PROCEEDINGS OF SCIENCE

Precision Hadron Spectroscopy at COMPASS - The Scalar Isoscalar Meson Spectrum -

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COMPASS is a fixed-target experiment at the CERN SPS, investigating the structure and the dynamics of hadrons. The experimental setup features a modern spectrometer with wide acceptance and precise momentum resolution for charged track reconstruction. Furthermore, particle identification and calorimetry make it an ideal tool to access a broad range of final states. In 2008 and 2009, a world leading data set was recorded with 190 GeV/c hadron beams impinging on a liquid hydrogen target. Precision studies of the light-quark meson spectrum are pursued by the means of partial-wave analysis.

These proceedings focus on the spectrum of scalar isoscalar mesons, which is accessible in COMPASS through two different reactions. The central production of mesons in proton-proton reactions is well suited for the search of glueball candidates, where the amount of the COMPASS data and their precision can largely outperform previous experiments. As a complementary approach, scalar mesons are produced as intermediate resonances in the diffractive dissociation of pions. A novel method allows to extract amplitudes for two-meson subsystems from the decomposition of these multi-hadron final states into partial waves. We will introduce both methods and present selected results.

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1. Introduction

The strong interaction is described by quantum chromodynamics (QCD) within the standard model of particle physics. The colour-charged quarks interact by the means of gluons in analogy to quantum electrodynamics. However, the gluons interact among themselves due to their own colour charge, which results in the confinement of the quarks into colour-neutral objects. These hadrons are the relevant degrees of freedom at low energies, and they can be grouped into three-quark and quark-antiquark states, which are called baryons and mesons respectively. On the other hand, no known effect of the theory of strong interaction forbids the formation of the formation of pure-gluon bound states into colour-neutral hadrons. The existence of these so-called glueballs is one of the unsolved problems in modern particle physics and can be regarded as a stringent test for quantum chromodynamics.

Many QCD guided models agree in estimating the glueball ground state with scalar quantum numbers $J^{PC} = 0^{++}$ in the mass range from 1.0 to 1.8 GeV/c^2 [1]. However, no unambiguous experimental observation has been reported so far. Grouping mesons in nonets of the approximate flavour-SU(3) symmetry has been found to be extraordinarily successful in the pseudoscalar and vector meson sectors in order to identify the ground states predicted by the constituent-quark model. In contrast, the assignment of the supernumerous scalar isoscalar mesons $f_0(500)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ to one singlet and one octet state is controversially discussed [1, 2]. Even if the resonances below 1 GeV/c^2 originate from meson-meson dynamics, the remaining three states can be subject to mixing effects between $q\bar{q}$ mesons and pure gluonic bound states. In this context, the existence and the properties of the f_0 mesons are crucial for the interpretation but much disputed. The COMPASS[1] experiment at CERN was proposed to make significant contributions to this field.

2. Experimental Access

COMPASS [3, 4] is a multi-purpose experiment at the CERN SPS, which investigates the structure and the dynamics of hadrons. It employs both positively and negatively charged hadron beams impinging with a momentum of 190 GeV/c on liquid hydrogen or nuclear targets in order to produce hadronic states and measure their properties precisely. The experimental setup with a two-stage magnetic spectrometer provides a uniform angular acceptance in a broad kinematic range for charged hadrons in the final state. In addition, one electromagnetic calorimeter in each stage allows for the precise reconstruction of neutral hadrons. Furthermore, a ring-imaging Cherenkov detector is installed for the identification of final-state hadrons involving strange quarks. Flavour-dependent branching ratios help to determine the nature of produced resonances.

Scalar isoscalar resonances are studied in two different reactions in COMPASS. First of all, central production (cf. Figure 1) was considered to be an ideal reaction for the formation of glueballs due to its gluon-rich environment. A proton beam is impinging on a proton target, but both protons stay intact in the reaction and are detected. No valence quarks are thus exchanged with the system produced at central rapidities in the centre-of-mass frame. Centrally produced resonances are detected via their decay into two pseudoscalar mesons. The study of these reactions has

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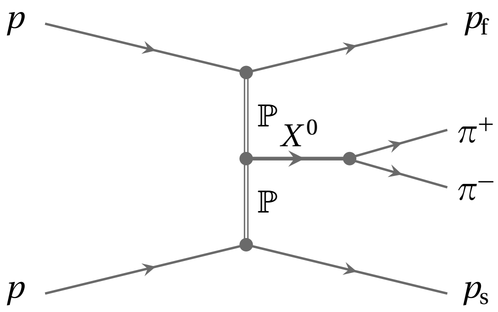

Figure 1: Central production.

