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Light and Strange Meson Spectroscopy: New Results on Exotic and High-Mass Mesons from COMPASS

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1. Introduction

The spectroscopy of light and strange mesons is driven by the search for exotic states and by extending the spectrum to masses above $2\,\mathrm{GeV}/c^2$. The first exotic meson established due to its quantum numbers is the $\pi_1(1600)$ with $J^{PC}=1^{-+}$. Following inconsistent initial claims, the COMPASS experiment clearly established its existence using a beam of high-energy negative pions of $190\,\mathrm{GeV}/c$ in its decay into three pions [1, 2] and $\eta(\eta')\pi$ [3, 4] observed with a high-acceptance magnetic spectrometer [5]. Over the last decade, a plethora of exotic mesons containing charm and bottom quarks have been identified, including the long-time elusive tetraquark and pentaquark states. In the light meson sector, claims for other spin-exotic $J^{PC}=1^{-+}$ have either been refuted or have been reconciled with the $\pi_1(1600)$ by Ref. [4] using COMPASS data. The search for exotic strange mesons cannot benefit from spin-exotic quantum numbers, as C-parity is undefined. Instead, one must rely on confirming the systematics of strange meson multiplets as determined by the constituent quark model, while also searching for states that fall outside this scheme — these are known as crypto-exotic states.

Currently, the spectrum of light mesons with masses above $2\,\mathrm{GeV}/c^2$ is characterised by numerous individual claims, which are often statistically weak or lack systematic studies and uncertainties. Most single observations stem from the analysis of $\bar{p}p$ annihilations recorded by the Crystal Barrel experiment over 30 years ago. All states observed have a relative decay width between 15 % and 25 %. Besides the basic interest in observing high-spin mesons and their radial excitations, chiral symmetry restoration is often claimed to occur at high masses leading to a mass degeneracy of parity doublets [6, 7]. However, the large number of claimed states, their assignments, together with their large decay widths, will make such comparisons difficult. Therefore, confirmation of these observations and the evidence presented, as well as the observation of complementary states, is essential. This will establish the systematics of excitations for both parity states. With the COMPASS experiment we can address all states with C=+1, thus π_n and a_n, requiring their coupling to pions. Through the analysis of intermediate decay products (so called isobars we can study low-mass states with $C=-1$ as well as $C=+1$ isoscalars.

1.1 The method

We performed a two-step partial wave analysis for all the data presented here. First, we modeled the angular distributions and momenta of all outgoing particles using a set of partial waves. These partial waves are constructed to describe effective two-body (two meson) decays. These mesons can be either the final state particles themselves (e.g. $K\overline{K}$) or be intermediate resonances (isobars), which themselves subsequently decay into two mesons. The model assumes that diffractive scattering processes generate an intermediate state $X^{\breve{}}$ with definite quantum numbers J^{PC}, of which the spin J can be aligned and described by the quantum number M. Generally, we assume that the scattering process proceeds via Pomeron exchange, which is dominated by natural parity exchange. To fully avoid artifacts in the description of the observed kinematic distribution in the full event sample, the set of partial waves must contain all possible isobars and values of J^{PC} and M. For practical purposes, a selection must be made. This is now performed automatically using the dataset itself. The fit algorithm selects waves drawn from a large wave pool and requires a minimal population. This selection is made in intervals of the mass of the final state and the squared 4-momentum transfer

t' of the reaction process. For the analysis depicted here, we divided the t' range 0.1 to 1.0 $(\mathrm{GeV}/c)^2$ into bins with approximately equal event numbers.

