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Search for exclusive photoproduction of $Z_c^\pm(3900)$ at COMPASS

The COMPASS Collaboration

Abstract

A search for the exclusive production of the $Z_c^\pm(3900)$ hadron by virtual photons has been performed in the channel $Z_c^\pm(3900) \rightarrow J/\psi\pi^\pm$. The data cover the range from 7 GeV to 19 GeV in the centre-of-mass energy of the photon-nucleon system. The full set of the COMPASS data set collected with a muon beam between 2002 and 2011 has been used. An upper limit for the ratio $BR(Z_c^\pm(3900) \rightarrow J/\psi\pi^\pm) \times \sigma_{\gamma N \rightarrow Z_c^\pm(3900) N} / \sigma_{\gamma N \rightarrow J/\psi N}$ of 3.7×10^{-3} has been established at the confidence level of 90%.

Keywords: COMPASS, $Z_c(3900)$, photoproduction, tetraquark.

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The $Z_c^\pm(3900)$ state was recently discovered by the BES-III and Belle Collaborations in $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ reactions at $\sqrt{s} = 4.26$ GeV [1, 2] via the decay channel

$$Z_c^\pm(3900) \rightarrow J/\psi \pi^\pm. \quad (1)$$

It has been interpreted as a tetraquark state [3–6], although other explanations like a molecular state [7–11], a cusp effect [12] and an initial-single-pion-emission mechanism [13] were also proposed. According to the vector meson dominance (VMD) model, a photon may behave like a J/ψ so that a $Z_c^\pm(3900)$ can be produced by the interaction of an incoming photon with a virtual charged pion provided by the target nucleon

$$\gamma N \rightarrow Z_c^\pm(3900) N. \quad (2)$$

The corresponding diagram is shown in Fig. 1a.

Based on the VMD model, the authors of Ref. [14] predict a sizable cross section of the reaction in Eq. (2) for $\sqrt{s_{\gamma N}} \sim 10$ GeV. Under the assumption that the decay channel of Eq. (1) is dominant and that the total width Γ_{tot} of the $Z_c^\pm(3900)$ particle is $46 \text{ MeV}/c^2$, as measured by BES-III, the cross section reaches a maximum value of 50 nb to 100 nb at $\sqrt{s_{\gamma N}} = 7$ GeV. The J/ψ production in photon-nucleon interactions at COMPASS covers the range $\sqrt{s_{\gamma N}}$ from 7 GeV to 19 GeV and thus can be used to also study $Z_c^\pm(3900)$ production and to estimate the partial width $\Gamma_{J/\psi\pi}$ of the decay channel $Z_c^\pm(3900) \rightarrow J/\psi \pi^\pm$.

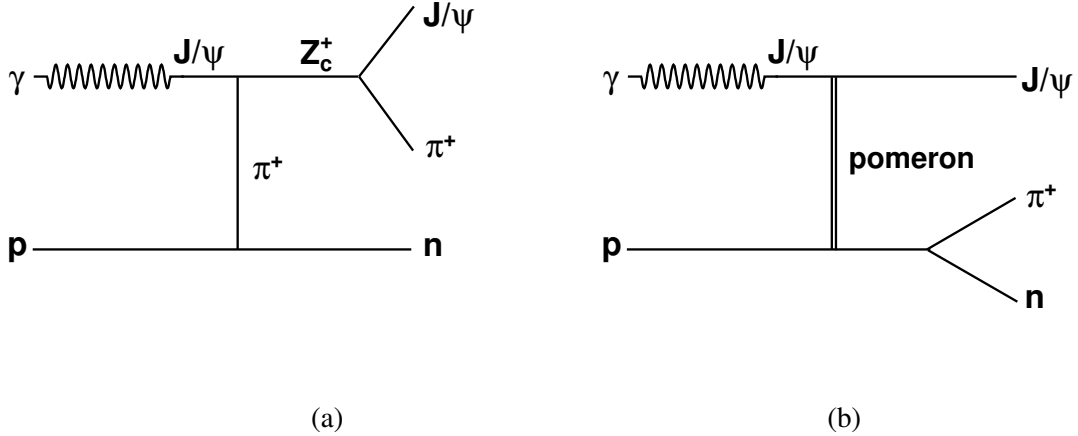


Fig. 1: Diagrams for (a) $Z_c^+(3900)$ production via virtual π^+ exchange and (b) $J/\psi\pi^+$ production via pomeron exchange.

