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Resonances of the systems $\pi^-\eta$ and $\pi^-\eta'$ in the reactions $\pi^- p \to \pi^-\eta\, p_{\mathbf{slow}}$ and $\pi^- p \to \pi^-\eta' p_{\mathbf{slow}}$ at COMPASS

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We describe partial-wave analyses of the systems $\pi^-\eta$ and $\pi^-\eta'$ produced in interactions of a π^- beam ($190\,\mathrm{GeV}/c$) with a liquid hydrogen target. The data were recorded during the 2008 COMPASS run, where a slow recoiling proton ($|t| > 0.1\,\mathrm{GeV}^2$) was required by the trigger. We compare analyses of the $\pi^-\eta$ and $\pi^-\eta'$ data. Significant contributions can be attributed to the resonances $a_2(1320)$, observed in the D_+-wave, and $a_4(2040)$, observed in the G_+-wave. Between the two systems, we find similar compositions of the even partial waves D_+ and G_+ after taking phase-space factors into account, but a much enhanced P_+-wave in $\pi^-\eta'$. Relative phase-differences indicate a large incoherent contribution of in the P_+-wave of the $\eta'\pi^-$ system, but other interpretations are not excluded. The known resonances $a_2(1320)$, $a_4(2040)$ and their parameters could be extracted from the data; their branchings are found to roughly agree with predictions from $\eta-\eta'$ mixing.

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1. Introduction

Exotic quantum number mesons which cannot be accomodated by $q\overline{q}$ states have been a long sought-for prediction of QCD. Recent reviews of the field, which also give references, are Refs. [7, 10]. The PDG [11] lists a spin-exotic $\pi(1400)$ decaying to $\eta\pi$, and a spin-exotic $\pi(1600)$ decaying to $\eta'\pi$ (both in P-wave, with quantum number $J^{PC} = 1^{-+}$). These claims came surprising not only because of the unexpectedly low mass of the $\eta\pi$ resonance, but also because hybrid mesons are expected to preferentially decay into final-states involving P-wave mesons such as $b_1\pi$ or $f_1\pi$, and because by $SU(3)$ arguments a hybrid meson should prefer decays to $\eta'\pi$ over the $\eta\pi$ channel, but it should decay to both. Furthermore the analyses leading to the PDG entries have been questioned, and alternative theoretical models have been proposed.

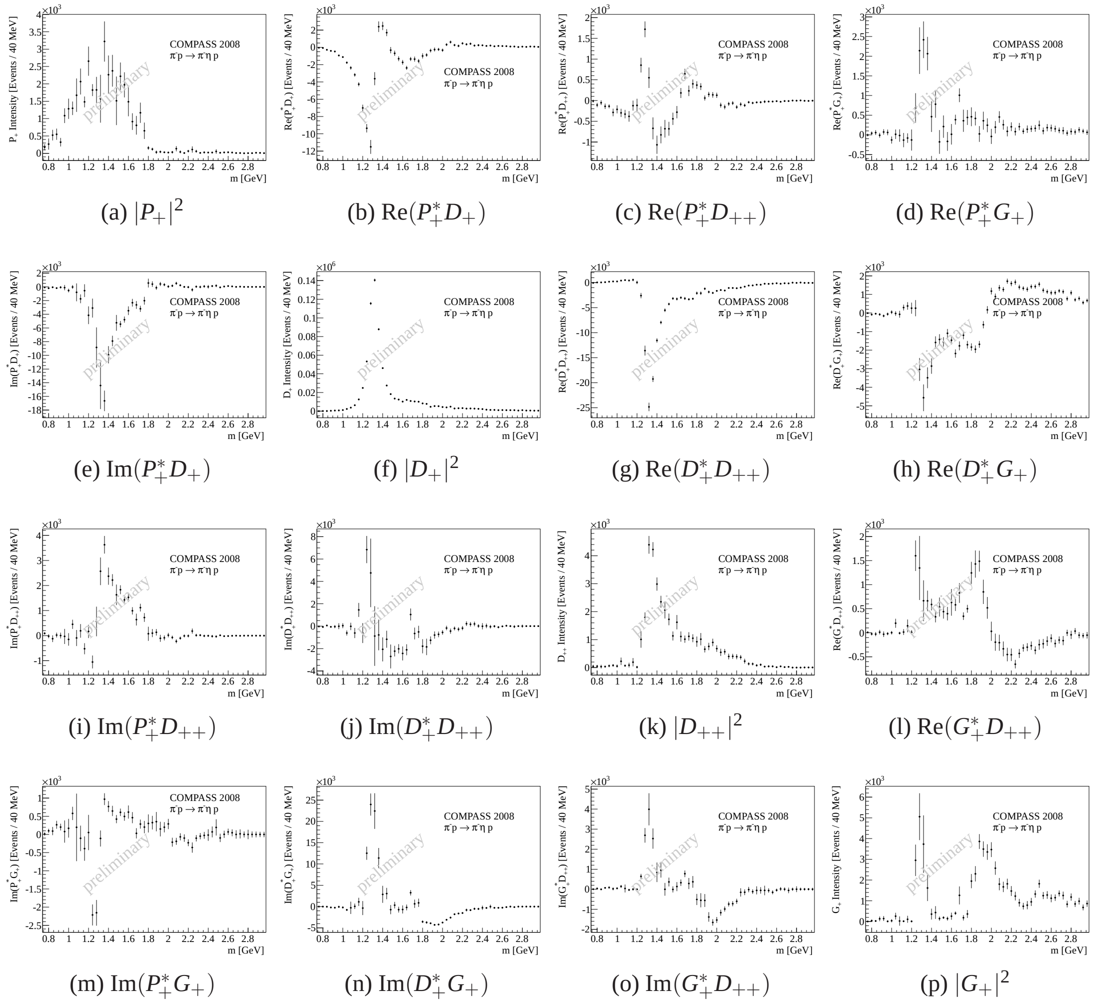
The COMPASS collaboration has extracted large data sets, covering an unprecendented range of invariant masses, and hopes to clarify the situation. In 2008 the experiment [1] took data with a 190 GeV pion beam impinging on a liquid hydrogen target, aiming at collecting large samples of data for spectroscopy. First results for the $\eta'\pi^-$ system were given at a previous conference [14]. The data selection is also described in the reference, up to minor refinements having taken place in the meantime. The reactions under consideration are $\pi^- p \to \pi^-\eta^{(\prime)} p$. We will focus on the $\eta\pi^-$ system and on the comparison between the two systems. Additionally, we will briefly discuss fits to the partial-wave results with resonance models. The data for both final states were analyzed with the same partial-wave software, where the full four-body dynamics of the $\pi^-\pi^-\pi^+\pi^0$ and $\pi^-\pi^-\pi^+\eta$ systems was taken into account in order to separate the three-body decays of the isoscalars from the inevitable background. Additionally, the data were analyzed with a two-body program that was also used in another analysis presented at this conference [3]. The results were found to be compatible between the two approaches.

