

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

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## 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  $3.7 \times 10^{-3}$  has been established at the confidence level of 90%.

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

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, 4, 5, 6], although other explanations like a molecular state [7, 8, 9, 10, 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  $J/\psi$  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.

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<sup>19</sup>Deceased

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  $\Gamma_{\text{tot}}$  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  $50 \text{ nb}$  to  $100 \text{ nb}$  at  $\sqrt{s_{\gamma N}} = 7 \text{ GeV}$ . The  $J/\psi$  production in photon-nucleon interactions at COMPASS covers the range  $\sqrt{s_{\gamma N}}$  from  $7 \text{ GeV}$  to  $19 \text{ GeV}$  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  $Z_c^\pm(3900) \rightarrow J/\psi \pi^\pm$ .

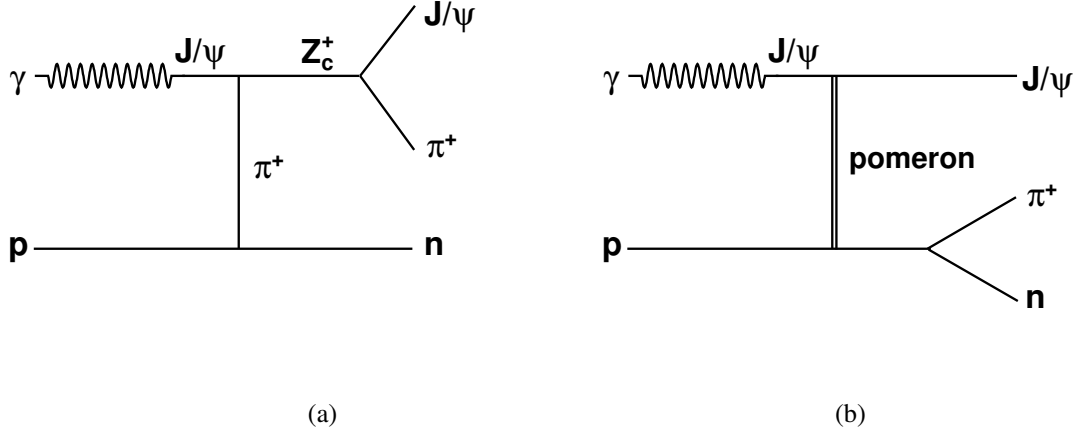


Figure 1: Diagrams for (a)  $Z_c^+(3900)$  production via virtual  $\pi^+$  exchange and (b)  $J/\psi \pi^+$  production via pomeron exchange.

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  $160 \text{ GeV}/c$  (2002-2010) or  $200 \text{ GeV}/c$  momentum (2011) off solid  $^6\text{LiD}$  (2002-2004) or  $\text{NH}_3$  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 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 a  $J/\psi$  candidate if the difference between its reconstructed mass  $M_{\mu^+\mu^-}$  (Fig. 2a) and the nominal  $J/\psi$  mass is less than  $150 \text{ MeV}/c^2$  that is 3 times larger than the mass resolution. In case both  $\mu^+\mu^-$  combinations satisfy this condition, the event is rejected. Except for the tiny recoil of the target nucleon, the sum of the scattered muon energy,  $E_{\mu'}$ , and the energies of produced  $J/\psi$  and  $\pi^\pm$  mesons,  $E_{J/\psi}$  and  $E_{\pi^\pm}$ , 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  $3 \text{ GeV}$ , 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  $J/\psi$  and a  $\pi^\pm$  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.

