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Photoproduction at COMPASS

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Abstract
COMPASS is a multipurpose fixed target experiment at CERN using muon and hadron beams of high intensity for study of hadron structure and hadron spectroscopy. The precision test of the chiral perturbation theory predictions using charged pion scattering off a virtual photon with small momentum transfer is one of the main points of the COMPASS physics programme. The important results for the charged pion polarizability, radiative widths of $a_2(1320)$ and $\pi_2(1670)$ mesons and the cross section dynamics for the reactions $\gamma^*\pi^- \to 3\pi$ are obtained recently. The new results and perspectives for search for photo(lepto-)production of exotic charmonium-like states are also reported.

Keywords
COMPASS; photoproduction; Primakoff reactions; exotic charmonia.

1 Test of chiral perturbation theory predictions in meson-photon scattering

The Chiral Perturbation Theory (χPT) is one of the most successful effective field theories of strong interaction at low energies. It is based on the low-momentum expansion of the QCD lagrangian. The triplet of π-mesons in the limit $m_u, m_d \to 0$ or the octet of pseudoscalar mesons (π, K, η) under the SU(3) symmetry assumption that $m_u, m_d, m_s \to 0$ are the Goldstone bosons. The $\pi(K)\gamma$ interaction together with the $\pi\pi(KK)$ scattering is one of the main instruments for control of applicability of the χPT.

Stringent test of χPT predictions in the pion-photon scattering with different final states is one of the main points of the COMPASS physics programme [1, 2]. The Primakoff reaction, a scattering of a beam pion off a quasi-real photon of the nuclear Coulomb field, is used for that. The Primakoff cross section $\sigma_{\pi Z}$ can be connected to the $\pi\gamma$ cross section using the equivalent-photon approximation:

$$\frac{d\sigma_{\pi Z}}{ds\, dQ^2\, d\Phi_n} = \frac{Z^2\alpha}{\pi(s - m_\pi^2)}\, F^2(Q^2)\, \frac{Q^2 - Q^2_{\rm min}}{Q^4}\, \frac{d\sigma_{\pi\gamma}}{d\Phi_n}. \tag{1}$$

Here, the cross section for the process πZ$\to XZ$ is factorized into the quasi-real photon density provided by the nucleus of charge Z and $\sigma_{\pi\gamma\to X}$ the cross section for the embedded $\pi\gamma \to X$ reaction. The function $F(Q^2)$ is the electromagnetic form factor of the nucleus and $d\Phi_n$ is the n-particle phase-space element of the final-state system X. The minimum value of the negative 4-momentum transfer squared, $Q^2 = -(p^\mu_{\rm beam} - p^\mu_X)^2$, is $Q^2_{\rm min} = (s - m_\pi^2)^2/(4E^2_{\rm beam})$ for a given final-state mass $m_X = \sqrt{s}$. For scattering of the negative pions of $E_{\rm beam}$=190 GeV off a nuclear target at COMPASS the typical values of $Q^2_{\rm min}$ are about 1 (MeV/c)^2.

1.1 Pion polarizability

Pion electric α_π and magnetic β_π polarizabilities characterize the pion interacting as a complex QCD system with external electromagnetic fields. They are fundamental parameters of pion physics and can be probed in the $\pi\gamma$ Compton scattering. In the two-loop approximation, for the charged pion polarizabilities, χPT predicts $\alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \times 10^{-4}$ fm^3 and $\alpha_\pi + \beta_\pi = 0.16 \times 10^{-4}$ fm^3 [3].

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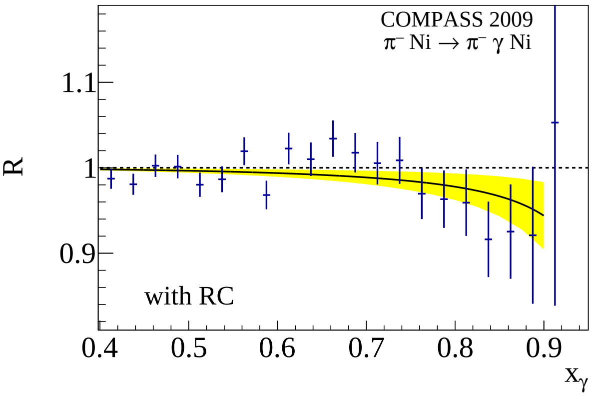

Fig. 1: The measured ratio R_π.