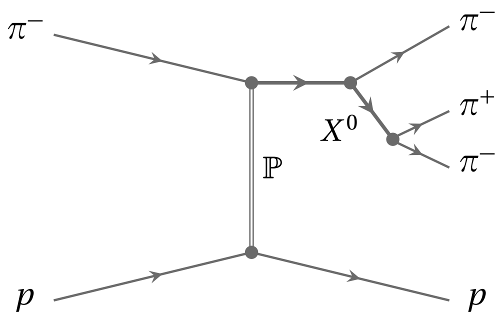

Figure 2: Diffractive Dissociation.

a long tradition at CERN, starting from the first evidence for the process at the ISR[2] [5]. Several groups decomposed the data recorded at the ISR (e.g. [6]) and later at the Omega spectrometer at SPS (e.g. [7]) into partial-wave amplitudes in order to extract the resonant content of the *S*-wave. However, the quality of the data only allowed the interpretation of the *S*-wave intensity, disregarding the relative phase with respect to other waves which provides additional input to disentangle resonances from non-resonant components. COMPASS data surpass previous experiments in terms of amount and precision. In addition, all possible decay modes are accessible with the versatile experimental setup. We will focus here on charged pion and kaon final-states.

A novel method to access the scalar meson spectrum was developed for the analysis of diffractively dissociated pions into three-pion final-states on a proton target (cf. Figure 2). Subsequent two-body decays with intermediate di-pion resonances, the so-called isobars X^0, have to be assumed in order to formulate amplitudes for a partial-wave decomposition of these data. In conventional analyses (e.g. [8]), the parametrisation of the isobars had to be fixed beforehand. Isolated and well-studied resonances, like the $\rho^0(770)$, are parametrised with relativistic Breit-Wigner functions. On the other hand, considerable bias had to be introduced in the scalar sector, where established models for the $\pi\pi$ *S*-wave [9] are separated from narrow isobar components, e.g. for the $f_0(980)$, which are described by Breit-Wigner functions. The large data set recorded at COMPASS allows the model-independent extraction of di-pion amplitudes for each three-pion decay with definite spin and parity quantum numbers. This complementary approach may provide valuable insights into the hadron dynamics.

3. Central Production of Two-Pseudoscalar Meson Systems

A 190 GeV$/c$ proton beam impinging on a liquid hydrogen target was intended to study the central production of scalar mesons in COMPASS. The trigger on the recoil proton resulted in a large kinematic separation between the slow proton p_s and the other final-state particles measured in the forward spectrometer (cf. Figure 3). In contrast, pronounced baryon resonances in the $p_\mathrm{f}\pi^\pm$ subsystems indicate a dominant contribution from diffractive dissociation of the beam proton. A series of selection criteria was studied in order to enhance the centrally produced sample. Requiring a rapidity gap of at least two units between the fast proton p_f and the central di-pion system turned

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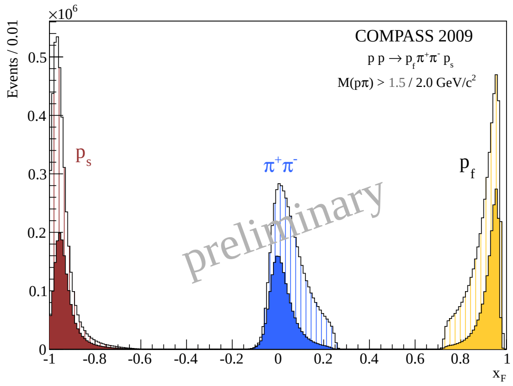


Figure 3: Feynman x_F distributions.