2. Partial-wave Analysis in Mass Bins

The analysis of the $\eta\pi^-$ data is performed in the same way as was done for the $\eta'\pi^-$ data described in our previous report, but due to the larger data set, we were able to add another wave, namely the $m = 2$ spin-2 D_{++}-wave. This wave was previously observed in interference terms extracted from the $\eta\pi^0$ system [8]. We mention that unlike most previously published analyses we also include the spin-4 G_+-wave.

Additional fits including natural-exchange spin-3, spin-5 and spin-6 waves were also performed, their presence being expected from a prior analysis of the $K^-K^0_S$ system and double-Regge phenomenology [9, 15]. With these waves included, the data can be described without recourse to unnatural-exchange waves all the way up to 3 GeV, in accordance with the expected dominance of the spin-parity natural Pomeron exchange. Since the inclusion of these waves leads to mathematical ambiguities [6], and since the data in the resonance-dominated range up to approx. 2 GeV is well-described with the smaller set, we have omitted them in the depicted fits.

The fit results for the $\eta\pi^-$ data are shown in Figs. 1 and the relative phases in red in Fig. 3. Only the intensities and relative real parts can be extracted by the fit, this leaves an ambiguity in the sign of the imaginary part, which can in turn lead to discontinuities and jumps in the calculated phases. Additionally, interpretation of these fits comes with the caveat that a continuous ambiguity



(a) $|P_+|^2$ (b) $\mathrm{Re}(P_+^* D_+)$ (c) $\mathrm{Re}(P_+^* D_{++})$ (d) $\mathrm{Re}(P_+^* G_+)$

(e) $\mathrm{Im}(P_+^* D_+)$ (f) $|D_+|^2$ (g) $\mathrm{Re}(D_+^* D_{++})$ (h) $\mathrm{Re}(D_+^* G_+)$

(i) $\mathrm{Im}(P_+^* D_{++})$ (j) $\mathrm{Im}(D_+^* D_{++})$ (k) $|D_{++}|^2$ (l) $\mathrm{Re}(G_+^* D_{++})$