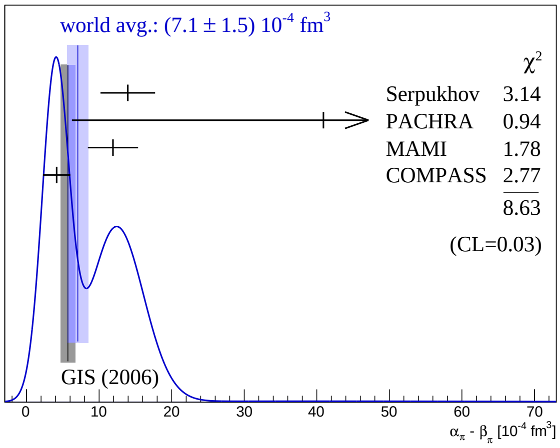

Fig. 2: $\alpha_\pi - \beta_\pi$ measured assuming $\alpha_\pi + \beta_\pi = 0$ in the dedicated experiments including COMPASS.

The first measurement of the pion polarizabilities was performed via the Primakoff scattering by the SIGMA-AYAKS Collaboration [4].

For the pion polarizability measurement at COMPASS the reaction $\pi^-\mathrm{Ni} \to \pi^-\mathrm{Ni}\gamma$ was used. A muon beam with similar parameters was used to study and control systematic effects. About 63 000 exclusive $\pi^-\gamma$ events in the kinematic range $p_T > 40$ MeV/c, $m_{\pi\gamma} < 3.5\ m_\pi$, $Q^2 < 1.5 \times 10^{-3}$ GeV$^2/c^2$ and $0.4 < x_\gamma (= E_\gamma/E_{beam}) < 0.9$ were used for pion polarizability extraction under the assumption $\alpha_\pi + \beta_\pi = 0$. Here $m_{\pi\gamma}$ is the mass of the final $\pi\gamma$ state, p_T is the transverse momentum of the scattered pion, E_γ is the energy of the produced photon in the laboratory system. The polarizability is determined from the x_γ dependence of the ratio R_π of the measured cross section $\sigma_{\pi Z\to\pi Z\gamma}$ to the calculated one for the point-like pion

$$R_\pi = \left(\frac{d\sigma_{\pi Z\to\pi Z\gamma}}{dx_\gamma}\right) \Bigg/ \left(\frac{d\sigma^0_{\pi Z\to\pi Z\gamma}}{dx_\gamma}\right) = 1 - \frac{3}{2}\cdot\frac{m_\pi^3}{\alpha}\cdot\frac{x_\gamma^2}{1-x_\gamma}\alpha_\pi. \tag{2}$$

This ratio is presented in Fig. 1 from which we obtained the result $\alpha_\pi = (2.0 \pm 0.6_{\mathrm{stat}} \pm 0.7_{\mathrm{syst}}) \times 10^{-4}$ fm^3, compatible with the expectation from χPT [3,5]. The COMPASS result together with results of the previous dedicated measurements is presented in Fig 2. The details of the analysis can be found in Ref. [6]. The uncertainty of presented the result is still by a factor two larger than the accuracy of the χPT prediction. For this reason COMPASS took data for a full year in 2012. Analysis of these data is still ongoing. As the result, the improved accuracy of α_π measurement under assumption $\alpha_\pi + \beta_\pi = 0$ and independent determination of α_π and β_π are expected.

1.2 Kaon polarizability

Since the kaon is a more compact and rigid object than the pion, it would be natural to expect smaller values for kaon polarizabilities. The prediction of the χPT states that for the charged kaon the polarizability α_K is $(0.64 \pm 0.10) \times 10^{-4}$ fm^3 under the assumption $\alpha_K + \beta_K = 0$ [7]. While the prediction of the quark confinement model is rather different: $\alpha_K = 2.3 \times 10^{-4}$ fm^3, $\alpha_K + \beta_K = 1 \times 10^{-4}$ fm^3 [8]. As for the experimental results, only the upper limit $\alpha_K < 200 \times 10^{-4}$ fm^3 (CL = 90%) has been established from the analysis of X-rays spectra of kaonic atoms [9].