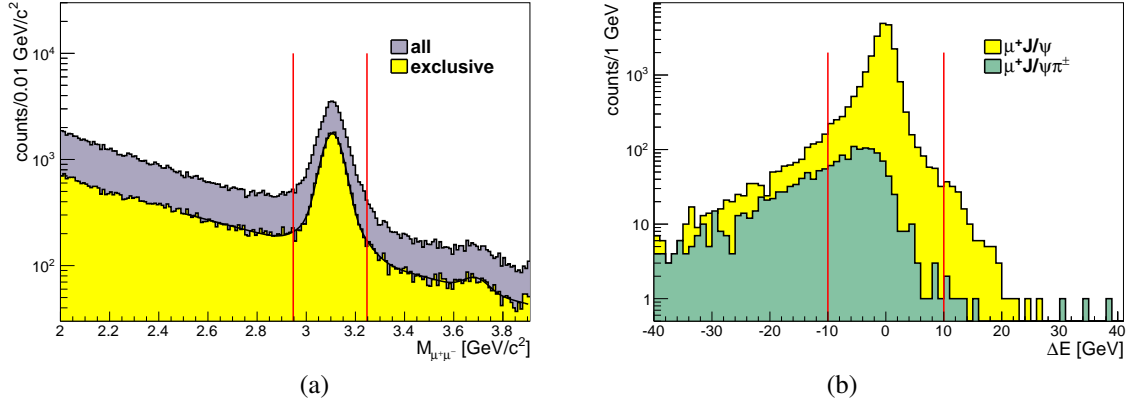


Figure 2: (a) The dimuon mass distribution for all dimuons produced in muon-nucleon scattering (blue, upper curve), and for exclusively produced dimuons (yellow, lower curve). (b) Distribution for the energy balance  $\Delta E$  in the reactions Eq. (7) (yellow, upper curve) and Eq. (3) (green, lower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

The mass spectrum for  $J/\psi \pi^\pm$  events is shown in Fig. 4a. It does not exhibit any statistically significant resonant structure around  $3.9 \text{ GeV}/c^2$ . In order to quantify possible contribution from the  $Z_c$  decay we define the signal range  $3.84 \text{ GeV}/c^2 < M_{J/\psi \pi^\pm} < 3.96 \text{ GeV}/c^2$ . It is selected according to the measured mass and width of  $Z_c$ , their uncertainties, observed in the previous experiments, and the COMPASS setup resolution for  $M_{J/\psi \pi^\pm}$  of about  $15 \text{ MeV}/c^2$ . The observed number of events  $N_{J/\psi \pi}$  in this range 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

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

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 ( $A \cdot e^{-a M_{J/\psi \pi}} + B \cdot e^{-b M_{J/\psi \pi}}$ ) to the  $J/\psi \pi^\pm$  mass spectrum in the range  $3.3 \text{ GeV}/c^2 < M_{J/\psi \pi^\pm} < 6.0 \text{ GeV}/c^2$  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  $49.7 \pm 3.4$  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

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

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  $J/\psi$  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  $J/\psi$  mesons

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

and  $Z_c^\pm(3900)$  hadrons. To separate  $J/\psi$  production and non-resonant production of dimuons, the dimuon mass spectrum is fitted by a function consisting of three Gaussians (two to describe the  $J/\psi$  peak and one for the  $\psi(2S)$  peak) and an exponential background under the peaks (see Fig. 2a). Finally  $18.2 \times 10^3$  events of exclusive  $J/\psi$

production remain in the sample. The distribution of the squared transverse momentum  $p_T^2$  of the  $J/\psi$  (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  $\text{NH}_3$  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 the 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  $R_a = 0.5 \pm 0.1_{\text{syst.}}$ , 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  $\sigma_{\gamma N \rightarrow J/\psi N} = 14.0 \pm 1.6_{\text{stat.}} \pm 2.5_{\text{syst.}}$  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 main contribution to the systematic uncertainty of the result shown in Eq. (8) comes from the background description in the signal range of the  $J/\psi \pi$  spectrum. Changes of the fitting function and the fitting ranges shift the result within  $\pm 15\%$ . The absolute normalization is performed with a relative accuracy of about 25% that includes our limited knowledge of the ratio  $R_a = 0.5 \pm 0.1_{\text{syst.}}$  and systematic errors in the estimation of the nonexclusive contamination in the reference  $J/\psi$  sample (15%), determined from the  $p_T$  dependence of the energy balance  $\Delta E$ . Nevertheless, this relatively large uncertainty may change the upper limit just by up to 3%. Contribution of the absolute normalization remains small with respect to the contribution related to the background fitting even for result in Eq. (9), where the uncertainty of the  $\sigma_{\gamma N \rightarrow J/\psi N}$  measurement by NA14 contributes. So, the systematic uncertainty of the results in Eq. (8) and (9) is about 15%.

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  $\Gamma_{J/\psi \pi} \times 430 \text{ pb/MeV}$  for  $\Lambda_\pi = 0.6 \text{ GeV}$ , a free parameter of the  $\pi NN$  vertex, yielding

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

Assuming  $\Gamma_{\text{tot}} = 46 \text{ MeV}/c^2$ , we obtain an upper limit  $\Gamma_{J/\psi \pi} < 2.4 \text{ MeV}/c^2$ . While the results in Eq. (8) and (9) are model independent, the result for the partial width  $\Gamma_{J/\psi \pi}$  is strongly model dependent.

