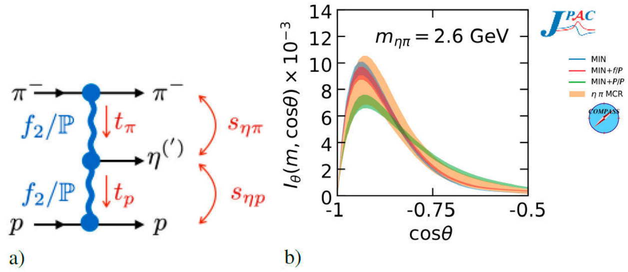

FIGURE 3. Double-Regge exchange models for non-resonant processes in the $\eta\pi^-$ and $\eta'\pi^-$ final states by JPAC. a) shows one possible graph for a double-Regge exchange process. b) shows in orange the experimental intensity distribution as a function of the angle of the η with respect to the direction of the beam π^- in the $\eta\pi^-$ center-of-momentum frame (see Ref. [6] for details). The blue, red, and, green bands represent predictions from three double-Regge models. Taken from Ref. [6]. Some labels were modified.

set for the $\eta\pi^-$ final state produced in the scattering of a high-energy photon beam. Recently, they performed a first partial-wave analysis of this high-precision data set. The obtained intensity distribution of the $J^{PC} = 2^{++}$ partial wave (see Fig. 1) shows, as expected, a clear peak from the well known $a_2(1320)$ resonance and only little background. This demonstrates that the GlueX data is well suited for partial-wave analyses and shows the potential to study in the future more interesting partial waves such as the $J^{PC} = 1^{-+}$ wave, in which spin-exotic π_1 states may appear. Furthermore, also other final states are under study at GlueX such as the $\eta\pi^0$ and $\omega\pi^-\pi^0$ final states, which will provide complementary information on exotic states [4].

Also the COMPASS experiment studies the π_1, for example in its decay via $\rho(770)\pi$ to the $\pi^-\pi^-\pi^+$ final state [1]. As shown by the intensity distribution in Fig. 2, COMPASS observes a resonance-like signal in the $J^{PC} = 1^{-+}$ partial wave, which is at a similar mass as the $\pi_1(1600)$ that is listed by the PDG [13]. Furthermore, without a resonance in the model, the COMPASS data cannot be described as shown by the dashed red curve in Fig. 2. In summary, the COMPASS data show clear indications for a spin-exotic $\pi_1(1600)$ resonance decaying via $\rho(770)\pi$ to the $\pi^-\pi^-\pi^+$ final state.

2.2. Non-resonant processes

In the scattering of high-energy pion or kaon beams, the measured hadronic final state may be produced by processes that do not involve the decay of a resonance. Such non-resonant processes are, for example, double-Regge exchanges as exemplarily shown in Fig. 3a) for the $\eta^{(\prime)}\pi^-$ final states. Typically, non-resonant processes cannot be fully separated kinematically from resonance production. Therefore, they have to be taken into account when formulating resonance models in partial-wave analyses. This was done, *e.g.*, in the analysis of the COMPASS $\pi^-\pi^-\pi^+$ data (see green curve in Fig. 2). Especially with recent high-precision data from various experiments, modeling those non-resonant contributions introduces significant systematic uncertainties, because detailed models for non-resonant processes are still missing. In order to tackle this issue, JPAC recently studied various models for double-Regge exchanges for diffractive production of the $\eta\pi^-$ and $\eta'\pi^-$ final states based on COMPASS data [6]. They focused on the high-$m_{\eta^{(\prime)}\pi}$ region, because it is expected to be dominated by non-resonant contributions. In general, their models (blue, red, and green bands in Fig. 3b) reproduce well the COMPASS data (orange band in Fig. 3b). With their analysis, JPAC deepened our understanding of non-resonant processes. This not only may improve the extraction of light-meson resonances, but it also gives us valuable insight into the various processes involved in the production of the $\eta\pi^-$ and $\eta'\pi^-$ final states. While the exchange at the bottom vertex was assumed to be dominated by Pomeron exchange for the high center-of-momentum energy at COMPASS, JPAC found an important contribution also from f_2 exchange in the high-$m_{\eta^{(\prime)}\pi}$ region. Furthermore, the JPAC analysis revealed that Pomeron-Pomeron fusion is necessary to describe especially the $\eta'\pi^-$ final state, which points towards a large gluon affinity of this final state.