The intensity (the number of observed events corrected for acceptance) is described by the coherent sum of the squares of all the selected waves (amplitudes), allowing for an incoherent, flat background in phase space. The simplified expression for the intensity is:

$$\mathscr{L}\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\mathrm{diff}}\,\mathrm{d}t'\,\mathrm{d}\tau} = \left|\sum_{a=1}^{N_{\mathrm{waves}}} \mathcal{T}_a(m_{\mathrm{diff}},t')\,\psi_a(\tau)\right|^2 + |\mathcal{T}_{\mathrm{flat}}(m_{\mathrm{diff}},t')|^2\,. \tag{1}$$

Here, $\mathcal{T}_a$ is the amplitude to produce the wave indexed a, ψ_a describes the decay pattern of this wave, $\mathscr{L}$ is the luminosity, m_{diff} is the final state mass, τ describes the phase space variables and N_{waves} is the number of waves in the particular bin built by m_{diff} and t'.

The fit parameters, $\mathcal{T}_a$, obtained from a reduced log-likelihood fit, are complex numbers that, in their entity, constitute the spin density matrix in this bin. Since Gaussian error propagation is not appropriate for this problem, we use a bootstrap method to evaluate the covariance matrix. For this, we generate a large number of pseudo event samples from the actual dataset, with each pseudo sample composed of a subsample of the true dataset. Numerous events are used several times to arrive at the same sample size as the original dataset. Each such pseudo data set is subjected to the same log-likelihood fit, and we calculate the covariance matrix from the resulting distribution for each $\mathcal{T}_a$.

In a second step, we model the mass dependence of the spin density matrix. This model comprises a set of resonances, which are usually characterised by Breit-Wigner (BW) amplitudes with a mass-dependent width, as well as a smooth, non-resonant amplitude with a fixed mathematical shape and variable dependence on t'. These amplitudes are added coherently. For practical reasons, only a subset of the partial waves, and thus of the spin density matrix, is used in the second step, known as the resonance model fit. The χ^2 fit determines the free parameters of the Breit–Wigner amplitude and the non-resonant component. If several waves are assigned the same value for J^{PC}, the BW parameters describing the same meson resonance in these waves must coincide. We perform the χ^2 fit using the method described in Ref. [8] and the `sfitter` software [9]. We compare our model $\widehat{\lambda}$ for the real-valued spin-density vector (a linearized spin density matrix), calculated from the model $\widehat{\mathcal{T}}_a$, to the bootstrap estimates λ, by calculating the residuals

$$\Delta\lambda_i(m_{\mathrm{diff}},t') = \lambda_i(m_{\mathrm{diff}},t') - \widehat{\lambda}_i(m_{\mathrm{diff}},t') \tag{2}$$

for every spin-density matrix index i and every (m_{diff},t') cell. $\widehat{\mathcal{T}}_a$ contain all unknown shape parameters for the model amplitudes, e.g. BW parameters. The minimized function χ^2 then reads

$$\chi^2 = \sum_{m_{\mathrm{diff}},t'}\sum_{i,j=1}^{N_{\mathrm{waves}}^2} \Delta\lambda_i(m_{\mathrm{diff}},t')\ \mathrm{Cov}^{-1}\left[\lambda_i(m_{\mathrm{diff}},t'),\lambda_j(m_{\mathrm{diff}},t')\right]\ \Delta\lambda_i(m_{\mathrm{diff}},t') \tag{3}$$

In this contribution, we will present examples of partial wave amplitude analysis (PWA) targeting the decay of light unflavoured mesons into $\omega(782)\pi^-\pi^0$ and $K_s^0K^-$, as well as the decay of strange mesons into $K^-\pi^+\pi^-$.

