Photoproduction of heavy vector meson at the LHC

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The strong electromagnetic fields associated with high energy protons and nuclei may lead to exclusive photoproduction of vector mesons in proton-proton and nucleus-nucleus collisions at the LHC. This paper will discuss the expected cross sections and rapidity and transverse momentum distributions.

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Proton-proton and ultra-peripheral nucleus-nucleus collisions at the Large Hadron Collider (LHC) will allow two-photon and photon-nucleon interactions to be studied at energies higher than at any existing accelerator. A photon from the electromagnetic field of one of the projectiles may interact with the other projectile in a variety of ways. For a recent review of so-called ultra-peripheral collisions (UPC), see [1]. This paper will deal with exclusive photoproduction of vector mesons [2].

As was first pointed out by Fermi, the effect of the electromagnetic field of a moving, charged particle is equivalent to that of a corresponding flux of photons with a certain energy spectrum. The equivalent photon spectrum depends on the velocity of projectile and can be calculated from the form factor (most appropriate for protons [3]) or in the impact parameter representation (most appropriate for nuclei [4]). The equivalent photon spectrum in proton-proton (pp) and nucleus-nucleus (AA) collisions has been discussed by several authors, for details see [3, 4] and references therein. From the photon energy spectrum, \( \frac{dn_\gamma}{dk} \), the equivalent photon luminosity is defined by

\[
\frac{dL}{dk} = \mathcal{L}_{pp/AA} \frac{dn_\gamma}{dk},
\]

where \( \mathcal{L}_{pp/AA} \) is the collider luminosity and \( k \) is the photon energy. This quantity is useful for comparing the photon fluxes at different accelerators and for different colliding systems. The photon luminosities in proton-proton (\( \sqrt{s} = 14 \mathrm{TeV} \)) and Pb+Pb (\( \sqrt{s} = 5.5 \mathrm{A TeV} \)) interactions at the LHC are shown in Fig. 1.

The photon spectrum of a nucleus with charge \( Z \) is proportional to \( Z^2 \). This enhancement is, however, not enough to compensate for the lower beam luminosity expected at the LHC for Pb+Pb interactions compared with p+p interactions, as can be seen in Fig. 1. The photon spectrum in Pb+Pb interactions is furthermore cut-off at a lower photon energy owing to the larger minimum impact parameter. Nevertheless, nuclear beams will add to the physics potential of ultra-peripheral
Fig. 1. The equivalent photon luminosity in p+p and Pb+Pb collisions at the LHC. $k$ is the photon energy in the rest frame of one of the projectiles. The calculations are for the collider luminosities $L_{\text{pp}} = 1.0 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and $L_{\text{PbPb}} = 1.0 \cdot 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$.

collisions. For example, the modification of the parton distribution functions in nuclei (shadowing) can be studied by comparing photoproduction on proton and nuclear targets. From an experimental point of view, the identification of exclusive events might also be easier with nuclear beams, as will be discussed below.

The exclusive production of heavy vector mesons on proton and nuclear targets,

$$\gamma + p \rightarrow V + p \quad \text{or} \quad \gamma + A \rightarrow V + A,$$

(2)

has been studied over a wide energy range. The exclusive production of the light vector mesons $\rho$, $\omega$ and $\phi$ is usually described by the exchange of a soft Pomeron, and the cross section accordingly rises slowly with the photon-proton center-of-mass energy $W_{\gamma p}$, $\sigma \propto W_{\gamma p}^{0.22}$ \[^5\]. Fixed target experiments and experiments at the electron-proton collider HERA have found that the cross section for exclusive $J/\Psi$ production rises much faster with $W_{\gamma p}$. The total cross section can be parameterized as

$$\sigma_{\gamma p \rightarrow J/\Psi p} = 1.5 \cdot W_{\gamma p}^{0.8} \text{ [nb]},$$

(3)

with $W_{\gamma p}$ in GeV. This has been interpreted as evidence for the existence of a hard Pomeron \[^5\]. In QCD based models, where the $J/\Psi$ is produced via two-gluon exchange, it is seen as a consequence of the increased gluon density at low Bjorken-x. The $J/\Psi$ cross section is then proportional to the gluon density squared, $\sigma \propto [g(x, Q^2)]^2$ \[^6, 7\].