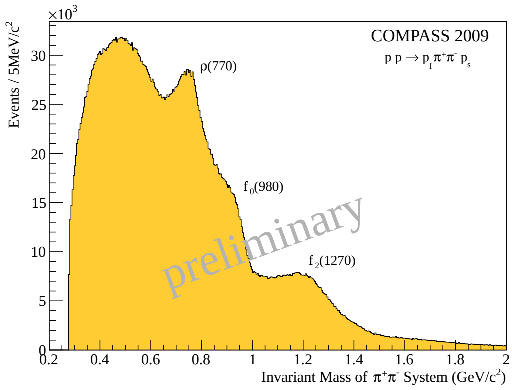


Figure 4: Central $\pi^+\pi^-$ invariant mass spectrum.

out to be more effective in suppressing diffractive processes than a mere selection based on the invariant mass as it was used in the past [7]. Nonetheless, the visible $\rho(770)$ signal in the invariant mass spectrum of the central di-pion system (cf. Figure 4) shows that the kinematic selection is not able to isolate a pure sample of events produced by double-Pomeron exchange at the centre-of-mass energy of $\sqrt{s} = 19\,\mathrm{GeV}/c^2$. A spin-parity decomposition of the selected sample is therefore essential.

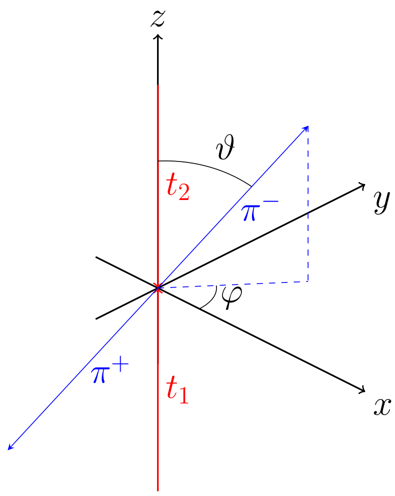


Figure 5: Definition of the decay angles

Assuming the central system X^0 to be produced by the collision of two space-like exchange particles, its decay can be fully described by the invariant mass and two additional variables. We define a coordinate system where the momentum transfer t_1 from the beam proton in the di-pion centre-of-mass frame forms the z-axis. The y-axis of the right-handed system is fixed by the normal to the production plane in the pp centre-of-mass. For the amplitude analysis, we chose the polar and azimuthal angles of the momentum-vector of the negative pion with respect to these axes and decompose the angular distributions into complex-valued amplitudes $Y^L_M(\vartheta,\varphi)$, which correspond to definite spin and parity quantum numbers. In order to avoid assumptions on the mass-dependence, we perform this expansion in narrow mass bins of $10\,\mathrm{MeV}/c^2$ of the central system. The parameters of the maximum likelihood fit, the so-called transition amplitudes T_{LM}, are therefore complex-valued constants which we determine independently in each mass bin. The quantum-mechanical interference between the amplitudes, expressed in the coherent sum over all terms, allows to extract their relative phases. Summarising, the intensity $I(\vartheta,\varphi)$ in one mass bin is expressed as

$$I(\vartheta,\varphi) = \left| \sum_{LM} T_{LM} Y^L_M(\vartheta,\varphi) \right|^2 .$$

