Photoproduction of pentaquarks states at the LHC

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In this paper we investigate the production of pentaquark states in the photon – proton interactions present in hadronic collisions at the LHC. We consider two phenomenological models for the $J/\Psi$ photoproduction that consider the presence of the $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$ resonances in the $s$ – channel of the $\gamma p \rightarrow J/\Psi p$ reaction. The rapidity distribution is estimated for $pPb$ collisions in the collider and fixed – target modes of the LHC. Predictions for $PbAr$ and $PbHe$ fixed – target collisions are also presented. We demonstrate that the experimental analysis of the $J/\Psi$ photoproduction in fixed – target collisions can provide complementary and independent checks on these states, and help to understand their underlying nature.

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FIG. 1: The $Pb + p \rightarrow Pb + J/\Psi + p$ process through the (a) Pomeron exchange and (b) $P_c$ exchange.

In these collisions, both hadrons act as a source of almost real photons, with the equivalent photon flux associated to the nucleus being enhanced by a factor $Z^2$ in comparison to the proton one. Consequently, in a ultra peripheral $pPb$ collision, where $b > R_p + R_{Pb}$, the photon-induced interactions become dominant and the total hadronic cross section for the $J/\Psi$ production can be expressed in terms of the equivalent flux of photons and the photon – hadron cross section as follows [19]

$$\sigma(p + Pb \rightarrow p \otimes J/\Psi \otimes Pb; s) = \int d\omega n_p(\omega) \sigma_{\gamma P \rightarrow J/\Psi \otimes P}(W_{\gamma P}) + \int d\omega n_{Pb}(\omega) \sigma_{\gamma Pb \rightarrow J/\Psi \otimes Pb}(W_{\gamma Pb}) + \int d\omega n_{Pb}(\omega) \sigma_{\gamma pb \rightarrow J/\Psi \otimes Pb}(W_{\gamma Pb}) , \quad (1)$$

where $\sqrt{s}$ is center-of-mass energy for the $pPb$ collision, $\otimes$ represents the presence of a rapidity gap in the final state, $\omega$ is the energy of the photon emitted by the hadron and $n_h$ is the equivalent photon flux of the hadron $h$ integrated over the impact parameter. Moreover, $\sigma_{\gamma h \rightarrow J/\Psi h}$ describes the vector meson production in photon - hadron interactions.

In our analysis we will estimate the cross section for ultra peripheral collisions using the STARLight Monte Carlo, in which the photon spectrum is calculated as follows [20, 21]

$$n(\omega) = \int d^2 b P_{NH}(b) N(\omega, b) , \quad (2)$$

where $P_{NH}(b)$ is the probability of not having a hadronic interaction at impact parameter $b$ and the number of photons per unit area, per unit energy, derived assuming a point-like form factor, is given by

$$N(\omega, b) = \frac{Z^2 \alpha_{gm}}{\pi^2 \gamma^2} \left[ K_1^2(\zeta) + \frac{1}{\gamma^2} K_0^2(\zeta) \right]$$

with $\zeta \equiv \omega b/\gamma$ and $K_0(\zeta)$ and $K_1(\zeta)$ being the modified Bessel functions. The coherent $\gamma Pb \rightarrow J/\Psi Pb$ cross section is expressed in the STARlight MC as follows

$$\sigma(\gamma Pb \rightarrow J/\Psi Pb) = \int_{-\infty}^{t_{min}} dt \frac{d\sigma(\gamma Pb \rightarrow J/\Psi Pb)}{dt}|_{t=0} |F(t)|^2$$

where $F(t)$ is the nuclear form factor and $t_{min} = -(M^2_{J/\Psi}/4\omega\gamma)^2$. For Lead ions, the form factor is assumed to be the convolution of a hard sphere potential with a Yukawa potential of range 0.7 fm. The differential cross section for a photon - nucleus interaction is determined using the optical theorem and the generalized vector dominance model (GVDM) [22]

$$\frac{d\sigma(\gamma Pb \rightarrow J/\Psi Pb)}{dt}|_{t=0} = \frac{\alpha \sigma_{tot}(J/\Psi Pb)}{4f^2_{\phi}}$$

where $f_{\phi}$ is the $J/\Psi$ - photon coupling and the total cross section for the vector meson - nucleus interactions is found using the classical Glauber calculation. As a consequence, it is possible to express $\sigma(\gamma Pb \rightarrow J/\Psi Pb)$ in terms of $\sigma(\gamma p \rightarrow J/\Psi p)$ [See Eq. (9) in Ref. [20]].
FIG. 2: Predictions of the phenomenological models proposed in Refs. [24, 25] for the energy dependence of the $\gamma p \rightarrow J/\Psi p$ cross section considering the Pomeron exchange and the production of the $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$ resonances in the $s$–channel.