2. Light unflavoured mesons

2.1 Decay into $\omega\pi^-\pi^0$

The $\omega(782)$ meson is both, a heavy quasi stable vector and an iso-singlet. Together with one of the two accompanying pions it can form the heavy $b_1(1235)$ isobar, which is predicted to be a favoured decay product of the $\pi_1(1600)$ spin-exotic mesons. Using approximately 660 kevts, we performed a PWA in all bins of t' and with masses up to 3.5 GeV/c^2. The rich isobaric structure required an automated selection of active waves to be used in the fit. The algorithm drew from a wave pool of 893 waves selecting a total of 257 waves. However, these waves are not present simultaneously across the entire mass range. We selected a subset of 23 waves, which we included in the resonance model fit. As an example, in Fig. 1 we present the results for the spin-exotic wave, $a_3(2080)$ and $a_6(2450)$ in one particular bin of t' and in one wave only. The fit simultaneously uses diagonal and non-diagonal elements of the spin density matrix in all four bins of t' and connects the BW parameters of the same resonance observed in different waves. For waves with the same J^{PC} and spin projection M, also the production characteristics of the same resonances are linked. It is remarkable that most resonances are observed in at least three different partial waves, except for $\pi(1800)$, the excited a_1, which was only observed in two waves and the $a_5(2650)$, only observed decaying into the $\rho(770)$ $\omega(782)$ with a D wave. Unlike for the analysis of the $\pi^-\pi^-\pi^+$ final state, plagued by complex Deck-type backgrounds, the spin-exotic wave is observed clearly and with phase variation of 180° with respect to a wave with J^{PC} =2^{++}, which exhibits no proper resonance in the same mass region. This allows for much smaller systematic uncertainties in the determination of the BW parameters. The plethora of states include first observations of excited $a_3(2080)$, $\pi_4(2250)$, $a_6(2450)$, $a_5(2650)$ and the solid confirmation of many other states.

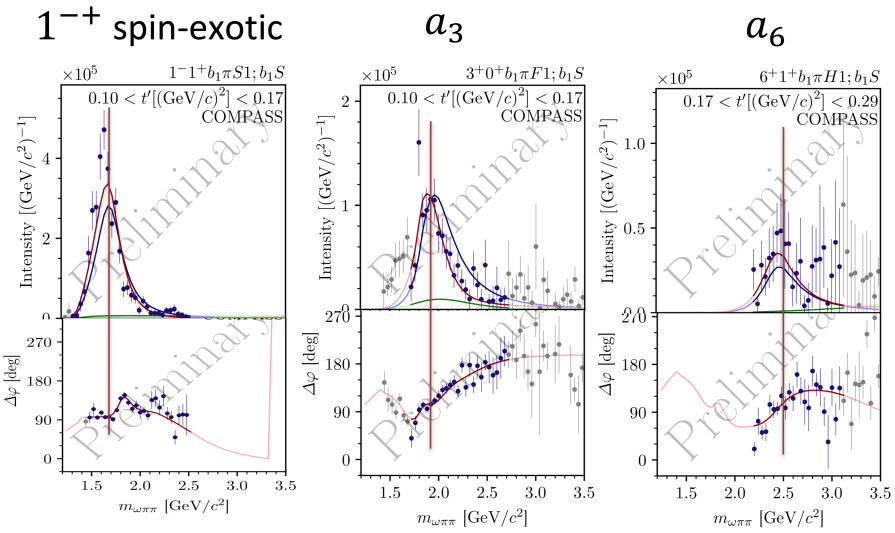
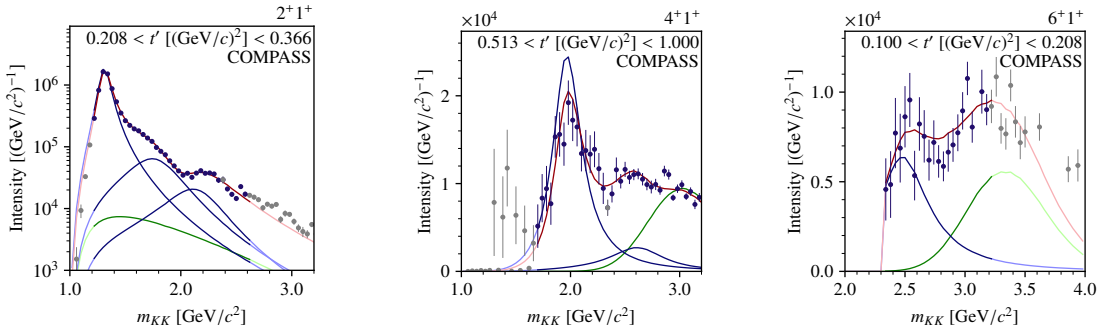


Figure 1: Mass distribution and phases for three waves in the $\omega(782)\pi^-\pi^0$ final state in the lowest bin of t'. The signal for the spin-exotic $\pi_1(1600)$ is shown on the left, the excited $a_3(2080)$ in the central panel and the $a_6(2450)$ in the right panel. The red line indicates the full model, blue and green curves the resonant and non-resonant contributions, respectively. The red vertical lines indicate the resonant position.