2.3. Combined analysis of different data sets

In general, non-resonant and background contributions appear differently in different final states and different production mechanisms, while the resonance signals are the same. Hence, studying the same states in combined analyses of several data sets on different final states and different production mechanisms helps to improve the separation of resonance signals from non- resonant and background contributions.

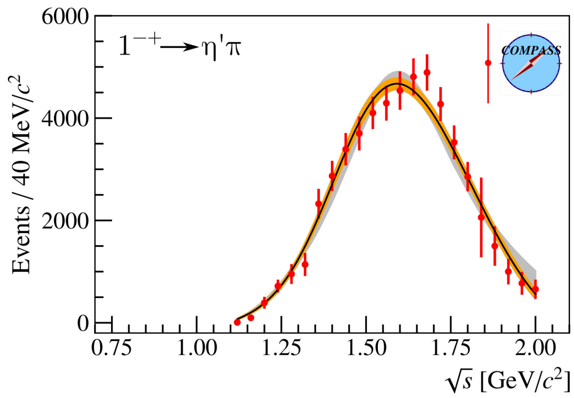

FIGURE 4. Intensity distribution of the $J^{PC} = 1^{-+}$ partial wave in the $\eta'\pi^-$ decay. The red data points represent the COMPASS measurement. The black line represents the resonance model, which is based on a K-matrix approach, as obtained from a combined fit to data from the COMPASS and the Crystal Barrel experiments and to data on $\pi\pi$ scattering. The orange and gray bands represent the corresponding statistical and systematic uncertainties, respectively. Taken from Ref. [7]. Some labels were modified for consistency.

Such a combined analysis was performed by the authors of Ref. [7] using Crystal Barrel data on $p\bar{p} \to \pi^0\pi^0\eta$, $\pi^0\eta\eta$, $K^+K^-\pi^0$; COMPASS data on the $J^{PC} = 2^{++}$ and $J^{PC} = 1^{-+}$ partial waves in the $\eta\pi^-$ and $\eta'\pi^-$ final states; and various data sets on $\pi\pi$ scattering. As shown in Fig. 4 exemplarily for the $J^{PC} = 1^{-+}$ partial wave in the $\eta'\pi^-$ COMPASS data, this combined analysis reproduces the data well. Most notably, a single pole consistent with the $\pi_1(1600)$ is sufficient to describe the $J^{PC} = 1^{-+}$ partial waves in both, the $\eta\pi$ and the $\eta'\pi$ final states, which is consistent with a previous analysis of only the COMPASS data set [8]. This puts the existence of the $\pi_1(1400)$ into questions, which is another exotic π_1 state that is listed by the PDG and that was observed mainly in the $\eta\pi$ final state [13].

2.4. The π_1 from lattice QCD

The lightest π_1 is also studied in recent lattice QCD calculations. Figure 5 shows the results from Ref. [9], which predicts the partial decay widths of the decay of the lightest π_1 state. Interestingly, they found that the $b_1(1235)\pi$ decay is the by far dominant decay mode, while other decay modes such as $\rho(770)\pi$ or $\eta'\pi$ have a more than one order of magnitude smaller partial decay width. However, the $b_1(1235)\pi$

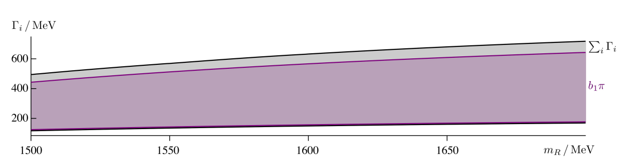

FIGURE 5. Total decay width (gray) and partial decay width for the $b_1\pi$ decay mode (purple) for the lightest π_1 state as a function of the π_1 pole mass as predicted by lattice QCD. Taken from Ref. [9]. Some curves were removed for simplicity.

decay is experimentally much more challenging to access, because the $b_1(1235)$ is a resonance itself. The $b_1(1235)\pi$ decay mode can be studied, for example, in 5-pion final states. Analyzing such a 5-body final state requires involved modeling of all the possible decay chains, which is more complex than for a 2- or 3-body final state. Nonetheless, indications for the decay $\pi_1 \to b_1(1235)\pi$ were claimed by BLN E852 [10] and the Crystal Barrel [11] experiments. Also, searches for the decay $\pi_1 \to b_1(1235)\pi$ are currently ongoing based on high-precision data sets from the COMPASS and the GlueX experiments.