In our analysis we will consider that the $J/\Psi + p$ final state can be generated by a Pomeron exchange and by a $P_c$ resonance in the $s$–channel, as represented in the Figs. (a) and (b), respectively. The contribution associated to the Pomeron exchange for the $\gamma p \rightarrow J/\Psi p$ cross section will be described following the STARLight MC, where this cross section is described by a parametrization inspired in the Regge theory given by

$$\sigma_{\gamma p \rightarrow J/\Psi p} = \sigma_{\Psi} \times W_{\gamma p}^r.$$  

The free parameters on the parametrization, $\sigma_{\Psi}$ and $\epsilon$, are fitted using the HERA data [22]. In addition, the STARLight MC supplements this cross section by a factor that accounts for its behavior for energies near the threshold of production. On the other hand, the contribution associated to the $P_c$ resonance will be described considering two different phenomenological models present in the literature [24, 25]. We will consider the model presented in the Ref. [24, 25], denoted Model I hereafter, in which the cross section for the production of the $P_c$ state in the $s$–channel of the $\gamma p \rightarrow J/\Psi p$ reaction was estimated using the approach proposed in Refs. [26, 27] and considering a range of values for the branching ratio $B(P_c \rightarrow J/\Psi p)$ derived using the branching ratios and fractions measured by the LHCb and GlueX collaborations. In addition, we also will consider the model proposed in Ref. [27], denoted Model II hereafter, where the photoproduction of the $P_c$ states is estimated within the framework of an effective Lagrangian approach combined with the vector meson dominance assumption [22]. Following Ref. [27], in our calculations using the Model II we will assume that the $J/\Psi p$ channel accounts for 3% of total widths of the $P_c$ states. We refer the reader to the original references [24, 25] for more details about these phenomenological models for the $P_c$ photoproduction. The resulting predictions of these models for the energy dependence of the $\gamma p \rightarrow J/\Psi p$ cross section considering the Pomeron exchange and the production of the $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$ resonances in the $s$–channel are presented in Fig. 2. The presence of the resonances modifies the energy dependence of $\sigma(\gamma p \rightarrow J/\Psi p)$ at low energies. We have that these models differ in its predictions for the impact of the resonances on the cross section, with the Model II predicting a larger contribution associated to the resonances.

In our study we will consider the phenomenological models discussed above as input in our calculations of the $J/\Psi$ photoproduction in $pPb$ collisions at the LHC. In particular, we have modified the STARLight MC and included the contribution of the $P_c$ resonances. Initially, let’s consider $pPb$ collisions in the collider mode of the LHC, in which $\sqrt{s} = 8.1$ TeV. Our predictions for the rapidity distribution of the dimuons generated in the $J/\Psi \rightarrow \mu^+\mu^-$ decay are presented in Fig. 3 (a). For comparison we present the predictions derived with and without the inclusion of the $P_c$ resonances, which are denoted $P+P_c$ and Pomeron, respectively. We have that the rapidity distribution is asymmetric about midrapidity ($y_{\mu^+\mu^-} \approx 0$) and that the inclusion of the $s$–channel contribution implies an enhancement of the rapidity distribution for $y_{\mu^+\mu^-} \approx -7.5$, which is model dependent. Such results are expected. For $pPb$ collisions the rapidity distributions are asymmetric in rapidity due to the asymmetry on the initial photon fluxes associated to a proton and a nucleus, with the nuclear photon flux being enhanced by a factor $(82)^2$. One important consequence is that the behaviour of the distribution is dominated by $\gamma p$ interactions with the rapidity directly determining the value of $W_{\gamma p}$ that is being probed: $W_{\gamma p} \propto e^Y$. Therefore, for negative values of rapidity we are probing $\sigma(\gamma p \rightarrow J/\Psi p)$ at low energies, where the presence of the resonances modifies the cross section (See Fig. 2). In the lower part of Fig. 3 (a) we present our results for the ratio between the $P+P_c$ and Pomeron predictions. We have that the Model I (II) predicts an enhancement of order of 1.8 (5.3) for $y_{\mu^+\mu^-} \approx -7.5$. Unfortunately, this enhancement occurs for rapidities
beyond those covered by the current detectors of the LHC. Moreover, we only observe one peak, which implies that we will not be able to discriminate the contribution of the different resonances, which are very close in mass.