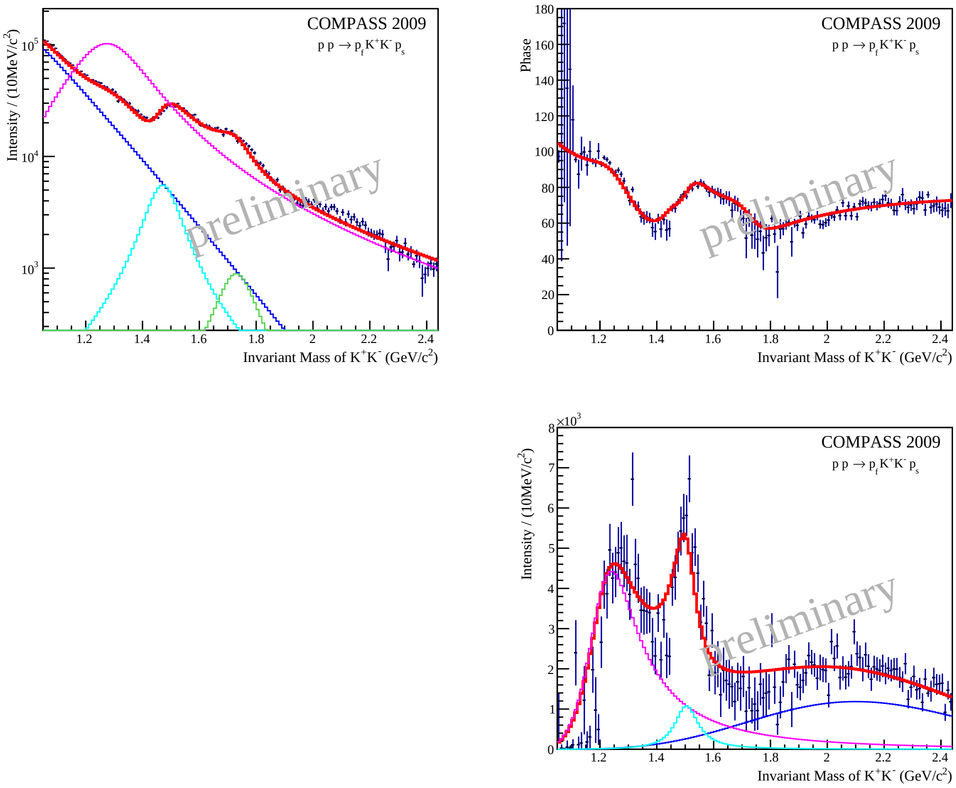


Figure 6: Mass-dependent parametrisation (red curve) of S_0-wave (top left) and D_0-wave (bottom right) intensities and their relative phase (top right) for the centrally produced K^+K^- system. The non-resonant (blue) and Breit-Wigner (other colours, see text) contributions to the intensity spectra are indicated.

The comparison of the measured angular distributions with a weighted Monte Carlo sample shows that the infinite sum over the relative angular momenta can be truncated at $L \leq 2$; and over the magnetic quantum numbers at $M \leq 1$. A detailed description of the amplitudes and the treatment of the inherent mathematical ambiguities of this decomposition can be found in [10]. From the results, we construct the spin-density matrix, where the diagonal elements $|T_{LM}|^2$ correspond to the measured intensities in each partial wave. This analysis reaches unprecedented precision, notably in the non-diagonal elements, which indicate the relative phases between the waves.

As a second step, the mass-dependence of the spin-density matrix is parametrised by a model. In each wave, this model consists of resonances, which are parametrised by relativistic Breit-Wigner functions, and a phenomenological description with a constant phase for the non-resonant contribution. The relative strengths and phases of each component is described by a complex-valued coefficient.

Figure 6 illustrates the results of the spin-parity decomposition of the centrally-produced K^+K^- system in $10\,\mathrm{MeV}/c^2$ mass bins together with one possible model description. The intensities of the S_0- and D_0-waves as well as their relative phases are depicted in dark blue together with their statistical error provided by the fit method. Even though the decomposition was performed independently in each mass bin, the continuity of the distributions shows the high precision of the results. Two distinct peaks corresponding to the $f_2(1270)$ and the $f_2'(1525)$ resonances are visible in the D_0-wave. Through the relative phase with respect to the S_0-wave, these well-known states provide an excellent interferometer to study the resonant components. No additional $f_2(2150)$ [11] was required to match the mass-dependence of the spin-density matrix.

Three scalar resonances are used for this model, namely the $f_0(1370)$, the $f_0(1500)$ and the $f_0(1710)$. For this example, the first state has an unusually large contribution, which has its roots in the region near threshold. There, we used only a non-resonant description, even though the coupling to $f_0(980)$ should be large. Fits with an additional Breit-Wigner function altered the ratios substantially, systematic studies on the model dependence of the results are ongoing. In particular, a four-momentum transfer-dependent analysis is currently studying effects of the production mechanism on the observed resonances. Ultimately, a coupled-channel analysis of $\pi\pi$ and $K\bar{K}$ systems will be able to solve the remaining ambiguities at threshold.