2.2 Decay into $K^0_s K^-$



$J^P = 2^+$ in the second t' interval from 0.21 to 0.37 $(\mathrm{GeV}/c)^2$ with logarithmic vertical scale.

$J^P = 4^+$ in the highest t' interval from 0.51 to 1.00 $(\mathrm{GeV}/c)^2$.

$J^P = 6^+$ in the lowest t' interval from 0.100 to 0.208 $(\mathrm{GeV}/c)^2$

Figure 2: Results of the mass-dependent fit for $K^0_s K^-$. Red: total fit function, blue: resonance contributions, green: non-resonant contribution.

The decay of mesons into $K\overline{K}$ has been pivotal for meson spectroscopy and it lead to the first observations of the higher spin states a_2 and $a_4(1970)$ [10–12] and gave first evidence for the spin 6 meson $a_6(2450)$ [11]. Despite the suppression of a decay into $K\overline{K}$ for ordinary mesons due to the OZI rule, which resulted in much smaller event samples compared to favoured decay modes, the quasi-absence of non-resonant production processes enabled clean observations. In addition, the $K\overline{K}$ decay can be indicative for an exotic flavour structure of mesons, as both, a large gluon and $s\bar{s}$ content will break the OZI rule enhancing the $K\overline{K}$ partial decay width. At high beam energies, Pomeron exchange dominates the production process and only natural parity exchange contributes. This restricts the quantum number of the intermediate state to $J^{PC} = n^{++}$ with n even, $n \geq 2$ and spin alignment $M \geq 1$. We model the decay angular distributions as spherical harmonics and use $n_{\max} = 6$. We have treated the ambiguities appearing for the fit solutions for two-pseudoscalar final states as described in [13]. The almost background-free observation of three a_2 states is depicted in the left panel of Fig. 2. For $J^P = 4^+$, we observe an excited state $a_4(2610)$ above the ground state with a mass of $2609 \pm 9\,(\mathrm{stat.})\,^{+5}_{-38}\,(\mathrm{sys.})\,\mathrm{MeV}/c^2$ and width of $\Gamma = 609 \pm 22\,(\mathrm{stat.})\,^{+35}_{-311}\,(\mathrm{sys.})\,\mathrm{MeV}/c^2$, which is shown in the central panel of Fig. 2. Together with $a_5(2600)$ this we observed the highest mass meson observed to date. The highest spin meson a_6 is observed with a mass of $M = 2430 \pm 9\,(\mathrm{stat.})\,^{+21}_{-25}\,(\mathrm{sys.})\,\mathrm{MeV}/c^2$ and width $\Gamma = 523 \pm 22\,(\mathrm{stat.})\,^{+39}_{-119}\,(\mathrm{sys.})\,\mathrm{MeV}/c^2$. It is depicted in the right panel of Fig. 2. These values are in good agreement with the values cited by Ref. [11]. A clear phase variation over 90° is observed with respect to all waves. The significance of the signal is $27.4\,\sigma$.

