Physics Letters B 742 (2015) 330–334

Contents lists available at ScienceDirect

Physics Letters B

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

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http://dx.doi.org/10.1016/j.physletb.2015.01.042

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ARTICLE INFO

Article history:
Received 29 July 2014
Received in revised form 25 November 2014
Accepted 27 January 2015
Available online 30 January 2015
Editor: M. Doser

Keywords:
COMPASS
$Z_c(3900)$
Photoproduction
Tetraquark

ABSTRACT

A search for the exclusive production of the $Z_c^\pm(3900)$ hadron by virtual photons has been performed in the channel $Z_c^\pm(3900) \to J/\psi\pi^\pm$. 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 $BR(Z_c^\pm(3900) \to J/\psi\pi^\pm) \times \sigma_{\gamma N \to Z_c^\pm(3900) N}/\sigma_{\gamma N \to J/\psi N}$ of 3.7×10^{-3} has been established at the confidence level of 90%.

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

$$Z_c^\pm(3900) \to J/\psi\pi^\pm. \tag{1}$$

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

$$\gamma N \to Z_c^\pm(3900) N. \tag{2}$$

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 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

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[11] Supported by SAIL (CSR), Govt. of India.

[12] Supported by CERN-RFBR Grants 08-02-91009 and 12-02-91500.

[13] Supported by the Portuguese FCT – Fundação para a Ciência e Tecnologia, COMPETE and QREN, Grants CERN/FP/109323/2009, CERN/FP/116376/2010 and CERN/FP/123600/2011.

[14] Supported by the MEXT and the JSPS under the Grants No. 18002006, No. 20540299 and No. 18540281; Daiko Foundation and Yamada Foundation.

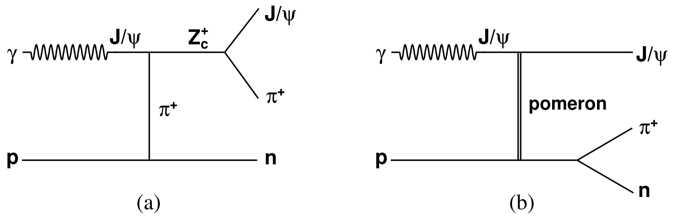
[15] Supported by the DFG cluster of excellence 'Origin and Structure of the Universe' (www.universe-cluster.de).

[16] Supported by EU FP7 (HadronPhysics3, Grant Agreement number 283286).

[17] Supported by the Israel Science Foundation, founded by the Israel Academy of Sciences and Humanities.

[18] Supported by the Polish NCN Grant DEC-2011/01/M/ST2/02350.

[19] Deceased.



(a) (b)

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

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 $Z_c^\pm(3900) \to J/\psi\pi^\pm$.

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}LiD (2002–2004) or NH$_3$ targets (2006–2011). The longitudinally or transversely polarized targets consisted of two (2002–2004) or three (2006–2011) cylindrical cells placed along the beam direction. Polarization effects were canceled out by combining data with opposite polarization 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

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

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/ψ candidate if the difference between its reconstructed mass $M_{\mu^+\mu^-}$ (Fig. 2a) and the nominal J/ψ mass is less than 150 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/ψ 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 GeV, the energy balance is required to be $|\Delta E| < 10$ 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 GeV/c in order to reduce the background of exclusive events with a J/ψ 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.

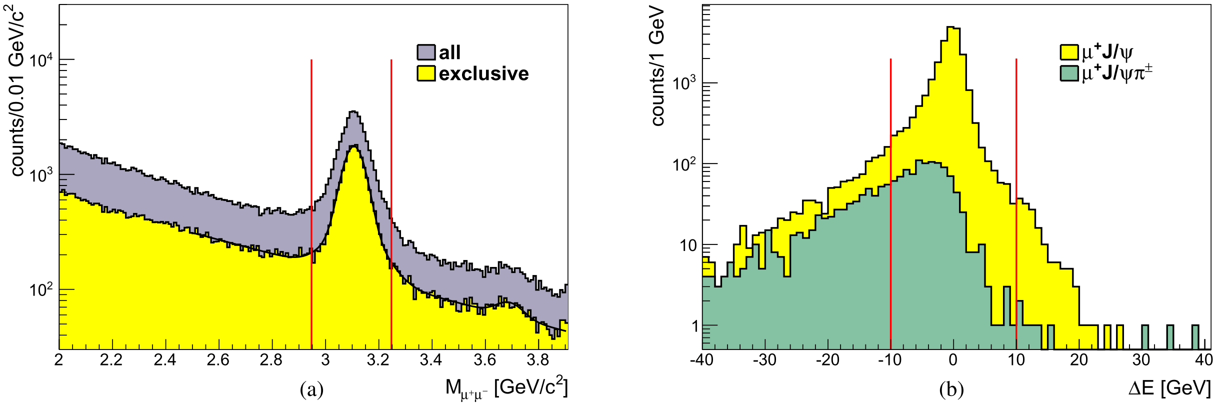
The mass spectrum for $J/\psi\pi^\pm$ events is shown in Fig. 4a. It does not exhibit any statistically significant resonant structure around 3.9 GeV/c^2. In order to quantify possible contribution from the Z_c decay we define the signal range 3.84 GeV/$c^2 < M_{J/\psi\pi^\pm} <$ 3.96 GeV/c^2. It is 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 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 $(A \cdot e^{-aM_{J/\psi\pi}} + B \cdot e^{-bM_{J/\psi\pi}})$ to the $J/\psi\pi^\pm$ mass spectrum in the range 3.3 GeV/$c^2 < M_{J/\psi\ \pi^+} <$ 6.0 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