4. Extraction of Two-Body Amplitudes from Diffractive Dissociation

A completely new approach to the scalar meson spectrum is enabled by the large data set of diffractively produced three-pion final-states recorded at the COMPASS experiment with a 190 GeV/c π^- beam impinging on a proton target. A detailed partial-wave analysis of about 50 million events (cf. Figure 7) is performed in 20 MeV/c^2 wide mass bins as well as in bins of the squared four-momentum transfer t [12, 13]. The amplitude for the decay of an excited state into three pions is modelled via sequential two-body decays, which is well justified by the distinct structures visible in the Dalitz-plot (cf. Figure 8). Even though the $\rho(770)$ and the $f_2(1270)$ can be safely approximated by Breit-Wigner functions, considerable assumptions on the $\pi\pi$ S-wave have to be made in the traditional analysis. In addition to a parametrised $(\pi\pi)_S$ amplitude [9], the narrow resonances $f_0(980)$ and $f_0(1500)$ were treated as separate isobars to allow for a possible variation in the relative phases of the contributions (cf. Figure 9).

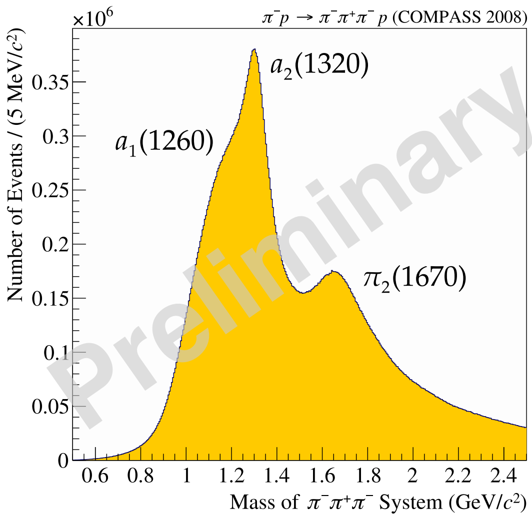


Figure 7: Invariant mass of the $\pi^-\pi^+\pi^-$ system.

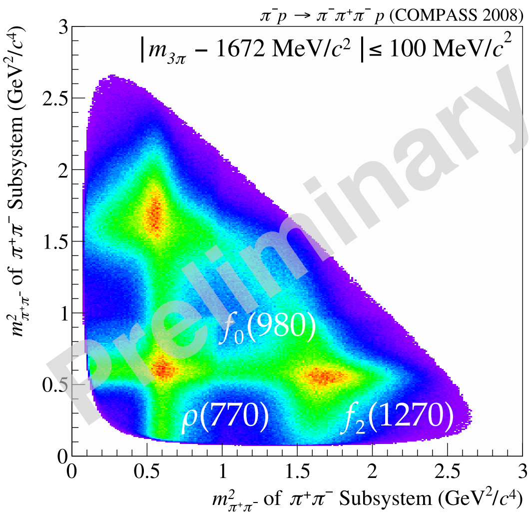


Figure 8: Dalitz plot for the $\pi_2(1670)$ region.

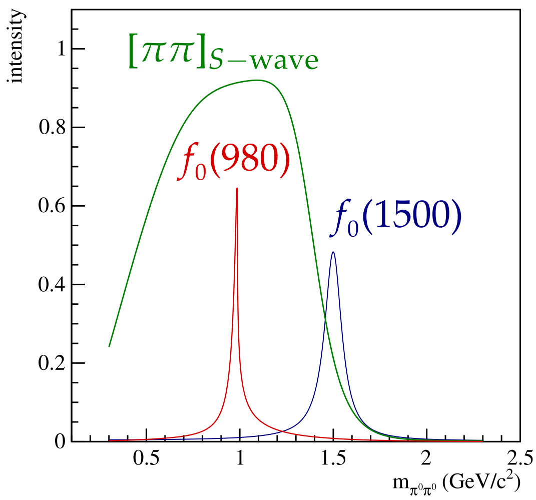


Figure 9: Parametrisation of isobar amplitudes.