The very limited statistics for $\Upsilon$ production does not allow an energy dependence to be extracted from the data. QCD based models predict an even more rapid
increase with $W_{\gamma p}$ than for the $J/\Psi$. The following parameterization (for $\Upsilon(1S)$) is consistent with the available data

$$\sigma_{\gamma p \rightarrow \Upsilon} = 0.06 \cdot W_{\gamma p}^{1.7} \ [pb], \quad (4)$$

with $W_{\gamma p}$ in GeV. The statistical and systematic errors in the experimental cross sections correspond to a range for the normalization constant between 0.054 and 0.175 $[pb]$. These parameterizations for the $J/\Psi$ and the $\Upsilon(1S)$ are used in the calculations below.

The threshold photon energy for producing a vector meson with a certain mass, corresponding to $W_{\gamma p} = m_p + m_V$, is $k = m_V + m_V^2/(2m_p)$ in the rest frame of the proton. This is $k = 8.2$ GeV and 57 GeV for the $J/\Psi$ and $\Upsilon$, respectively. The equivalent photon spectrum at the LHC extends far above these values. In fact, the maximum photon energy at the “knee” in Fig. 1 corresponds to a $W_{\gamma p}$ of about 1 TeV for Pb+Pb and 10 TeV for p+p. These center-of-mass energies are much larger than at HERA or anywhere else.

Heavy vector mesons can thus be produced over a wide range of photon energies at the LHC. There is a direct correspondence between the photon energy and the rapidity, $y$, of the vector meson, $y = \ln(2k/m_V)$, and the differential cross section for the process $p + p \rightarrow p + p + V$ is

$$\frac{d\sigma}{dy} = k \frac{dn_{\gamma p}}{dk} \sigma_{\gamma p \rightarrow V} (k), \quad (5)$$

and similarly for $A + A \rightarrow A + A + V$. If the photon spectrum is known, the cross section $d\sigma/dy$ is thus a direct measure of the vector meson photoproduction cross section for a given photon energy. Both projectiles can act as either photon emitter or target. Interchanging the photon target and emitter corresponds to a reflection around $y = 0$. At mid-rapidity, the photon energy is uniquely determined, $k = m_V/2$. For $y \neq 0$, there is a twofold ambiguity in $k$, depending on which
projectile emitted the photon. For example, a $\Upsilon$ with rapidity $y = 2$ can be produced by photons with energies of 35 GeV or 0.64 GeV in the laboratory frame.

The photon energies for production around mid-rapidity correspond to gluon x-values of $(2 - 6) \times 10^{-4}$ for $J/\Psi$ production and $(6 - 20) \times 10^{-4}$ for $\Upsilon$ production. The lower number is for p+p and the higher is for Pb+Pb. If the twofold ambiguity in the photon energy can be resolved, i.e. if the contribution from the lower of the two photon energies can be estimated, considerably lower values of x can be reached away from mid-rapidity.

The calculated differential cross sections as a function of rapidity are shown in Figs. 2 and 3. The shaded areas in Fig. 3 correspond to the uncertainty in the measured $\sigma(\gamma p \rightarrow \Upsilon p)$. The integrated cross sections are listed in Table 1. For further details, see [2].

The cross sections in Figs. 2 and 3 have been calculated by adding the cross sections for the two photon emitter/target configurations. Under certain conditions the two processes may interfere [8]. The interference will be maximal at mid-rapidity, where the amplitudes for the two contributions are equal because of symmetry. Because of the long range of the electromagnetic force and the high collision energies, vector mesons may be produced when the protons or nuclei are separated by several tens of fermi. The production will, however, always be located to within $\sim 1 \text{ fm}$ from the proton or nucleus, because of the short range of the nuclear force. When the spatial extension of the protons/nuclei is neglected and the produced vector mesons are treated as plane waves, the sum of the amplitudes for a given impact parameter $\vec{b}$ can be written

$$|A_1 + A_2| = 2|A_1|^2 [1 \pm \cos(pT \cdot \vec{b})].$$

(6)