2.5. Exotic states beyond spin-exotics

Exotic states may also have conventional quantum numbers. For example, lattice QCD predicts a pion-like hybrid state with $J^{PC} = 0^{-+}$ quantum numbers [2]. Recently, COMPASS presented an updated analysis of their $\pi^-\pi^-\pi^+$ data set, in which they studied partial waves with $J^{PC} = 0^{-+}$ that decay via different decay modes [12]. The COMPASS data exhibit nearly identical resonance-like signals at a mass of about $1.8\,\mathrm{GeV}/c^2$ in three partial waves that represent three different $f_0\pi$ decays (see blue, green, and orange data points in Fig. 6). These signals are consistent with the $\pi(1800)$. The COMPASS data also exhibit a clear signal in the decay via $f_2(1270)\pi$, however, shifted towards lower masses. Various interpretations of this shift are possible. There could be, for example, two different states, which dominantly decay via different decay modes. As quark-model states are not expected to be so close in mass, one of these states must be

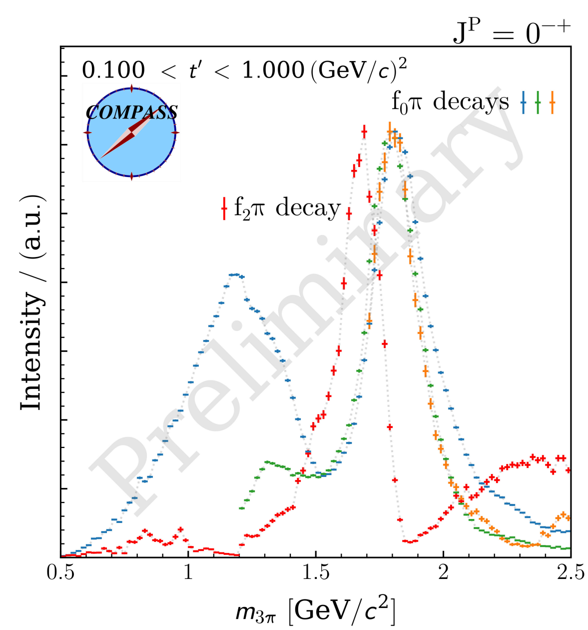

FIGURE 6. Intensity distribution of four $J^{PC} = 0^{-+}$ partial waves for the decays via $[\pi\pi]_S^{\mathrm{AMPK}}\pi$ (blue), $f_0(980)\pi$ (green), $f_0(1500)\pi$ (orange), and $f_2(1270)\pi$ (red) to the $\pi^-\pi^-\pi^+$ final state as obtained by COMPASS. Take from Ref. [12]. Some labels were modified for consistency.

an exotic supernumerary state in this interpretation. Another explanation is, that there is only a single resonance in this mass region, but its peak position is shifted due to interference effects of the resonance with the non-resonant contributions, which may be different for different partial waves. Detailed studies using more elaborate resonance models are needed to shade more light on these puzzling signals.

3. Strange mesons

In order to establish supernumerary non-strange exotic mesons, an important goal is to also find all the strange partners, *i.e.* to complete the corresponding SU(3) flavor nonets. Furthermore, strange mesons play an important role in other fields of particle physics, *e.g.* in searches for CP violation in B- or D-meson decays to multi-body hadronic final states with kaons. Hence, a complete knowledge of the excitation spectrum of strange mesons is important. However, compared to the non-strange light-meson sector, many parts of the strange-meson sector are still only poorly explored. Figure 7 shows our current knowledge of the strange-meson sector according to the PDG [13]. In total, only 25 strange mesons are listed and only 16 of them are considered as established states (blue points). Furthermore, many states predicted by quark-models [14] are experimentally missing. Especially in the high-mass region, many states need further confirmation and many predicted states are missing. This is because at higher masses the states typically become broader, which leads to large overlaps among them. Hence, they are experimentally more challenging to extract.