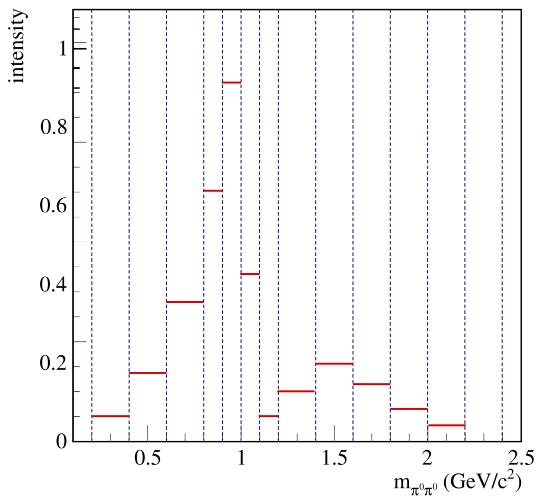


Figure 10: Constant amplitudes in $m_{\pi\pi}$ mass bins.

88 partial-waves with a maximal total spin of 6 were used to decompose the data, the largest wave-set to date. For the novel method described here, 7 of these partial-waves with scalar isobars were replaced by amplitudes with piece-wise constant functions in $40\,\mathrm{MeV}/c^2$ bins of the di-pion mass. Steps of $10\,\mathrm{MeV}/c^2$ were used in the region around $1\,\mathrm{GeV}/c^2$ in order to obtain more detailed information about the coupling to the narrow $f_0(980)$ resonance (cf. Figure 10). As a result, a complex-valued isobar amplitude is extracted from the data for each three-pion mass bin and each of the so-called 'deisobarred' partial-waves. This significant increase in the number of fit parameters is balanced by a drastic reduction of model bias. A report on the details of the analysis can be found in [14].

A Monte Carlo sample with isobaric shapes was generated for one exemplary bin of the three-pion mass in order to evaluate this new technique. Given one partial-wave with a fixed isobar parametrisation is used as reference, the remaining isobar shapes are well reproduced by the fit. Not only intensity spectra, but complex-valued amplitudes for the involved di-pion subsystems are obtained for different partial-waves at the same time.

Figure 11 shows one exemplary result of this method for real data. For the three-pion system with the quantum numbers $J^{PC}M = 0^{-+}0$ decaying into a bachelor pion and a scalar two-pion system in a relative S-wave, we obtain the mass-dependence of the two-pion amplitude. The analysis was performed independently in three-pion mass bins from 1.1 to $2.0\,\mathrm{GeV}/c^2$, but the correlation of the $\pi(1800)$ with the scalar resonances $f_0(980)$ or $f_0(1500)$ is obvious. The depth of this result is illustrated in Figure 12, where we show the amplitude of the $\pi\pi$ S-wave for only one mass bin of Figure 11. A distinct peak followed by a characteristic drop in the intensity spectrum around $1\,\mathrm{GeV}/c^2$ marks the $f_0(980)$ resonances, another peak is visible at the position of the $f_0(1500)$ meson. In addition, the Argand plot is showing two full circles when running through the entire mass range, a clear sign for resonant behaviour. On the other hand, these amplitudes are not yet properly normalised and include the phase motion of the mother three-pion resonance. Only a model that describes the mass dependence of both two- and three-pion systems at the same time may be able to extract pure $\pi\pi$ amplitudes.