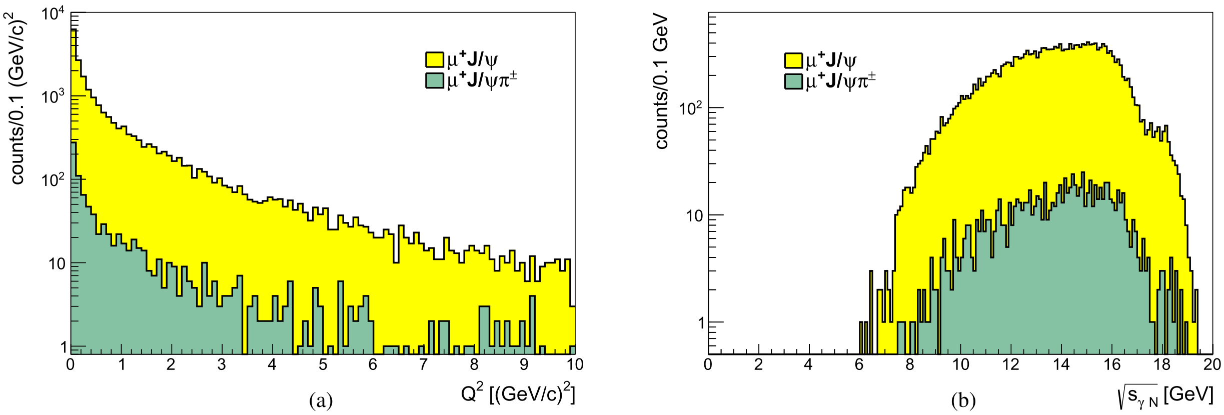
$$\int_0^{N_{Z_c}^{UL}} g(N_{Z_c}) = 0.9 \quad (5)$$

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



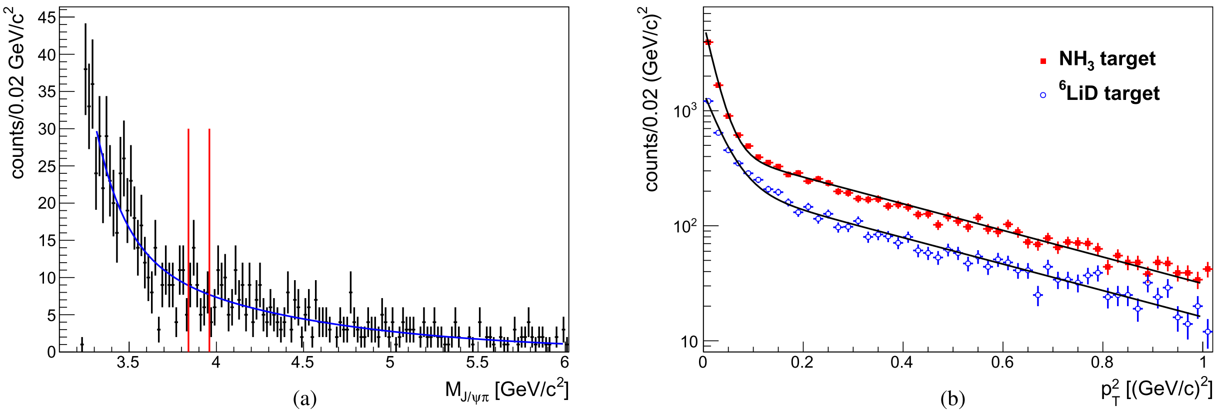
(a) (b)

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). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



(a) (b)

Fig. 3. Kinematic distributions for the reactions Eq. (7) (yellow, upper curves) and Eq. (3) (green, lower curves) (a) Q^2, (b) $\sqrt{s_{\gamma N}}$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



(a) (b)

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}LiD (blue, lower) and NH$_3$ (red, upper) targets. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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

$$\gamma N \to J/\psi N, \tag{6}$$

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

$$\mu^+ N \to \mu^+ J/\psi N, \tag{7}$$

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 Gaussians (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}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 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

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

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

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

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 ±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/ψ sample (15%), determined from the p_T dependence of the energy balance ΔE.

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 GeV $< \sqrt{s_{\gamma N}} <$ 14.1 GeV	13.2	3.7
14.1 GeV $< \sqrt{s_{\gamma N}} <$ 15.4 GeV	14.7	4.5
15.4 GeV $< \sqrt{s_{\gamma N}}$	16.4	6.0

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 $\sigma_{\gamma N \to J/\psi N}$ measurement by NA14 contributes. So, the systematic uncertainty of the results in Eqs. (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 $\Gamma_{J/\psi\pi} \times 430$ pb/MeV for $\Lambda_\pi = 0.6$ GeV, a free parameter of the πNN vertex, yielding

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

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

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 $Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}$ decay probability normalized to the cross section of incoherent exclusive photoproduction of J/ψ 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 $Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}$ cannot be the dominant one. This result is a significant input to clarify the nature of the $Z_c^{\pm}(3900)$ state.

Acknowledgements

We gratefully acknowledge the support of the CERN management and staff as well as the skills and efforts of the technicians of the collaborating institutions.

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