Let’s now investigate the $P_c$ photoproduction in fixed – target collisions at the LHC. The study of fixed - target collisions at the LHC became recently a reality by the injection of noble gases in the LHC beam pipe by the LHCb Collaboration [28] using the System for Measuring Overlap with Gas (SMOG) device [29]. More results are expected in forthcoming years [30]. As discussed in detail in Ref. [18], the study of photon - induced interactions is expected to be possible in fixed - target collisions. In particular, Ref. [18] demonstrated that in fixed – target collisions we will be able to constrain, in the kinematical range probed by the LHCb detector, the behaviour of the $\gamma p \rightarrow J/\Psi p$ cross section at low center – of – mass energies, near to the threshold of production. Such results motivate the analysis of the $P_c$ photoproduction in fixed – target collisions. In our analysis we will assume $Pbp$ collisions with $\sqrt{s} = 69$ GeV, with the proton being the fixed target. Our results are presented in Fig. 3 (b). For the fixed – target energy the rapidity distribution is narrower and concentrated in the rapidity range $1 \leq y_{\mu^+\mu^-} \leq 4.6$. We have that the enhancement associated to the $s$ – channel reaction now occurs for $y_{\mu^+\mu^-} \approx 1.8$, being of order of 1.6 (3) for the Model I (II). Such result demonstrate that the analysis of fixed – target collisions at the LHC can be useful to constrain the presence of the pentaquark states.

As the recent studies were performed by injecting the noble gases ($He, Ne, Ar$) in the LHC beam pipe and similar configurations should also be present in future analysis, we have extended our previous analysis for the $J/\Psi$ photoproduction in $PbAr$ and $PbHe$ fixed – target collisions. The predictions are presented in Fig. 4. As in the case of $pPb$ fixed – target collisions, we predict an enhancement of the rapidity distribution for $y_{\mu^+\mu^-} \approx 1.8$ that is model dependent. We also predict a second enhancement of the distribution for $y_{\mu^+\mu^-} \approx 6.7$ which is associated to events associated to photon emitted by the target. Unfortunately, the position of this second enhancement is beyond the rapidity range covered by the current detectors.

As a summary, in this paper we have investigated the impact of the $P_c$ resonances on the $J/\Psi$ photoproduction at the LHC. We have considered $pPb$ collisions in the collider and fixed – target modes of the LHC, as well $PbAr$ and $PbHe$ fixed – target collisions, and estimated the rapidity distributions of the $J/\Psi$ meson taking into account its decay in a $\mu^+\mu^-$ pair. Our goal was to verify if the study of this process can be useful to confirm the existence of the resonances as well to constrain its properties. The fact that the presence of the resonances implies a large enhancement of the $\gamma p \rightarrow J/\Psi p$ cross section near the threshold modifies the associated rapidity distribution. We have demonstrated that in the collider mode, the rapidity distribution is enhanced for $y_{\mu^+\mu^-} \approx -7.5$, which is beyond of rapidity range covered by the current detectors of the LHC. On the other hand, in the fixed – target mode, this enhancement is predicted to occur in a rapidity range that can be covered in future fixed – target studies. Our results indicate that the study of $\gamma p$ interactions at LHC can also provide complementary and independent checks on the properties of the pentaquark states, and help to understand their underlying nature.
FIG. 4: Rapidity distribution for the $J/\Psi$ photoproduction in (a) $Pb-Ar$ and (b) $Pb-He$ fixed-target collisions at LHC.

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