The COMPASS experiment [15] is situated at the M2 beam line of the CERN Super Proton Synchrotron. The data used in the present analysis were obtained scattering positive muons of 160 GeV/c (2002–2010) or 200 GeV/c momentum (2011) off solid ${}^6\text{LiD}$ (2002–2004) or NH_3 targets (2006–2011). The longitudinally or transversely polarised targets consisted of two (2002–2004) or three (2006–2011) cylindrical cells placed along the beam direction. Polarisation effects were canceled out by combining data with opposite polarisation orientations. Particle tracking and identification were performed in a two-stage spectrometer, covering a wide kinematic range. The trigger system comprises hodoscope counters and hadron calorimeters. Beam halo was rejected by veto counters upstream of the target.

In the analysis presented in this Letter, the reaction

$$\mu^+ N \rightarrow \mu^+ Z_c^\pm(3900) N \rightarrow \mu^+ J/\psi \pi^\pm N \rightarrow \mu^+ \mu^+ \mu^- \pi^\pm N \quad (3)$$

was searched for. In order to select samples of exclusive $\mu^+ J/\psi \pi^\pm$ events, a reconstructed vertex in the target region with an incoming beam track and three outgoing muon tracks (two positive and one

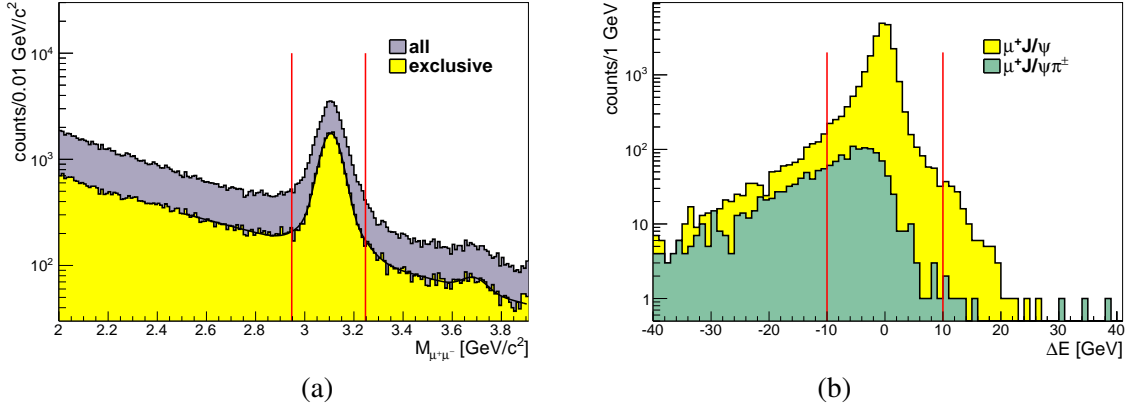


Fig. 2: (a) The dimuon mass distribution for all dimuons produced in muon-nucleon scattering (blue, upper curve), and for exclusively produced dimuons (yellow, lower curve). (b) Distribution for the energy balance ΔE in the reactions Eq. (7) (yellow, upper curve) and Eq. (3) (green, lower curve).

negative) is required. Tracks are attributed to muons if they cross more than 15 radiation lengths of material. Only the events with exactly three muons and one pion in the final state were selected. A pair of muons is treated as J/ψ candidate if the difference between its reconstructed mass $M_{\mu^+\mu^-}$ (Fig. 2a) and the nominal J/ψ mass is less than $150 \text{ MeV}/c^2$. In case both $\mu^+\mu^-$ combinations satisfy this condition, the event is rejected. Except for the tiny recoil of the target nucleus, the sum of the scattered muon energy, $E_{\mu'}$, and the energies of produced J/ψ and π^\pm mesons, $E_{J/\psi}$ and E_{π^\pm} , should be equal to the beam energy E_b for the exclusive reaction of Eq. (3). The distribution of events as a function of the energy balance $\Delta E = E_{\mu'} + E_{J/\psi} + E_{\pi^\pm} - E_b$ is presented in Fig. 2b. With the experimental energy resolution of about 3 GeV, the energy balance is required to be $|\Delta E| < 10 \text{ GeV}$. The distribution of the negative squared four-momentum transfer $Q^2 = -(P_b - P_{\mu'})^2$ is shown in Fig. 3a. Here $P_{\mu'}$ and P_b are four-momenta of the scattered and incident muons, respectively. The momentum of the produced pion is required to be larger than $2 \text{ GeV}/c$ in order to reduce the background of exclusive events with a J/ψ and a π^\pm in the final state produced via pomeron exchange (Fig. 1b). The total number of selected $\mu^+ J/\psi \pi^+$ and $\mu^+ J/\psi \pi^-$ events is 565 and 405, respectively. The distribution of the centre-of-mass energy of the photon-nucleon system $\sqrt{s_{\gamma N}}$ is shown in Fig. 3b.