The COMPASS experiment collected the so far world's largest data set on the diffractively produced $K^-\pi^-\pi^+$ final state of about $720\,000$ exclusive events. It is about 3.5 times larger than the previously largest data set measured by the WA03 experiment at CERN [17]. COMPASS performed a comprehensive partial-wave analysis, which gives access to in principle all K_J^* and K_J states [15, 16]. In the following sub-sections, selected results from this COMPASS analysis

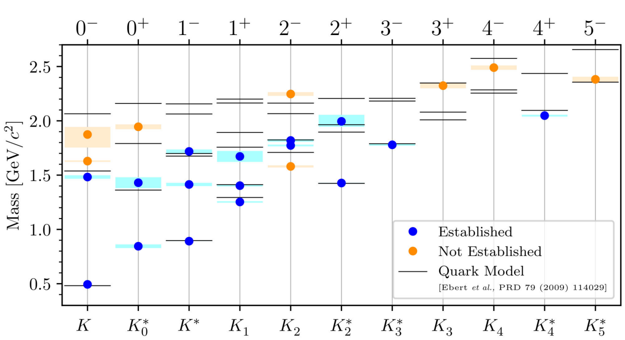

FIGURE 7. Spectrum of strange mesons, *i.e.* nominal masses of strange mesons grouped by their J^P quantum numbers. The blue data points show the masses of established states, the orange data points those of not established states as listed by the PDG [13]. The similarly colored boxes represent the corresponding uncertainties. The black horizontal lines show the masses of states as predicted by the quark-model calculation in Ref. [14].

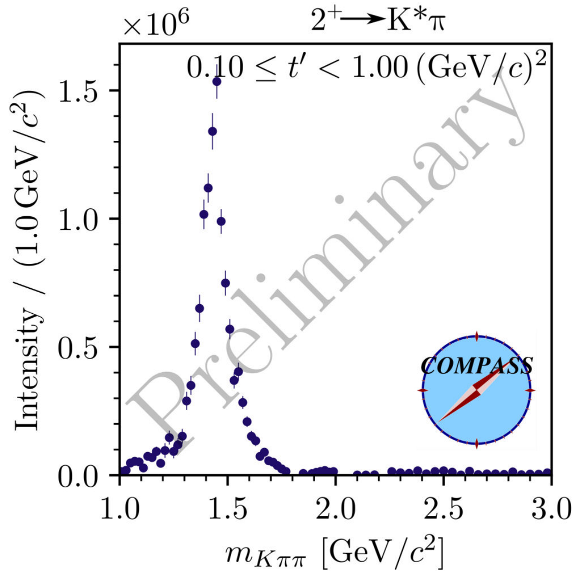

FIGURE 8. Intensity distribution of the $J^P = 2^+$ partial wave in the decay via $K^*(892)\pi$ to the $K^-\pi^-\pi^+$ final state as obtained by COMPASS [15]. Some labels were modified for consistency.

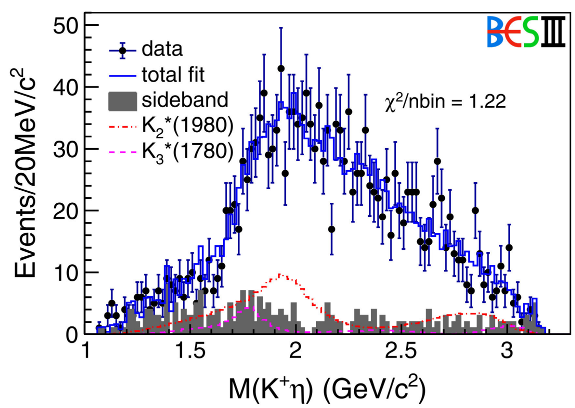

FIGURE 9. Invariant mass distribution of the $K^+\eta$ subsystem from an analysis of the decay $\psi(3686) \to K^+K^-\eta$ by BESIII. The blue curve represents the total partial-wave model. The red dash-dotted curve represents the contribution from the $K_2^*(1980)$. The magenta dashed curve represents the contribution from the $K_3^*(1780)$. Taken from Ref. [19]. Some labels were modified for consistency.

will be presented along with recent results from other experiments in the strange-meson sector.

3.1. Searching established and unestablished K_2^* states

COMPASS observed a clear signal of the well-known $K_2^*(1430)$ as exemplarily shown in Fig. 8 for the decay via $K^*(892)\pi$. This observation is consistent with previous measurements of the $K_2^*(1430)$ and is a first validation of the COMPASS analysis.

