Exclusive electromagnetic production of pion pairs in lead-lead collisions at LHC

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Abstract. The cross section for $\pi^+\pi^-$ and $\pi^0\pi^0$ meson pairs production in peripheral ultrarelativistic heavy-ion collisions is calculated in the impact parameter space equivalent photon approximation. The cross section is calculated at the energy available at the CERN Large Hadron Collider, $\sqrt{s_{NN}} = 3.5$ TeV. For the first time the world data for $\gamma\gamma \rightarrow \pi\pi$ are described, both for the total cross section and for the angular distribution. This is obtained simultaneously for $\gamma\gamma \rightarrow \pi^+\pi^-$ and $\gamma\gamma \rightarrow \pi^0\pi^0$ at all experimentally available energies.

1 Introduction

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{pion_pair_diagram.png}
\caption{The diagram illustrating the formation of the pion pair. For the LHC the $A_1$ and $A_2$ letters denote the $^{208}$Pb nuclei.}
\end{figure}

It is known that ultrarelativistic colliding heavy ions are a source of high-energy $\gamma\gamma$ collisions. Recently we have studied several processes initiated by the photon-photon collisions such as $\rho^0\rho^0$ [1], $\mu^+\mu^-$ [2], $Q\bar Q$ [3], $J/\Psi J/\Psi$ [4] and $\pi\pi$ [5, 6]. We have shown there that inclusion of realistic charge form factors, being Fourier transforms of realistic charge distributions, is crucial to estimate...
reliable nuclear cross sections. We consider $PbPb \rightarrow PbPb\pi^+\pi^-$ and $PbPb \rightarrow PbPb\pi^0\pi^0$ reactions. In figure 1 we show the basic mechanism of the exclusive production of $\pi^+\pi^-$ and $\pi^0\pi^0$ meson pairs. To calculate nuclear cross section, we have to take into account the correct form of the elementary cross section. We discuss $\gamma\gamma \rightarrow \pi\pi$ reactions at low, intermediate and high sub-energies.

2 Elementary cross section

The $\gamma\gamma \rightarrow \pi\pi$ reaction is rather complicated. Different mechanisms contribute in general. We try to understand both $\gamma\gamma \rightarrow \pi^+\pi^-$ and $\gamma\gamma \rightarrow \pi^0\pi^0$ processes simultaneously, starting from the two-pion threshold ($W = 2m_\pi$) up to the maximal experimentally available energy $W_{\gamma\gamma} \approx 6$ GeV. We include both soft (figure 2), hard continuum (right panel of figure 3 - pQCD mechanisms proposed by Brodsky and Lepage [7] and the handbag mechanism proposed by Diehl, Kroll and Vogt [8]) as well as $s$-channel resonances (left panel of figure 3). We show that for a correct description of the low-energy experimental data we have to include also pion-pion rescattering (figure 4), which leads to a coupling between the $\pi^+\pi^-$ and $\pi^0\pi^0$ channels.

![Figure 2. The $\gamma\gamma \rightarrow \pi^+\pi^-$ continuum Born terms.](image2)

![Figure 3. $\gamma\gamma \rightarrow$ resonances $\rightarrow \pi^+\pi^-\pi^0\pi^0$ (left panel) and the Brodsky-Lepage or hand-bag perturbative mechanisms for large-angle $\gamma\gamma \rightarrow \pi\pi$ scattering (right panel).](image3)

![Figure 4. $\gamma\gamma \rightarrow \pi^0\pi^0$ in a simple coupled-channel model with $\rho^\pm$ exchange.](image4)

In figure 5 we show our model results against world data for $\gamma\gamma \rightarrow \pi\pi$. We get a good agreement with all available data for the first time in such a large range of energies. This make our model for
photoproduction of pions well suited for the predictions of the cross sections for nucleus-nucleus collisions.

In figure 6 we present a ratio of the neutral and charged pion pair cross sections as a function of γγ energy. The upper line represents the handbag model result, which is independent of \( z = \cos \theta \) and of the collision energy. Our result, which includes the BL pQCD and handbag contribution, describes the experimental data measured by the Belle Collaboration.

![Image](image1.png)

**Figure 5.** Results of our fit: \( \gamma \gamma \rightarrow \pi^+\pi^- (|\cos \theta| < 0.6) \) (left panel) and \( \gamma \gamma \rightarrow \pi^0\pi^0 (|\cos \theta| < 0.8) \) (right panel).

![Image](image2.png)

**Figure 6.** The ratio of the \( \gamma \gamma \rightarrow \pi^0\pi^0 \) and \( \gamma \gamma \rightarrow \pi^+\pi^- \) cross sections as a function of \( W_{\gamma \gamma} = \sqrt{s_{\gamma \gamma}} \).

### 3 Nuclear cross section

The nuclear cross section has been calculated with the help of \( b \)-space equivalent photon approximation (EPA). This approach allows to separate peripheral collisions of nuclei (\( b > R_1 + R_2 \approx 14 \text{ fm} \)). A compact formula for calculating the total cross section takes the form:

\[
\sigma(AA \rightarrow AA\pi\pi; s_{AA}) = \int \hat{\sigma}(\gamma \gamma \rightarrow \pi\pi; W_{\gamma \gamma}) S^2_{\text{abs}}(b) N(\omega_1, b_1) N(\omega_2, b_2) \frac{W_{\gamma \gamma}}{2} b_1 d^2 b_2 d W_{\gamma \gamma} d Y_{\pi\pi}.
\]

The details of its derivation can be found in our papers [2, 6].
Table 1. Cross section for different lower cuts on pion transverse momenta at the LHC energy.

<table>
<thead>
<tr>
<th>$p_{t,\text{min}}$ (GeV)</th>
<th>$\pi^+\pi^-$ (mb)</th>
<th>$\pi^0\pi^0$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>46.7</td>
<td>8.7</td>
</tr>
<tr>
<td>0.5</td>
<td>12.1</td>
<td>5.1</td>
</tr>
<tr>
<td>1.0</td>
<td>0.08</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Figure 7 shows two-dimensional distributions in pseudorapidity of charged (left panel) or neutral pion (right panel) and transverse momentum of one of the pions. With larger $p_{t,\pi}$ values, the pseudorapidity distribution becomes somewhat narrower.

In table 1 the total cross sections for $\sqrt{s_{NN}} = 3.5$ TeV are reported for both $\pi^+\pi^-$ and $\pi^0\pi^0$ channels and for different lower cuts on pion transverse momentum.

4 Conclusions

We have shown that in order to describe the world data for $\gamma\gamma \rightarrow \pi^+\pi^-$ and $\gamma\gamma \rightarrow \pi^0\pi^0$ reactions, one should consider several different mechanisms: soft two-pion continuum, several resonances, pion-pion rescattering, pQCD mechanisms proposed by Brodsky and Lepage, as well as the hand-bag mechanism proposed by Diehl, Kroll and Vogt. The energy-dependent cross sections for these two sub-processes have been used next in EPA in the impact parameter space to calculate for the first time corresponding production rate in ultraperipheral ultrarelativistic heavy-ion reactions. In this calculation we have taken into account realistic charge distributions in colliding nuclei.

The $\gamma\gamma \rightarrow \pi^+\pi^-$ sub-process constitutes a background to the exclusive $AA \rightarrow A\rho^0(\rightarrow \pi^+\pi^-)A$ process, initiated by photon-pomeron or pomeron-photon sub-processes. We have found [9] that only a part of the dipion invariant mass spectrum associated with $\gamma\gamma$-collisions can be potentially visible as the cross section for the $AA \rightarrow A\rho^0A$ reaction is very large.

References