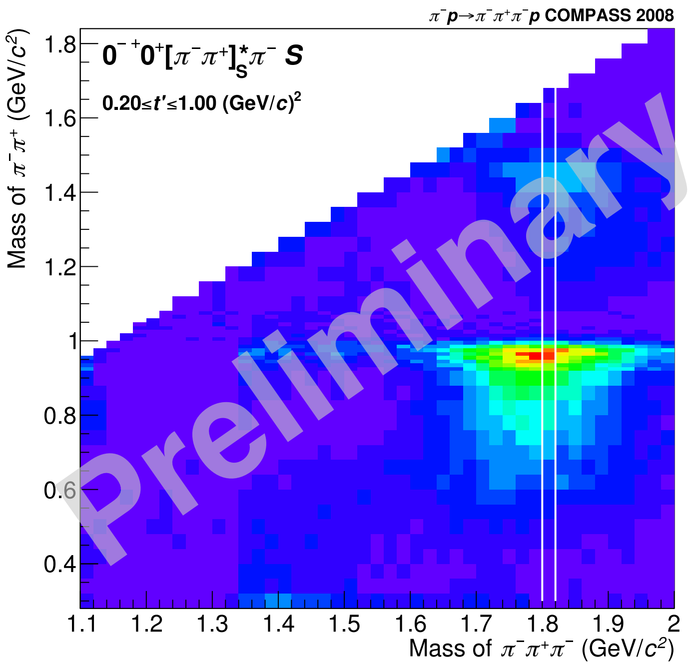
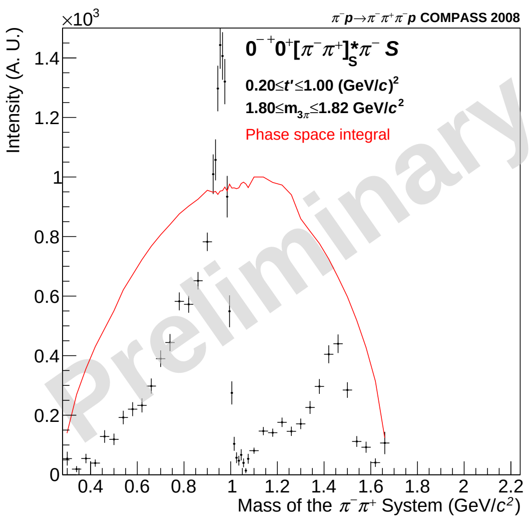
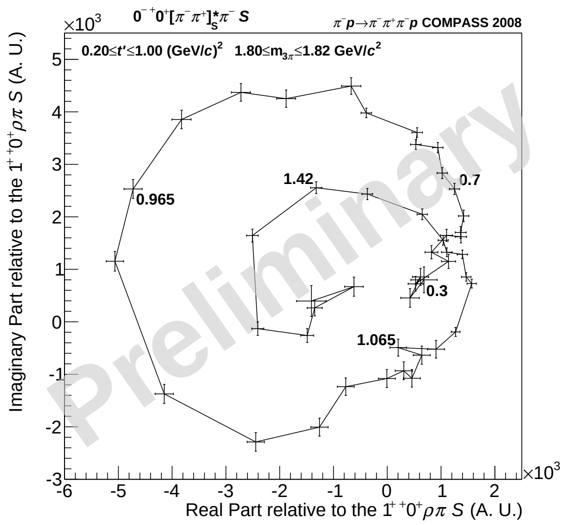


Figure 11: Intensity of the $0^{-+}0^+[\pi\pi]^*_S\,\pi S$ wave as a function of the three- and two-pion mass.



(a) Intensity



(b) Argand plot

Figure 12: $[\pi\pi]^*_S$ amplitude at $m_{3\pi} = 1.80\,\mathrm{GeV}/c^2$ (white lines in Figure 11).

5. Conclusion

COMPASS is a unique experiment to study light-quark hadron spectroscopy with large data samples, high precision and various accessible decay channels. Especially in the scalar isoscalar meson sector, a combination of different approaches will be able to shed light on the many remaining open questions. The full potential of the partial-wave analysis is explored for centrally produced final-states for the first time. In addition, a novel treatment of diffractive dissociation data was developed in order to extract the underlying meson dynamics. The combination of the results with rigorous theoretical models [15] will be able to clarify the discussion of the scalar meson spectrum.

Since light mesons are the final states of most high-energy physics experiments, an improved knowledge about their resonant behaviour is beneficial for many analyses. As an example, recent measurements of CP violation in B-decays suggest contributions from resonant processes [16]. In addition, the lessons learned on resonances and threshold effects in the light-quark sector may be important for the interpretation of the exotic XYZ states in heavy-quark spectroscopy.

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