COMPASS can measure the kaon polarizability with the same technique adopted for pions, using the 2.4% kaon contamination in the pion beam and the two Cherenkov detectors (CEDARs) to identify the beam particle, but:

1. the cross section is an order of magnitude smaller;

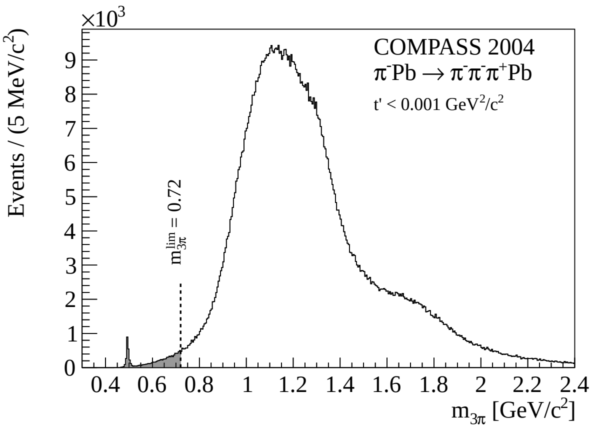

Fig. 3: The invariant mass spectrum of the $\pi^-\pi^+\pi^-$ final-state for events with low momentum transfer (below 10^{-3} (GeV/c)^2).

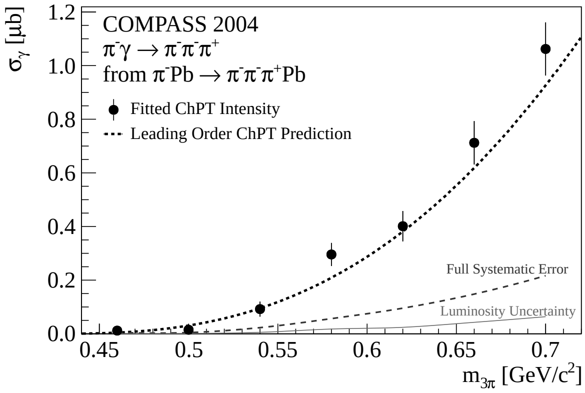

Fig. 4: The cross section for reaction $\pi^-\gamma \to \pi^-\pi^-\pi^+$ as a function of the total collision energy $\sqrt{s} = m_{3\pi}$.

2. the purity of particle identification provided by CEDARs is not enough;
3. the kinematic gap between the threshold and the first resonance K*(892) is much smaller than for the pion, that also limits the statistics potentially available for the analysis.

Possibility to measure the kaon polarizability using a dedicated RF-separated hadron beam enriched by kaons [10] is under investigation.

1.3 Chiral dynamics in $\pi^-\gamma \to 3\pi$ reactions and radiative width of $a_2(1320)$ and $\pi_2(1670)$ mesons

The cross sections of the reactions $\gamma\pi^- \to \pi^-\pi^+\pi^-$ and $\gamma\pi^- \to \pi^-\pi^0\pi^0$ are governed by the chiral $\pi\pi$ interaction [11]. The first reaction was studied at COMPASS via Primakoff scattering of the negative pion beam off a lead target. The invariant mass spectrum of the $\pi^-\pi^+\pi^-$ final-state for events with momentum transfer below 10^{-3} (GeV/c)^2 is shown in Fig. 3. The mass range from the threshold up to 5m$_\pi$ was used for the cross section determination. A partial wave analysis was performed to extract the intensity of the chiral contribution. In order to perform an absolute normalization the integrated beam flux was determined with good precision by using the decay $K^- \to \pi^-\pi^+\pi^-$ of beam kaons which fraction in the COMPASS hadron beam is precisely known. The result obtained for the cross section (Fig. 4) is in agreement with the tree-level expectation from the χPT [12].

The same data were used to study the photoproduction of the resonances $a_2(1320)$ and $\pi_2(1670)$. Since two production mechanisms are possible: Primakoff production via virtual photon exchange and diffractive production via pomeron exchange, the partial wave analysis procedure was used in order to estimate the electromagnetic contribution. The radiative widths obtained are: $\Gamma_{\pi\gamma}(a_2(1320)) = (358 \pm 6_{\text{stat}} \pm 42_{\text{syst}})$ keV and $\Gamma_{\pi\gamma}(\pi_2(1670)) = (118 \pm 11_{\text{stat}} \pm 27_{\text{syst}})$ keV. Radiative corrections to the π^-Pb cross section are the main contribution to the systematics. The detailed description of the analysis procedure can be found in Ref. [13]. The data for the process $\gamma\pi^- \to \pi^-\pi^0\pi^0$ collected with a nickel target are under analysis.