The mass spectrum for $J/\psi \pi^\pm$ events is shown in Fig. 4a. It does not exhibit any statistically significant resonant structure around $3.9 \text{ GeV}/c^2$. The observed number of events $N_{J/\psi \pi}$ in the signal range $3.84 \text{ GeV}/c^2 < M_{J/\psi \pi^+} < 3.96 \text{ GeV}/c^2$ is treated as consisting of an a priori unknown Z_c^\pm (3900) signal N_{Z_c} and a background contribution N_{bkg} . According to the method described in Ref. [16], the probability density function $g(N_{Z_c})$ is given by

$$g(N_{Z_c}) = n \int_0^\infty \frac{e^{-(N_{Z_c} + N_{bkg})} (N_{Z_c} + N_{bkg})^{N_{Z_c}}}{N_{Z_c}!} f(N_{bkg}) dN_{bkg}, \quad (4)$$

where n is a normalization constant and the probability density function $f(N_{bkg})$, assumed to be Gaussian, describes the background contribution in the signal interval. The mean value and the Gaussian width of $f(N_{bkg})$ are estimated by fitting a sum of two exponential functions ($A \cdot e^{-aM_{J/\psi \pi}} + B \cdot e^{-bM_{J/\psi \pi}}$) to the $J/\psi \pi^\pm$ mass spectrum in the range $3.3 \text{ GeV}/c^2 < M_{J/\psi \pi^+} < 6.0 \text{ GeV}/c^2$ excluding the signal region. The fitted function is shown as a line in Fig. 4a. The number of expected background events in the signal region is 49.7 ± 3.4 while 51 is observed. The upper limit $N_{Z_c}^{UL}$ for the number of produced Z_c^\pm (3900) events corresponding to a confidence level of $CL = 90\%$ is then determined from the expression

$$\int_0^{N_{Z_c}^{UL}} g(N_{Z_c}) = 0.9 \quad (5)$$

to be $N_{Z_c}^{UL} = 15.1$ events.

For the absolute normalization of the $Z_c^\pm(3900)$ production rate we estimated for the same data sample the number of exclusively produced J/ψ mesons from incoherent exclusive production in

$$\gamma N \rightarrow J/\psi N, \quad (6)$$

the cross section of which is known for our range of $\sqrt{s_{\gamma N}}$ [17]. The same selection criteria are applied for the exclusive production of the J/ψ mesons

$$\mu^+ N \rightarrow \mu^+ J/\psi N, \quad (7)$$

and $Z_c^\pm(3900)$ hadrons. To separate J/ψ production and non-resonant production of dimuons, the dimuon mass spectrum is fitted by a function consisting of three Gaussian (two to describe the J/ψ peak and one for the $\psi(2S)$ peak) and an exponential background under the peaks (see Fig. 2a). Finally 18.2×10^3 events of exclusive J/ψ production remain in the sample. The distribution of the squared transverse momentum p_T^2 of the J/ψ (Fig. 4b) for the exclusive sample is fitted by a sum of two exponential functions in order to separate the contributions from exclusive coherent production on the target nuclei and exclusive production on (quasi-)free target nucleons. The contribution from coherent production is found to be 30.3% for the ${}^6\text{LiD}$ target and 38.9% for NH_3 target (36.1% averaged over the sample). The amount of nonexclusive events in the exclusive incoherent sample is estimated to be about $30 \pm 10\%$. Since only the charged pion distinguishes the final state of process in Eq. (2) from the final state of the process in Eq. (6), the ratio R_a of their acceptances is in a first approximation equal to the acceptance for this pion. Based on previous COMPASS measurements and Monte Carlo simulations this ratio is about $R_a = 0.5$, averaged over all setup and target configurations. Thus we obtain the result