Also BESIII published recently a high-precision measurement of the $K_2^*(1430)$ decaying to $K\pi^0$ from a partial-wave analysis of their data set on the decay $J/\psi \to K^+K^-\pi^0$ [18]. BESIII also contributed to the search for excited K_2^* states decaying to $K\eta$ with a partial-wave analysis of their data set on the decay $\psi(3686) \to K^+K^-\eta$ [19]. They found a contribution from the excited $K_2^*(1980)$ as shown in Fig. 9. Based on this measurement, the $K_2^*(1980)$ is now marked as established by the PDG.

3.2. Studying $\mathbf{K_2}$ states over a wide mass range

Most of the measurements of strange mesons were focused on only a limited set of J^P sectors and on only limited mass ranges. The COMPASS $K^-\pi^-\pi^+$ analysis aims to simultaneously study a variety of J^P sectors and to cover a wide mass range in a single analysis. An example for this is the $J^P = 2^-$ sector. Here, the COMPASS analysis includes various partial waves representing different decay modes of K_2 states and covers a wide mass range up to $m_{K\pi\pi} = 3\,\mathrm{GeV}/c^2$. Figure 10 exemplarily show the intensity spectrum of the $J^P = 2^-$ partial wave decaying via $K_2^*(1430)\pi$. It exhibits a broad peak in the $1.8\,\mathrm{GeV}/c^2$ mass region with a pronounced high-mass shoulder reaching up to about $2.5\,\mathrm{GeV}/c^2$. The PDG lists the two established $K_2(1770)$ and $K_2(1820)$ in the peak region. The high-mass tail may arise from the $K_2(2250)$, which needs further confirmation. This would be the first observation of the $K_2(2250)$ in final states other than $\Lambda\bar{p}$ and $\bar{\Lambda}p$ in a partial-wave analysis and the first time all three K_2 state are determined in a single analysis.

The two ground states, $K_2(1770)$ and $K_2(1820)$, were also observed in a partial-wave analysis of the decay $B^+ \to J/\psi\phi K^+$ by LHCb [20]. Figure 11 shows the $m_{\phi K}$ distribution as obtained in the LHCb analysis (black data points) and the contributions from two K_2 states (open squares). However, the decay $B^+ \to J/\psi\phi K^+$ gives access to only a limited range of strange-meson masses, because of the large masses of the final-state particles. Hence, low- and also high-mass states, such as the $K_2(2250)$, cannot be accessed in this process. Recently, LHCb published an updated analysis of this B^+ decay mode based on an about three times larger data set. In order to describe the more precise data, they had to include the tails even of states with nominal masses outside their accessible mass region. However, this required input from other measurements for theses states, because they could not determine the resonance parameters of these states from their own data.

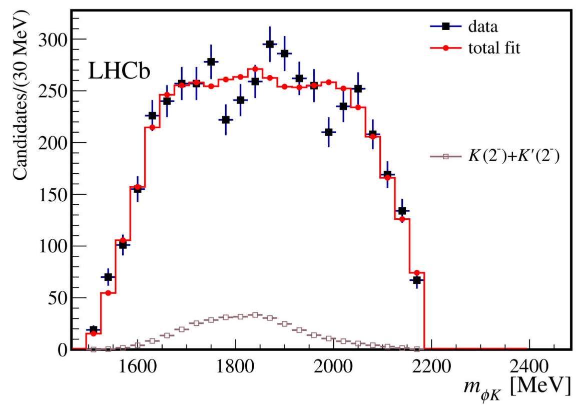

FIGURE 11. Invariant mass distribution of the ϕK^+ subsystem from an analysis of the decay $B^+ \to J/\psi\phi K^+$ by LHCb. The red curve represents the total partial-wave model. The open squares represent the contribution from two K_2 resonances. Taken from Ref. [20]. Some curves were removed for simplicity.