1.4 Chiral anomaly in $\pi^-\gamma \to \pi^-\pi^0$ process

The reaction $\pi^-\gamma \to \pi^-\pi^0$ allows one to determine the chiral anomaly amplitude $F_{3\pi}$, for which the chiral theory makes an accurate prediction already at the leading order by relating $F_{3\pi}$ to the neutral pion decay constant F_π:

$$F_{3\pi} = \frac{eN_c}{12\pi^2 F_\pi^3} = 9.78 \pm 0.05 \text{ GeV}^{-3}, \tag{3}$$

where e is the electric charge and N_c is the number of colors. The reaction has already been examined in the Primakoff scattering at the SIGMA spectrometer [14], where in the relevant region of $s < 10\ m_\pi^2$ only about 200 events were found, and in the πe scattering [15]. The corresponding results for $F_{3\pi}$ are (10.7 ± 1.2) GeV^{-3} and (9.6 ± 1.1) GeV^{-3}, respectively, and have much lower precision than theoretical predictions.

Acceptance of the COMPASS setup covers large range of the $\pi^-\pi^0$ invariant mass, in particular including the $\rho(770)$-meson peak. Using the approach based on the dispersive relations the data with $\pi^-\pi^0$ mass up to 1 GeV/c^2 can be used for extraction of the $F_{3\pi}$ constant [16]. The corresponding analysis is in progress.

2 Photoproduction of exotic charmonia

In the last years a lot of new charmonium-like hadrons, so-called the XYZ states, at masses above 3.8 GeV/c^2 were discovered. Several interpretations of the new states do exist: pure quarkonia, tetraquarks, hadronic molecules, hybrid mesons with a gluon content, etc. But at the moment many basic parameters of the XYZ states have not been determined yet. New experimental input is required to distinguish between the models that provide different interpretations of the nature of exotic charmonia. COMPASS has a unique possibility to contribute to XYZ physics by investigating photo(lepto-)production of these states. The experimental data obtained for positive muons of 160 GeV/c (2002–2010) or 200 GeV/c momentum (2011) scattering off solid ^{6}LiD (2002–2004) or NH_3 targets (2006–2011) were used for looking for exotic charmoia production.

2.1 Exclusive photoproduction of $X(3872)$

The exotic hadron $X(3872)$ was discovered by the Belle collaboration in 2003 [17]. Its mass is 3871.69 $\pm$ 0.17 MeV/c^2 that is very close to the $D^0\bar{D}^{*0}$ threshold. The decay width of this state was not determined yet, only an upper limit for the natural width $\Gamma_{X(3872)}$ of about 1.2 MeV/c^2 (CL=90%) exists. The quantum numbers J^{PC} of the $X(3872)$ were determined by LHCb to be 1^{++} [18, 19]. Approximately equal probabilities to decay into $J/\psi 3\pi$ and $J/\psi 2\pi$ final states indicate large isospin symmetry breaking.

Photoproduction of the $X(3872)$ at COMPASS was observed in the exclusive reaction $\mu^+ N \rightarrow \mu^+ N' X(3872)\pi^\pm \rightarrow \mu^+ N' J/\psi \pi^+\pi^-\pi^\pm$. The invariant mass spectrum of the $J\psi\pi^+\pi^-$ subsystem is shown in Fig. 5 (two entries per event). It demonstrates two peaks corresponding to production and decay of the $\psi(2S)$ and $X(3872)$ states. Statistical significance of the $X(3872)$ signal depends on the applied selection criteria and varies from 4.5σ to 6σ. The cross section of the reaction $\gamma N \rightarrow N' X(3872)\pi^\pm$ multiplied by the branching fraction for the decay $X(3872) \rightarrow J/\psi\pi^+\pi^-$ was found to be $71 \pm 28_{\text{stat}} \pm 39_{\text{syst}}$ pb in the covered kinematic range with a mean value of $\sqrt{s_{\gamma N}} = 14$ GeV. It was also found that the shape of the invariant mass distribution for $\pi^+\pi^-$ produced form the $X(3872)$ decay looks very different from previous results obtained by Belle, CDF, CMS and ATLAS. It could be an indication that the $X(3872)$ object could contain a component with quantum numbers different from 1^{++}. More detailed information can be found at Ref. [20].