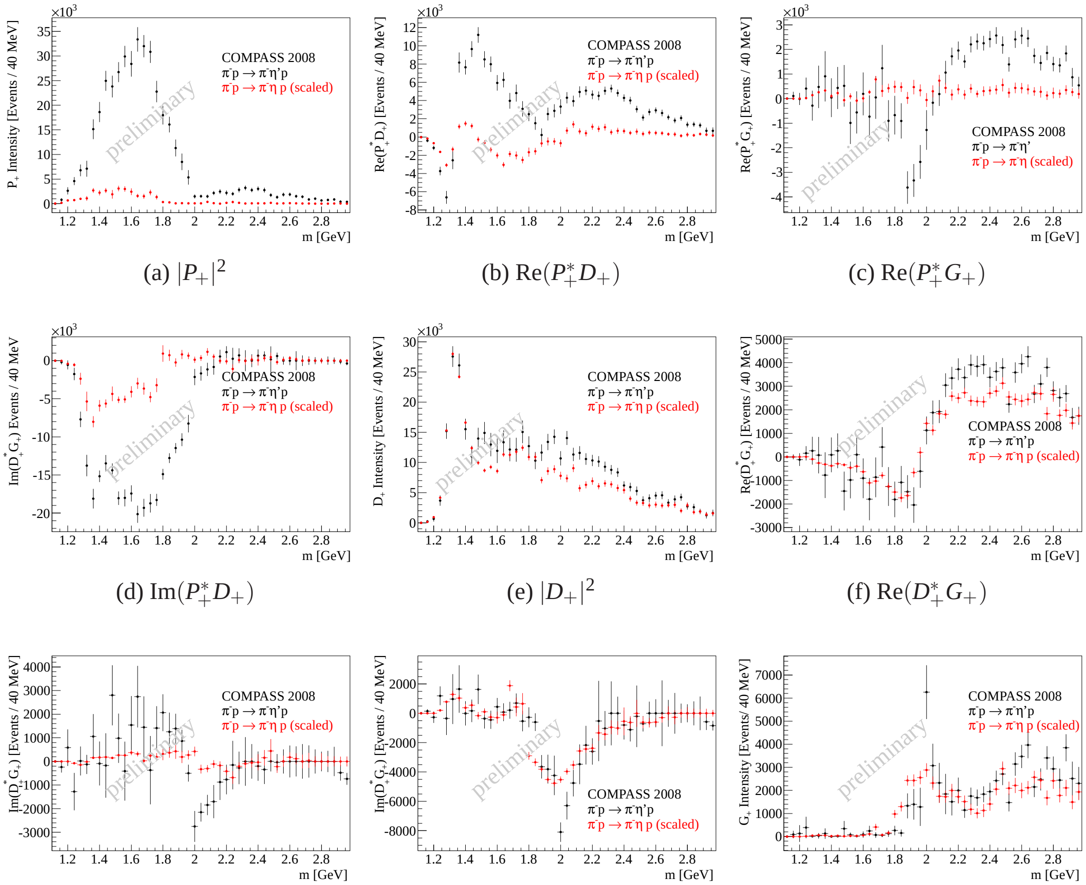
(m) $\mathrm{Im}(P_+^* G_+)$ (n) $\mathrm{Im}(D_+^* G_+)$ (o) $\mathrm{Im}(G_+^* D_{++})$ (p) $|G_+|^2$

Figure 1: Mass-independent partial-wave analysis of the $\pi^-\eta$ system. The matrix shows on the diagonal the intensities of the natural-parity waves. Above the diagonal are shown the respective relative real parts, below the respective relative imaginary parts. The signs of the imaginary parts are not determined by the fit. The dominating D_+ wave leaks into the G_{++} wave in the mass range near 1.3 GeV.

prevents the fit from accounting for incoherent contributions, the phases therefore cannot be interpreted without care [9]. Our data show a significant P_+ wave which interferes with the dominant D_+ wave. The size of the D_{++} wave relative to the D_+ wave is consistent with other COMPASS analyses [12]. Phase-motion due to the $a_2(1320)$ and $a_4(2040)$ resonances can be clearly seen. The relative phase motion of the D_+ and P_+ waves is consistent with previous analyses.

3. Comparison of the Systems $\eta\pi^-$ and $\eta'\pi^-$

The physical η and η' mesons are not independent objects but mixtures of the $SU(3)$ flavor basis states $\eta_s = s\bar{s}$ and $\eta_n = u\bar{u} + d\bar{d}$. As such, the relative strength of their production can be expressed in terms of the mixing angle ϕ and phase-space and dynamical (barrier) factors [13]. Taking the simplest form for the dynamical factor that yields the correct asymptotic behavior near threshold, $F_J(q) = q^J$ ($q^{(\prime)}$ the breakup momentum into $\eta^{(\prime)}\pi$ at the given invariant mass), and taking into account phase-space, we rescale the $\eta\pi^-$ amplitudes with the factor $(q'/q)^{J+1/2}$ and overlay them on the $\eta'\pi^-$ amplitudes. The resultant matrix of overlaid fit results (omitting the D_{++} not included in $\eta'\pi^-$) is shown in Fig. 2.