The sign of the interference term depends on the symmetry of the system [2]. It will be negative in a proton-proton or nucleus-nucleus collision, because of the negative parity of the vector meson; moving the vector meson from one production source to the other corresponds to a parity transformation in this case. In a proton-
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anti-proton collision, moving the vector meson from one production point to the other corresponds to a CP-transformation, and the sign of the interference term will be positive, since the vector meson has quantum numbers $J^{PC} = 1^{--}$.

\[ |t| \quad \text{GeV}^2 \]

\[
d\sigma/dydt \quad \text{[pb GeV}^{-2}] \]

\[
LHC \quad p+p \rightarrow p+p+\Upsilon
\]

\[
\text{Tevatron} \quad p+\bar{p} \rightarrow p+\bar{p}+\Upsilon
\]

Fig. 4. $d\sigma/dydt$ at $y = 0$ for photoproduction of $\Upsilon$ in pp and $p\bar{p}$ collisions at the LHC (a) and the Tevatron (b), respectively. The solid curve is with and the dashed curve is without interference. The four-momentum transfer squared is $t \approx -p_T^2$. The inset has an expanded $t$ scale.

The vector meson transverse momentum, $p_T$, is the sum of the transverse momentum of the virtual photon and the momentum transfer from the target, $\sqrt{|t|}$. The latter is usually much larger than the former, so the vector meson transverse momentum distribution is determined by the form factor of the target and $p_T^2 \approx -t$.

The interference is significant at low transverse momenta. For $p_T > 1/b$, the $\cos(p_T \cdot \hat{b})$ term in Eq. 4 oscillates rapidly in the integration over impact parameter, and the interference pattern is washed out. For small transverse momenta, $p_T << 1/\langle b \rangle$, the scalar product $p_T \cdot \hat{b}$ will be $\approx 0$ for all relevant impact parameters, and the interference will be noticeable. The effect on the transverse momentum distribution of the interference in pp collisions at the LHC is shown in Fig. 4 a). For comparison, the corresponding distribution for $p\bar{p}$ interactions at the Tevatron is shown in Fig. 4 b).

Table 1. Cross sections for exclusive $J/\Psi$ and $\Upsilon$ production at the LHC.

| System and energy | $J/\Psi$ | $\Upsilon(1S)$ |
|------------------|---------|--------------|
| $p+p \ \sqrt{s} = 14 \text{ GeV}$ | 120 nb | 3.5 nb |
| $Pb+Pb \ \sqrt{s_{\text{NN}}} = 5.5 \text{ GeV}$ | 32 mb | 170 $\mu$b |
The experimental feasibility of studying exclusive vector meson production in heavy ion reactions has been demonstrated at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. The STAR collaboration has studied the reaction \( \text{Au}+\text{Au} \rightarrow \text{Au}+\text{Au}+\rho^0 \) at center-of-mass energies of \( \sqrt{s} = 130 \) and 200 GeV per nucleon-nucleon collision \[9\]. The identification of the exclusive events is achieved by their low final-state multiplicity and the very low transverse momentum of the produced vector meson. Preliminary results indicate that the interference discussed above might have been observed \[10\].

There are no published experimental results on exclusive vector meson production in \( \text{pp} \) or \( \text{p} \overline{\text{p}} \) interactions. The cut on low vector meson transverse momentum will be less efficient in \( \text{pp} \) collisions because of the different form factor. The identification will have to rely on the presence of so-called rapidity gaps, intervals in rapidity void of particles. As the discussion in \[2\] shows, requiring one or more gaps with a total width of \( \Delta y = 3 \) units will probably be sufficient at the LHC.

To summarize, the cross sections and rapidity and transverse momentum distributions for exclusive production of the heavy vector mesons \( J/\Psi \) and \( \Upsilon(1S) \) at the LHC have been presented. The cross sections are large enough for these reactions to be studied. The center-of-mass energies at the LHC will be higher than what has been achieved previously. This could provide valuable information on the gluon distributions at low-x in protons and nuclei, and might help to resolve the nature of the hard Pomeron.

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