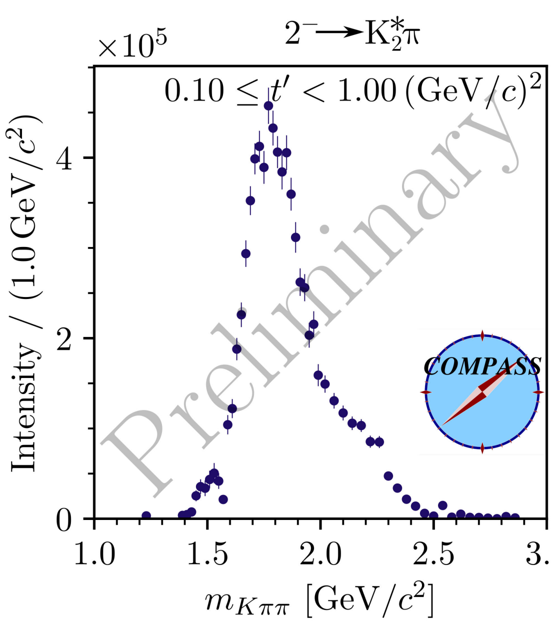

FIGURE 10. Intensity distribution of the $J^P = 2^-$ partial wave in the decay via $K_2^*(1430)\pi$ to the $K^-\pi^-\pi^+$ final state as obtained by COMPASS [15]. Some labels were modified for consistency.

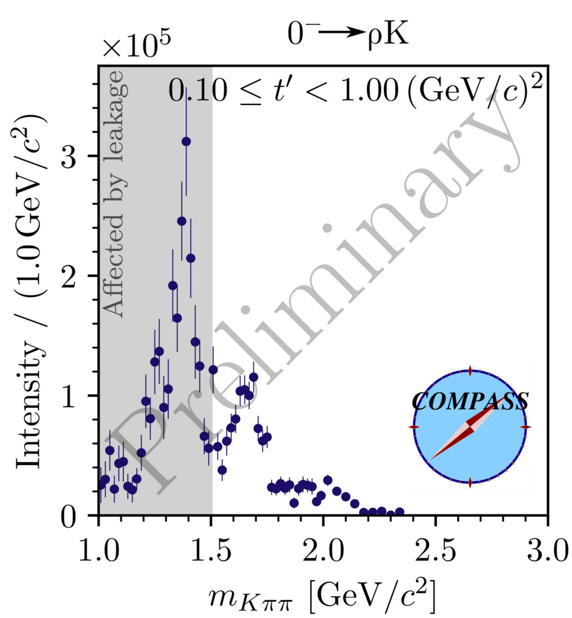

FIGURE 12. Intensity distribution of the $J^P = 0^-$ partial wave decaying via $\rho(770)K$ to the $K^-\pi^-\pi^+$ final state as obtained by COMPASS [15, 16].

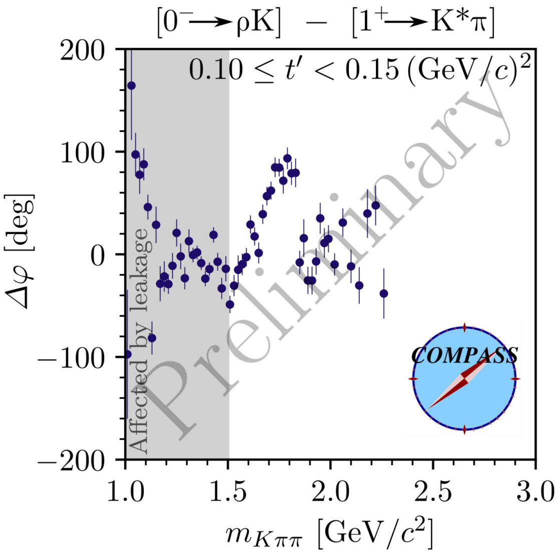

FIGURE 13. Phase of the $J^P{=}0^-$ partial wave decaying via $\rho(770)K$ to the $K^-\pi^-\pi^+$ final state with respect to the $J^P{=}1^+$ partial wave decaying via $K^*(892)\pi$ as obtained by COMPASS [15, 16].

3.3. Searching exotic strange mesons

There may also be exotic states in the strange-meson sector. However, as strange mesons are not eigenstates of C-parity, there are no spin-exotic quantum numbers for strange mesons. Thus, exotic strange mesons can only be identified as supernumerary states in addition to predicted quark-model states. An interesting sector to search for strange mesons is the $J^P = 0^-$ sector. Quark-model calculations [14] predict two excited pseudoscalar strange mesons in the mass region up to $2.5\,\mathrm{GeV}/c^2$ (see Fig. 7). At the same time, the PDG lists three excited pseudoscalar strange mesons [13]. The established $K(1460)$ matches the first excited quark-model state. The not-established $K(1830)$ matches best the second excited quark-model state. The PDG lists in addition the not-established $K(1630)$, which was seen so far by only a single experiment [22] with an surprisingly small width of only $16\,\mathrm{MeV}/c^2$. Furthermore, even if the PDG lists it as $K(1630)$, its quantum numbers are actually unclear.