3. Strange mesons

3.1 Decay into $K^-\pi^+\pi^-$

The incoming beam contains about 2 % K^-. We study strange mesons decaying into $K^-\pi^+\pi^-$ (720 kevts) and perform a PWA. We apply a novel algorithm to select the wave set, which is mass

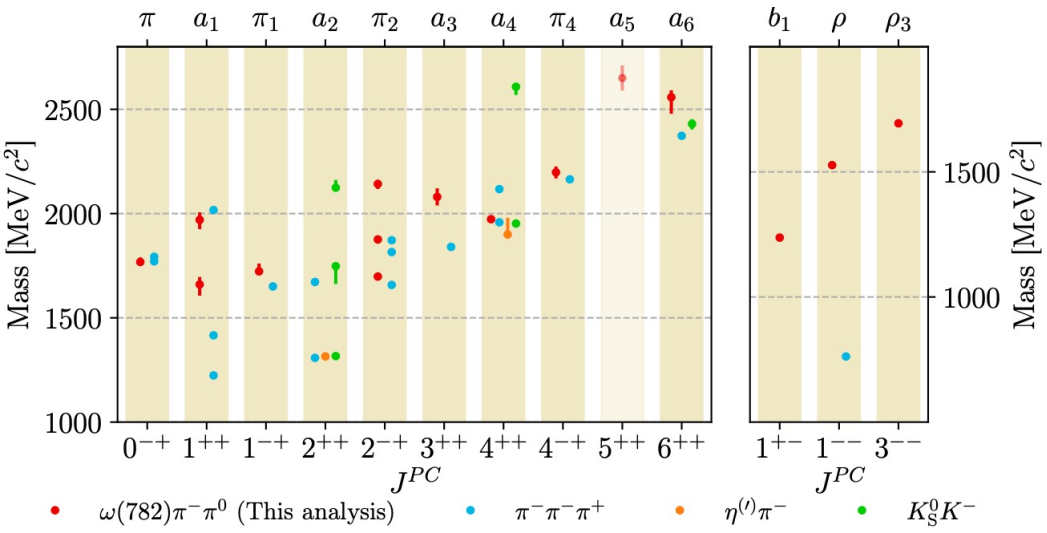


Figure 3: Mass spectrum of unflavoured mesons with $C = +1$ measured by the COMPASS experiment (left canvas). Mass values for states with $C = -1$ shown on the right are very preliminary and with no systematic uncertainties. Figure taken from Ref. [14].

dependent and draws waves from a pool of 596 waves up to spin 7. Unlike for unflavoured mesons, the PWA contains an additional incoherent term reflecting beam background from pions producing $\pi^-\pi^-\pi^+$ being misinterpreted as $K^-\pi^+\pi^-$. We use our $\pi^-\pi^-\pi^+$ analysis to generate the resulting background into each partial wave assuming the $K^-\pi^+\pi^-$ final state. We also use a bootstrapping method described above to estimate the statistical uncertainties of the spin density matrix. We use 14 waves in four bins of t' for our resonance model fit to extract thirteen resonances and to determine their parameters. We find all resonances in at least two waves, except for the three pseudoscalar kaons and $K_4(2210)$ being observed in only one wave.

The masses for our $K_3(2120)$ and $K_4(2210)$ are about 200 MeV/c^2 below the PDG masses of K_3 and K_4. This suggests that we have identified the K_3 and K_4 ground states, while the previous measurements may have observed the corresponding first excitations.

We identified three pseudoscalars with high significance shown in Fig. 4. The presence of three states does not match quark-model predictions of only two states in this mass region [15–19]. This indicates the presence of a supernumerary signal. The lighter of the two quark-model states is consistent with the $K(1460)$, the heavier matches best the $K(1830)$. This leaves our observation of a $K(1690)$ as the first clear candidate for a cyrpto-exotic strange meson with $J^P = 0^-$ with $M = 1687 \pm 17\,(\text{stat.})\,^{+13}_{-39}\,(\text{sys.})\,\text{MeV}/c^2$ and width $\Gamma = 140 \pm 20\,(\text{stat.})\,^{+50}_{-50}\,(\text{sys.})$

The new spectrum of strange mesons is shown in Fig. 5.