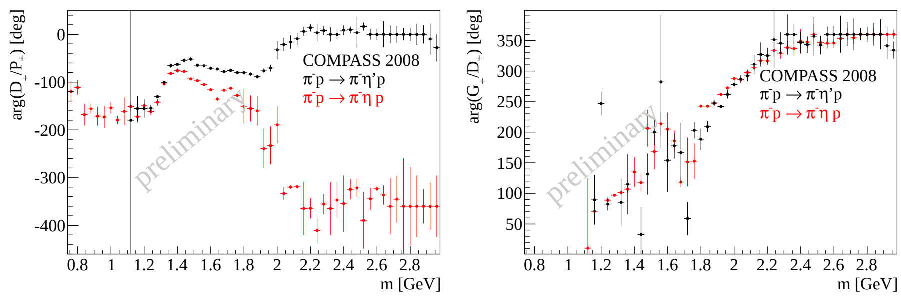
(a) $|P_+|^2$ (b) $\mathrm{Re}(P_+^* D_+)$ (c) $\mathrm{Re}(P_+^* G_+)$

(d) $\mathrm{Im}(P_+^* D_+)$ (e) $|D_+|^2$ (f) $\mathrm{Re}(D_+^* G_+)$

(g) $\mathrm{Im}(P_+^* G_+)$ (h) $\mathrm{Im}(D_+^* G_+)$ (i) $|G_+|^2$

Figure 2: Comparison of the partial-wave amplitudes obtained in the $\pi\eta'$ (black) and $\pi\eta$ systems (red) after re-scaling with the phase-space factors.

The comparison shows two striking features: first, the close similarity of the even partial waves, D_+ and G_+. The close match in the overall normalization is supposed to be accidental subject to further MC studies. Besides that it appears that the physical content of these waves is the same in both final states, even in the high-mass range where non-resonant production is expected to be dominant. On the other hand, and the second striking feature, the P_+ wave is strongly suppressed in the $\pi\eta$ final state in accordance with the suspected non-$q\bar{q}$ character of this wave and with a previous analysis by the VES collaboration [4]. Comparing the phase motions (which are not affected by the scaling procedure) as shown in Fig. 3, one finds that the P_+ wave has the same phase relative to the D_+ wave at the $\eta'\pi$ threshold, which suggests a common origin, but



(a) $\arg(D_+/P_+)$ (b) $\arg(G_+/D_+)$

Figure 3: Comparison of the relative phases. For the D_+/P_+ comparison we show only one of the ambiguous branches of the phase-motion in the $\pi^-\eta$ system (see text). The relative phase motion of the P_+ and G_+ waves is not shown as they have only very little overlap in the $\pi^-\eta$ data.

it then evolves differently which contradicts them having the same resonant content. The similarity of the scaled D_+ waves suggests that the difference in the relative phase motion of the P_+ and D_+ waves is mainly due to different contents of the P_+ wave. The aforementioned ambiguity in the phase determination allows reflecting the extracted phases on the line corresponding to -180 degrees, which would make the relative phase of the D_+ and P_+ waves of the $\eta\pi^-$ system return to the corresponding relative phases of the $\eta'\pi^-$ system at high masses, suggesting that the difference is due to an incoherent contribution, which in general tends to reduce relative phase differences [9].

4. Outlook and Conclusion

Beyond what we show here, we have fitted the data with resonance models. For the $a_2(1320)$ and $a_4(2040)$ we find parameters that agree with the PDG [11] and other COMPASS analyses [2], respectively. For a fit to the P_+ waves, we need large non-resonant backgrounds to account for both phase-shifts and intensities simultaneously. As remarked above, the phase-shifts seem to indicate that a more complex model allowing for incoherent contributions is needed. The studies with higher-spin waves indicate in particular that non-resonant models should be explored. An extraction of the branching fractions of the $a_2(1320)$ and $a_4(2040)$ and comparison to theoretical predictions [5], while in rough agreement, indicates that the cross-section of the $\eta'\pi^-$ data is slightly over-estimated and work is ongoing to understand potential error sources.

We have performed partial-wave analyses of the $\eta\pi^-$ and $\eta'\pi^-$ systems. In these we find as novel results an $m = 2$ contribution to the spin-2 wave, we find the $a_4(2040)$ resonance, and we found a transformation which allows a close comparison of the even-spin natural-parity partial-wave amplitudes between the two systems. A spin-exotic P_+-wave contrivution to the two systems could be confirmed, though its resonant character could not yet be confirmed unambiguously.

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