$$\frac{BR(Z_c^\pm(3900) \rightarrow J/\psi\pi^\pm) \times \sigma_{\gamma N \rightarrow Z_c^\pm(3900) N}}{\sigma_{\gamma N \rightarrow J/\psi N}} \Big|_{\langle\sqrt{s_{\gamma N}}\rangle=13.8 \text{ GeV}} < 3.7 \times 10^{-3}, \quad (8)$$

where BR denotes the branching ratio for the $Z_c^\pm(3900) \rightarrow J/\psi\pi^\pm$ decay channel. Assuming $\sigma_{\gamma N \rightarrow J/\psi N} = 14.0 \pm 1.6_{stat} \pm 2.5_{syst}$ nb as measured by the NA14 Collaboration for $\sqrt{s_{\gamma N}} = 13.7$ GeV [17], the result can be presented as

$$BR(Z_c^\pm(3900) \rightarrow J/\psi\pi^\pm) \times \sigma_{\gamma N \rightarrow Z_c^\pm(3900) N} \Big|_{\langle\sqrt{s_{\gamma N}}\rangle=13.8 \text{ GeV}} < 52 \text{ pb}. \quad (9)$$

The upper limits for the ratio of the cross sections in intervals of $\sqrt{s_{\gamma N}}$ are presented in Table 1.

The result shown in Eq. (9) can be converted into an upper limit for the partial width $\Gamma_{J/\psi\pi}$ of the decay in Eq. (1) based on the VMD model. According to Ref. [14] the cross section for the reaction in Eq. (2), averaged over the measured $\sqrt{s_{\gamma N}}$ distribution for $J/\psi\pi^\pm$ events is about $\Gamma_{J/\psi\pi} \times 430$ pb/MeV for $\Lambda_\pi = 0.6$ GeV, a free parameter of the πNN vertex, yielding

$$\frac{\Gamma_{J/\psi\pi}}{\Gamma_{tot}} \times \sigma_{\gamma N \rightarrow Z_c^\pm(3900) N} = \frac{\Gamma_{J/\psi\pi}^2 \times 430 \text{ pb/MeV}}{\Gamma_{tot}} < 52 \text{ pb}. \quad (10)$$

Assuming $\Gamma_{tot} = 46 \text{ MeV}/c^2$, we obtain an upper limit $\Gamma_{J/\psi\pi} < 2.4 \text{ MeV}/c^2$.

We estimate the systematic uncertainty of the result in Eq. (8) to be about 30%, where the main contributions come from limited knowledge of the acceptance ratio a , since the energy spectrum of the expected $Z_c^\pm(3900)$ events is unknown, from systematic effects in estimation of nonexclusive contamination in the reference J/ψ sample and from the background description in the signal range of the $J/\psi\pi$ spectrum. The uncertainty of $\sigma_{\gamma N \rightarrow J/\psi N}$ measurement by NA14 contributes to Eq. (9), so the total systematic uncertainty of this result is about 35%.