4. Conclusion

Despite the small sample size of final states involving $K\overline{K}$ and $\omega(782)\pi^-\pi^0$, the quasi-absence of non-resonant production processes enables us to obtain rich spectroscopic information extending to meson masses beyond 2.5 GeV/c^2. We obtain some complementary information in comparison with the $\pi^-\pi^-\pi^+$ final state, despite the latter being one hundred times more abundant. In particular,

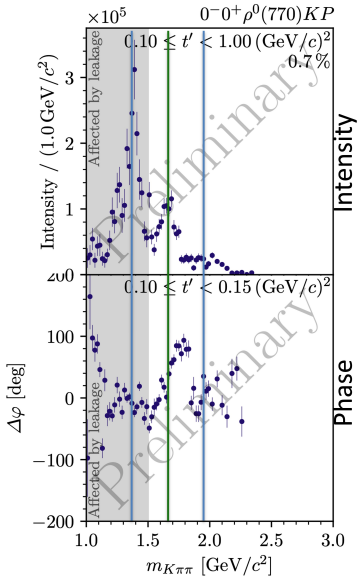


Figure 4: Mass spectrum for strange pseudoscalar mesons decaying into $\rho(770)$ K in a P wave. Vertical lines indicate the position of $K(1460)$, $K(1690)$, $K(1830)$.

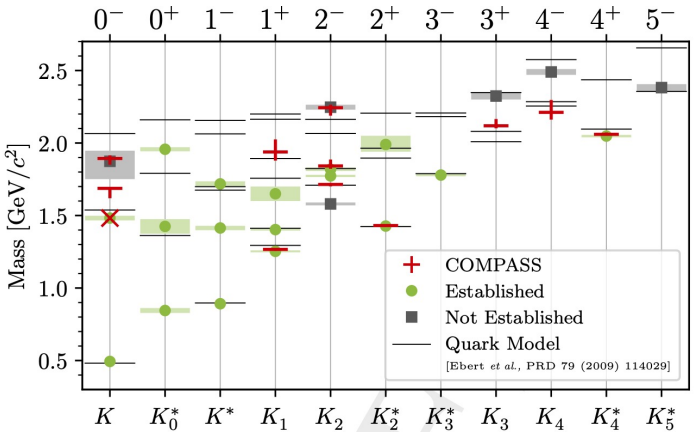


Figure 5: Mass spectrum of known strange mesons. States marked by a red cross stem from this analysis. Black lines are predictions from a quark model calculations. The vertical extension of colored boxes represent the uncertainties.

the spin-exotic meson is clearly observed in decay channels involving the $b_1(1245)$. It should be noted that we have not found any other spin-exotic mesons, neither with $J^{PC} = 1^{-+}$ nor 3^{-+} or 5^{-+}. We clearly observed the ground state $a_3(1875)$ an the excited $a_3(2080)$. The width of the latter disagrees with observations from Ref. [20]. We observe $a_6(2450)$ for the first time, confirming previous evidence. We also observe $a_4(2610)$ and $a_5(2650)$ for the first time. These are the mesons with the highest mass and spin observed to date.

COMPASS also provides by far the largest set of consistent observations of excited kaons with $J_{\max} = 4$, confirming and complementing previous observations. Furthermore, we have clarified the excitation spectrum for pseudoscalar strange mesons and have observed the first crypto-exotic strange mesons, $K(1690)$, with mass greater than $\kappa(700)$.

References

[1] C. Adolph *et al.*, [COMPASS], "Resonance production and $\pi\pi$ S-wave in $\pi^- + p \to \pi^-\pi^-\pi^+ + p_{\mathrm{recoil}}$ at 190 GeV/c," *Phys. Rev. D* **95** (2017) 032004.

[2] M. G. Alexeev *et al.*, [COMPASS], "Exotic meson $\pi_1(1600)$ with $J^{PC} = 1^{-+}$ and its decay into $\rho(770)\pi$," *Phys. Rev. D* **105** no. 1, (2022) 012005.

[3] C. Adolph *et al.*, [COMPASS], "Odd and even partial waves of $\eta\pi^-$ and $\eta'\pi^-$ in $\pi^- p \to \eta^{(\prime)} \pi^- p$ at 191GeV/c," *Phys. Lett. B* **740** (2015) 303.