2.2 Photoproduction of $Z_c^\pm(3900)$

The $Z_c^\pm(3900)$ state discovered via its decay into $J/\psi\pi^\pm$ by BESIII [21] and Belle [22] is one of the most promising tetraquark candidate. At COMPASS the search for $Z_c^\pm(3900)$ was performed in the exclusive reaction $\mu^+ N \rightarrow \mu^+ N' Z_c^\pm(3900) \rightarrow \mu^+ N' J/\psi\pi^\pm$. The $J/\psi\pi^\pm$ mass spectrum for exclusive events (see Fig. 6) does not exhibit any statistically significant resonant structure around the nominal mass of the $Z_c^\pm(3900)$. Therefore an upper limit was determined for the product of the cross section of the $\gamma N \rightarrow N' Z_c^\pm(3900)$ process and the relative $Z_c^\pm(3900) \rightarrow J/\psi\pi^\pm$ decay probability to be 52

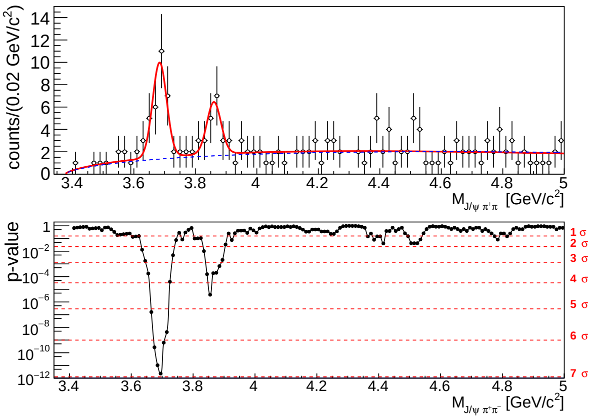

Fig. 5: The $J/\psi\pi^+\pi^-$ invariant mass distribution for the $J/\psi\pi^+\pi^-\pi^\pm$ final state (top). The statistical significance of the signal (bottom).

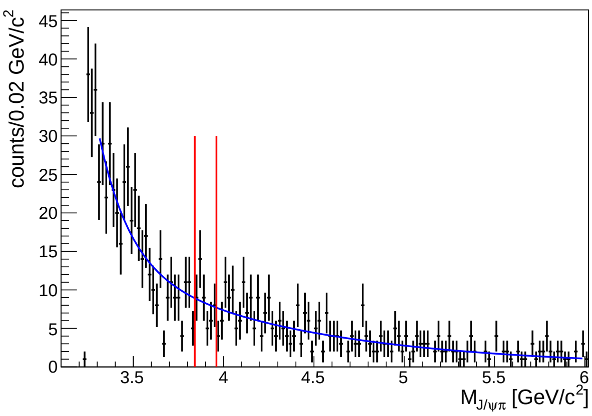

Fig. 6: The mass spectrum of the $J\psi\pi^\pm$ subsystem [23]. The searching range is shown by the vertical lines while the curve represents the background fitting.

pb (CL=90%) [23]. An upper limit for the partial width of the $Z_c^\pm(3900) \to J/\psi\pi^\pm$ decay was also established basing on the production model described in [24].

The $J/\psi\pi^\pm$ mass spectrum measured by COMPASS was used in [25] to estimate the production rate of the $Z_c^\pm(4200)$, another exotic state also observed by Belle [26].

2.3 New possibilities

Upgrade of the COMPASS setup related with the data taking in 2016–2017 within the framework of the GPD program [2] provides new opportunities to search for direct production of exotic charmonium-like states. A new, 2.5 m long liquid hydrogen target ($\sim 0.27X_0$) is much more transparent for photons than the ^{6}LiD and NH_3 targets used before. The target is surrounded by a 4 m long recoil proton detector which can be used to reconstruct and identify recoil protons via time-of-flight and energy loss measurements. The existing system of two electromagnetic calorimeters is extended by installation of the new large-aperture calorimeter. With the new calorimetry system one can expect much better selection of exclusive events. Searching for production of the neutral $Z_c^0(3900)$, discovered by BES-III, decaying into $J/\psi\pi^0$ will be possible. The final states decaying to the $\chi_{c0,1,2}$ -mesons could also be studied.

In more detail the question of the study of exotic charmonia at COMPASS is discussed at Ref. [27].

3 Conclusions

COMPASS is a unique apparatus to test of the chiral perturbation theory predictions in meson-photon scattering. Large data sets were collected for various final states. The important results for the charged pion polarizability, chiral dynamics of the $\gamma\pi^- \to \pi^-\pi^+\pi^-$ cross section and the radiative widths of the $a_2(1320)$ and $\pi_2(1670)$ mesons are published. More results are expected.

Photo(lepto-)production of exotic charmonia is a new direction in physics of the XYZ states started by COMPASS. The $X3872$ meson became the first exotic charmonium-like state observed in photo-production. The search results for exclusive production of the $Z_c^\pm(3900)$ state in the charge-exchange reaction are also reported.

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