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
$\sqrt{s_{\gamma N}} < 12.3 \text{ GeV}$	10.8	10
$12.3 \text{ GeV} < \sqrt{s_{\gamma N}} < 14.1 \text{ GeV}$	13.2	3.7
$14.1 \text{ GeV} < \sqrt{s_{\gamma N}} < 15.4 \text{ GeV}$	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  $Z_c^\pm(3900) \rightarrow$

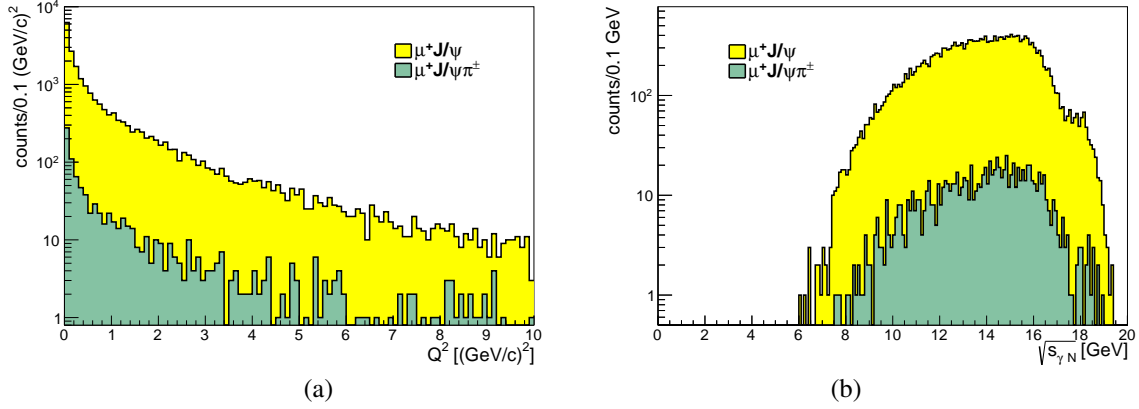


Figure 3: Kinematic distributions for the reactions Eq. (7) (yellow, upper curves) and Eq. (3) (green, lower curves) (a)  $Q^2$ , (b)  $\sqrt{s_{\gamma N}}$ .

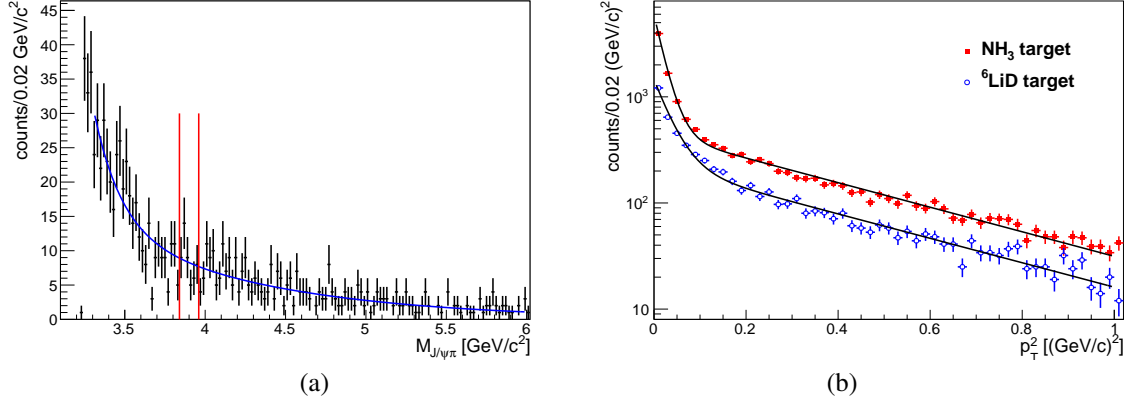


Figure 4: (a) Mass spectrum of the  $J/\psi \pi^\pm$  state. The fitted function is shown as a line. (b)  $p_T^2$  distributions for exclusively produced  $J/\psi$  mesons off the  ${}^6\text{LiD}$  (blue, lower) and  $\text{NH}_3$  (red, upper) targets.

$J/\psi \pi^\pm$  decay probability normalized to the cross section of incoherent exclusive photoproduction of  $J/\psi$  mesons. The obtained result was treated within the framework of  $Z_c$  production mechanism proposed in Ref. [14]. In case the assumptions made therein are correct, 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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