In the COMPASS analysis, pseudoscalar mesons are studied in their decay via $\rho(770)\pi$ to the $K^-\pi^-\pi^+$ final state. Figure 12 shows the corresponding intensity distribution. It exhibits a peak at about $1.4\,\mathrm{GeV}/c^2$, which presumably arises from the $K(1430)$. However, the $m \lesssim 1.5\,\mathrm{GeV}/c^2$ region is affected by known artifacts in the COMPASS analysis. The intensity distribution exhibits a second clear peak at about $1.7\,\mathrm{GeV}/c^2$, which is accompanied by a clear rise of the relative phase of this partial wave (see Fig. 13). Both, the intensity peak and the rising phase, indicate a resonance-like signal close to the $K(1630)$, however, with a width that is presumably much larger than the one observed in Ref. [22] for the $K(1630)$. This signal is too low in mass to agree with previous observations of the $K(1830)$. Hence, the signal in the $1.7\,\mathrm{GeV}/c^2$ mass region observed by COMPASS may potentially be a supernumerary state and thus a candidate for an exotic strange meson.

4. Conclusions

The non-strange and strange light-meson sector is a very active field of physics. It has entered a high-precision era with large data sets from experiments such as COMPASS, VES, GlueX, CLAS12, LHCb, Belle(II), and BESIII. These high-precision data not only yield smaller uncertainties for the measured meson masses and widths, but they mainly allows us to resolve weaker signals in the data and to get a more complete picture of the physical processes that are under study. For example, they allows us to also study non-resonant processes in kinematic regions where they are dominant. This will improve our models for these processes, which will reduce systematic uncertainties that arise from the separation of resonant and non-resonant contributions. Also, with these high-precision data, more challenging decay modes can be analyzed such as the $b_1(1235)\pi$ decay mode, which is expected to be the dominant decay mode of spin-exotic π_1 states. In the strange-meson sector, high-precision data sets, such as the $K^-\pi^-\pi^+$ data set measured by COMPASS, allow us to explore the strange-meson spectrum with a similar richness of detail as it was done for the non-strange light-mesons spectrum. With a more complete picture of the strange-meson spectrum, supernumerary states can be identified, which are candidates for exotic strange mesons. However, these high-precision data demand at the same time a more complete description of the data by the applied models, which requires developing more elaborate theory models. In the future, new data from currently running and upcoming experiments, for example from PANDA or from a possible new QCD facility at CERN called AMBER [23], will give access to even more aspects of the non-strange and strange light-meson spectrum.

1. M. G. Alexeev *et al.*, [COMPASS], Exotic meson $\pi_1(1600)$ with $J^{PC} = 1^{-+}$ and its decay into $\rho(770)\pi$, (2021), `https://arxiv.org/abs/2108.01744`.

2. J. Dudek *et al.*, [HadSpec], Toward the excited isoscalar meson spectrum from lattice QCD, *Phys. Rev. D* **88** (2013) 094505, `http://doi.org/10.1103/PhysRevD.88.094505`.

3. A. Austregesilo, [GlueX], Exploring the Hadron Spectrum with GlueX, JLUO Group Meeting, Wednesday June 24 2020, `https://www.jlab.org/conference/jluo2020/program`.

4. P. Pauli, [GlueX], Accessing glue through photoproduction measurements at GlueX, Hadron2021, Mexico, within these proceedings.

5. M. Aghasyan *et al.*, [COMPASS], Light isovector resonances in $\pi^- p \to \pi^-\pi^-\pi^+ p$ at 190 GeV/c, *Phys. Rev. D* **98** (2018) 092003, http://doi.org/10.1103/PhysRevD.98.092003.

6. L. Bibrzycki *et al.*, [JPAC], $\pi^- p \to \eta^{(\prime)}\pi^- p$ in the double-Regge region, *Eur. Phys. J. C* **81** (2021) 647, http://doi.org/10.1140/epjc/s10052-021-09420-1.