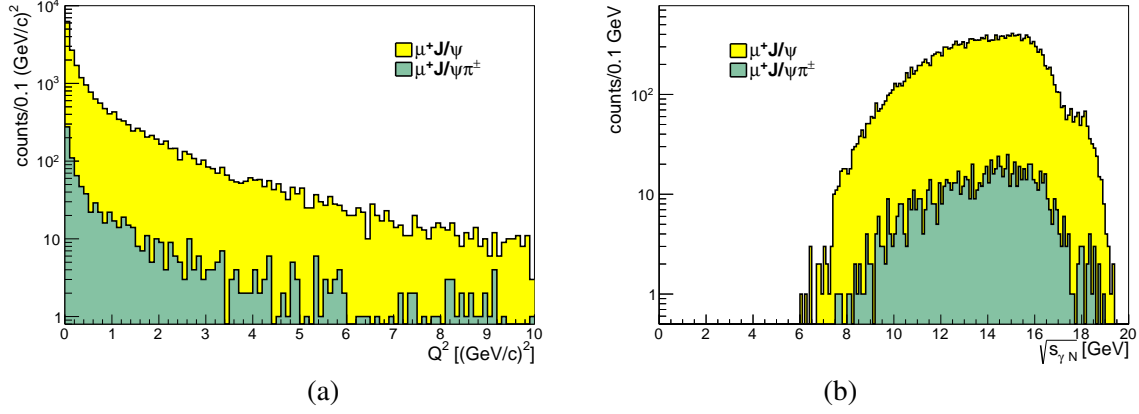


Fig. 3: Kinematic distributions for the reactions Eq. (7) (yellow, upper curves) and Eq. (3) (green, lower curves) (a) Q^2 , (b) $\sqrt{s_{\gamma N}}$.

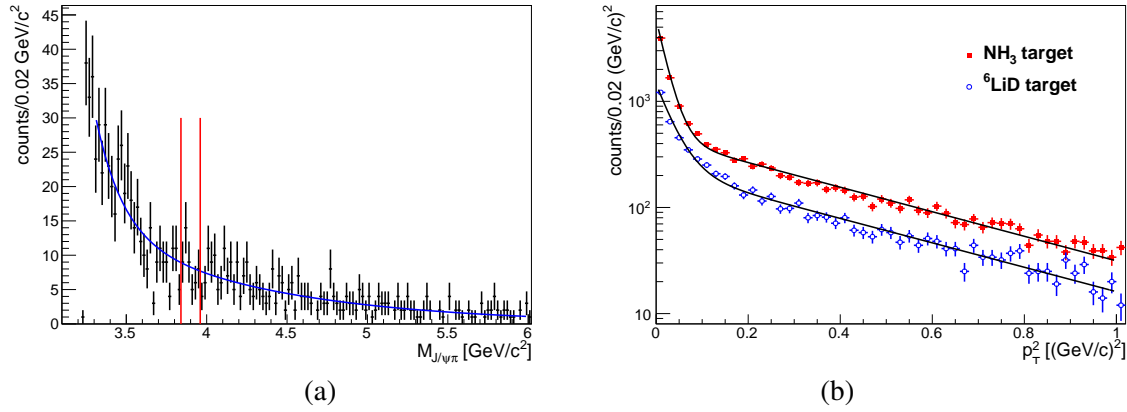


Fig. 4: (a) Mass spectrum of the $J/\psi\pi^\pm$ state. The fitted function is shown as a line. (b) p_T^2 distributions for exclusively produced J/ψ mesons off the ${}^6\text{LiD}$ (blue, lower) and NH_3 (red, upper) targets.

Table 1: Upper limits for $Z_c^\pm(3900)$ production rate for intervals of $\sqrt{s_{\gamma N}}$.

Interval	$\langle\sqrt{s_{\gamma N}}\rangle$, GeV	$BR(J/\psi\pi) \times \sigma_{Z_c}/\sigma_{J/\psi}$, 10^{-3}
Full	13.8	3.7
$\sqrt{s_{\gamma N}} < 12.3$ GeV	10.8	10
$12.3 \text{ GeV} < \sqrt{s_{\gamma N}} < 14.1$ GeV	13.2	3.7
$14.1 \text{ GeV} < \sqrt{s_{\gamma N}} < 15.4$ GeV	14.7	4.5
$15.4 \text{ GeV} < \sqrt{s_{\gamma N}}$	16.4	6.0

No signal of exclusive photoproduction of the $Z_c^\pm(3900)$ state and its decay into $J/\psi\pi^\pm$ was found. Therefore an upper limit was determined for the product of the cross section of this process and the relative $Z_c^\pm(3900) \rightarrow J/\psi\pi^\pm$ decay probability normalized to the cross section of incoherent exclusive photoproduction of J/ψ mesons. In case $Z_c^\pm(3900)$ is a real hadron state, the decay channel $Z_c^\pm(3900) \rightarrow J/\psi\pi^\pm$ can not be the dominant one. This result is a significant input to clarify the nature of the $Z_c^\pm(3900)$ state.

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