[4] A. Rodas *et al.*, [JPAC], "Determination of the Pole Position of the Lightest Hybrid Meson Candidate," *Phys. Rev. Lett.* **122** (2019) 042002.

[5] P. Abbon *et al.*, [COMPASS], "The COMPASS setup for physics with hadron beams," *Nucl. Instrum. Meth. A* **779** (2015) 69.

[6] E. S. Swanson, "Parity doubling in the meson spectrum," *Physics Letters B* **582** no. 3, (2004) 167–171.

[7] R. Wagenbrunn and L. Glozman, "Effective restoration of chiral symmetry in excited mesons," *Physics Letters B* **643** no. 2, (2006) 98–103.

[8] S. Wallner, "Exploring the Strange-Meson Spectrum with COMPASS in the Reaction $K^- + p \to K^-\pi^-\pi^+ + p$," PhD thesis, Technische Universität München, Feb., 2022. https://mediatum.ub.tum.de/1632535.

[9] [The COMPASS hadron subgroup]. https://gitlab.cern.ch/compass/hadron/analyses/K_pi_pi/sfitter. Resonance-model fit software *sfitter*.

[10] R. Baldi, T. Bähringer, P. Dorsaz, V. Hungerbühler, M. Kienzle-Focacci, M. Martin, A. Mermoud, C. Nef, and P. Siegrist, "Observation of a spin 4, isospin 1, meson resonance," *Physics Letters B* **74** no. 4, (1978) 413–416. https://www.sciencedirect.com/science/article/pii/0370269378906925.

[11] W. E. Cleland *et al.*, "Resonance Production in the Reaction $\pi^\pm p \to K^0_s K^\pm p$ at 30 GeV/c and 50 GeV/c," *Nucl. Phys. B* **208** (1982) 228–261.

[12] A. Martin, E. Ozmutlu, R. Baldi, T. Böhringer, P. Dorsaz, V. Hungerbühler, M. Kienzle-Focacci, M. Martin, A. Mermoud, C. Nef, and P. Siegrist, "A study of a2 and g resonance production in π p $\to$ K^-K^0 p," *Nuclear Physics B* **140** no. 1, (1978) 158–178. https://www.sciencedirect.com/science/article/pii/0550321378903188.

[13] J. Beckers, F. Kaspar, and J. Knollmüller, "Progress in the partial-wave analysis methods at COMPASS," *Nuovo Cim. C* **47** no. 4, (2024) 204, arXiv:2311.00449 [hep-ex].

[14] P. Haas, "The spectrum of isovector mesons in the $\omega(782)\pi^-\pi^0$ final state at compass," 2025.

[15] 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.

[16] J. Oudichhya, K. Gandhi, and A. K. Rai, "Kaon and strangeonium spectrum in Regge phenomenology," *Phys. Rev. D* **108** (2023) 014034.

[17] U. Taboada-Nieto, P. G. Ortega, D. R. Entem, F. Fernández, and J. Segovia, "Kaon spectrum revisited: bound states of high energy and spin," *Eur. Phys. J. A* **59** (2023) 40.

[18] C.-Q. Pang, J.-Z. Wang, X. Liu, and T. Matsuki, "A systematic study of mass spectra and strong decay of strange mesons," *Eur. Phys. J. C* **77** (2017) 861.

[19] S. Godfrey and N. Isgur, "Mesons in a relativized quark model with chromodynamics," *Phys. Rev. D* **32** (1985) 189.

[20] A. V. Anisovich, C. A. Baker, C. J. Batty, D. V. Bugg, V. A. Nikonov, A. V. Sarantsev, V. V. Sarantsev, and B. S. Zou, "Partial wave analysis of $\overline{p}p$ annihilation channels in flight with I = 1, C = +1," *Phys. Lett. B* **517** (2001) 261–272, arXiv:1110.0278 [hep-ex].