7. B. Kopf *et al*., Investigation of the lightest hybrid meson candidate with a coupled-channel analysis of $\bar{p}p$-, $\pi^- p$- and $\pi\pi$-Data, *Eur. Phys. J. C* **81** (2021) 1056, https://doi.org/10.1140/epjc/s10052-021-09821-2.

8. A. Rodas *et al*., [JPAC], Determination of the Pole Position of the Lightest Hybrid Meson Candidate, *Phys. Rev. Lett.* **122** (2019) 042002, http://doi.org/10.1103/PhysRevLett.122.04200.

9. A. J. Woss *et al*., [HadSpec], Decays of an exotic 1^{-+} hybrid meson resonance in QCD, *Phys. Rev. D* **103** (2021) 54502, http://doi.org/10.1103/PhysRevD.103.054502.

10. M. Lu *et al*., [E852], Exotic meson decay to $\omega\pi^0\pi^-$, *Phys. Rev. Lett.* **94** (2005) 032002, http://doi.org/10.1103/PhysRevLett.94.032002.

11. C. A. Baker *et al.*, Confirmation of $a_0(1450)$ and $\pi_1(1600)$ in $\bar{p}p \to \omega\pi^+\pi^-\pi^0$ at rest, *Phys. Lett. B* **563** (2003) 140, http://doi.org/10.1016/S0370-2693(03)00643-9.

12. F. M. Kaspar and S. Gerassimov, [COMPASS], Analysis of the Diffractively Produced $\pi^-\pi^-\pi^+$ Final State at COMPASS, Hadron2021, Mexico, within these proceedings.

13. P. A. Zyla et al., [PDG], Review of Particle Physics 2021 update, *Prog. Theor. Exp. Phys.* **2020** (2021) 083C01, http://doi.org/10.1093/ptep/ptaa104.

14. D. Ebert, R. N. Faustov, and V. O. Galkin, Mass spectra and Regge trajectories of light mesons in the relativistic quark model, *Phys. Rev. D* **79** (2009) 114029, http://doi.org/10.1103/PhysRevD.79.114029.

15. S. Wallner, [COMPASS], Strange-Meson Spectroscopy at COMPASS, HADRON2019, Guilin, China, 2020, 134, http://doi.org/10.1142/9789811219313_0019.

16. S. Wallner, Exploring the Strange-Meson Spectrum with COMPASS in the Reaction $K^- + p \to K^-\pi^-\pi^+ + p$, Ph.D. thesis: Technical University of Munich, 2022.

17. C. Daum et al., [ACCMOR], Diffractive production of strange mesons at 63 GeV, *Nucl. Phys. B* **187** (1981) 1, http://doi.org/10.1016/0550-3213(81)90114-0.

18. M. Ablikim *et al.*, [BESIII], Partial wave analysis of $J/\psi \to K^+K^-\pi^0$, *Phys. Rev. D* **100** (2019) 032004, http://doi.org/10.1103/PhysRevD.100.032004.

19. M. Ablikim *et al*., [BESIII], Partial wave analysis of $\psi(3686) \to K^+K^-\eta$, *Phys. Rev. D* **101** (2020) 032008, http://doi.org/10.1103/PhysRevD.101.032008.

20. R. Aaij *et al.*, [LHCb], Observation of $J/\psi\phi$ Structures Consistent with Exotic States from Amplitude Analysis of $B^+ \to J/\psi\phi K^+$ Decays, *Phys. Rev. Lett.* **118** (2017) 022003, http://doi.org/10.1103/PhysRevLett.118.022003.

21. R. Aaij et al., [LHCb], Observation of New Resonances Decaying to $J/\psi K^+$ and $J/\psi\phi$, *Phys. Rev. Lett.* **127** (2021) 082001, http://doi.org/10.1103/PhysRevLett.127.082001

22. V. M. Karnaukhov, V. I. Moroz, and C. Coca, A Narrow Structure with $M = 1.63\,\mathrm{GeV}/c^2$ in the Mass Spectrum of $K_S\pi^+\pi^-$ System, *Phys. Atom. Nucl.* **61** (1998) 203.

23. B. Adams *et al*., [AMBER], Letter of Intent: A New QCD facility at the M2 beam line of the CERN SPS (COMPASS++/AMBER), (2018), arXiv:https://arxiv.org/abs/1808.00848.