Photoproduction at the Relativistic Heavy Ion Collider with STAR

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Abstract

The strong electromagnetic fields of short duration associated with relativistic heavy ions make a heavy-ion collider a unique tool to study two-photon and photonuclear collisions. In this talk, we introduce the principles of photoproduction at hadron colliders, review recent results from RHIC on meson and $e^+e^-$ production. At RHIC, STAR has studied exclusive $\rho^0$ vector meson production and $\rho^0$ production accompanied by electromagnetic dissociation of both nuclei in collisions of AuAu at 62, 130 and 200 GeV. Recent results suggest the validity of the Glauber calculations for the vector meson photoproduction and inconsistency of the model based on the parton saturation phenomenon. The measurements are also sensitive to interference between production on the two nuclei: either ion can be the photon emitter or the target. The level of observed interference suggests that the final state wave function carries information about all possible decays long after the decay occurs. We also observe coherent photoproduction of a $\pi^+\pi^-\pi^+\pi^-$ state which may be associated with $\rho^0(1450)$.

1. Introduction

Photoproduction can be observed in ultra-peripheral heavy ion collisions (UPCs), which occur when the impact parameter $b$ is more than twice the nuclear radius $R_A$ and an electromagnetic field of one nucleus interacts with another nucleus [1]. The electromagnetic field of a relativistic nucleus may be represented as a flux of almost-real virtual photons, following the Weizsäcker-Williams method [2]. The photon flux scales as the square of the nuclear charge and so the cross-sections can be large in heavy ion interactions. These photons can fluctuate into a quark-antiquark pair, which can scatter elastically from the other nucleus, emerging as a real vector meson.

Also, purely electromagnetic interactions can take place. These processes can be described as two-photon interactions (in most cases) at energy scales below $\hbar/R_A$.

Processes with multiple photon exchanges are possible which may excite the target nuclei into a giant dipole resonance or higher excitation states. When excited nuclei decay they emit one or more neutrons.

2. Coherent and Incoherent Photoproduction

Several data sets were used to study the production cross section of $\rho^0$ mesons at $\sqrt{s_{NN}} = 62$, 130 and 200 GeV [3]. The STAR detector description, trigger setup and data analysis details can be found elsewhere [3, 4, 5, 6]. Recent results obtained with data collected at $\sqrt{s_{NN}} = 200$ GeV
allowed a detailed comparison between measured cross section and theoretical prediction [7, 8, 9]. The cross section comparison is shown in left panel of Fig. 1.

Due to the narrow acceptance in rapidity, we cannot distinguish between those theoretical models based on the shape. However, the measured cross section value can be used to eliminate models which significantly overestimate the total production cross-section in the measured rapidity range.

During the year 2004 run STAR took data of AuAu collisions at $\sqrt{s_{\text{NN}}} = 62$ GeV. The data set was accumulated with minimum bias trigger and contains mainly coherently produced $\rho^0$ accompanied by the mutual excitation. The event selection and analysis procedure closely follow the one outlined in [3]. The measured $\rho^0$ coherent production cross section with mutual excitation was compared with theoretical prediction and found to be in agreement with the model described in [7].

2.1. Interference

As was mentioned earlier the photoproduction can occur at large impact parameter $b$. For the $\rho^0$ photoproduction the median impact parameter $\langle b \rangle$ is about 46 fm (topology triggered data) which means that the $\rho^0$ source consists of two well-separated nuclei. As the result there are two indistinguishable possibilities: either nucleus 1 emits a photon which scatters off nucleus 2, or vice versa so that the system acts like a 2-slit interferometer with slit separation $b$. Since the produced vector mesons have negative parity, the two amplitudes combine with opposite signs and as the result the cross section is [10]

$$\sigma(p_T, b, y) = \left| A(p_T, b, y) - A(p_T, b, -y) \exp(i\vec{p}_T \cdot \vec{b}) \right|^2, \quad (1)$$

where $A(p_T, b, y)$ and $A(p_T, b, -y)$ are the amplitudes for $\rho^0$ production at rapidity $y$ and transverse momentum $p_T$ from the two photon directions.
The produced $\rho^0$’s decay almost immediately at two well-separated points, so any interference must develop after the decay, and involve the $\pi^+\pi^-$ final state. Since the pions go in different directions, this requires an entangled $\pi^+\pi^-$ wave function which cannot be factorized into separate $\pi^+$ and $\pi^-$ wave functions. A measurement of the two-source interference is sensitive to any loss of quantum mechanical coherence, be it due to interactions with the environment [11] or as a characteristic of the $\rho^0$ decay.

Figure 1 right shows the efficiency corrected minimum bias (MB) and topology data. All four distributions show a dip at small $t_\perp (\approx p_T^2)$. The dip at low $t_\perp$ is broader for the MB data because $\langle b \rangle$ is smaller. The suppression at $t_\perp = 0$ is larger for the small-rapidity samples because the amplitudes for the two photon directions are more similar.

The $dN/dt_\perp$ spectrum is fit by the 3-parameter form

$$\frac{dN}{dt_\perp} = A \exp(-kt_\perp)[1 + c(R(t_\perp) - 1)],$$

where $R(t_\perp)$ is the ratio of the simulated $t_\perp$-spectra with and without interference, $A$ is an overall (arbitrary) normalization and $c$ gives the degree of spectral modification.

We measured the interference to be at $87\pm5\text{(stat.)}\pm8\text{(syst.)}\%$ of the expected level [12]. This demonstrates that the final state wave function retains amplitudes for all possible decays, long after the decay occurs.

### 2.2. $\pi^+\pi^-\pi^+\pi^-$ Production

During the 2004 and 2007 runs STAR took data in AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV with modified version of the minimum bias trigger. The trigger has been modified to accept events with multiplicity similar to events with four charged primary tracks.

The measurement of diffractive photoproduction of charged four-pion states available right now are mostly from $\gamma p$ and $\gamma d$ fixed target experiments at photon energies below 10 GeV. The heaviest nucleus used up to this point was carbon and photon energies ranging from 50 to 200 GeV [13]. The experiments observed a broad peak at the order of 200 MeV in the range from 1430 to 1500 MeV/$c^2$. One possible explanation is that this distribution is caused by the overlap of two separate states $\rho(1450)$ and $\rho(1700)$.

In the data analysis events with four charged tracks with net charge zero and with total transverse momentum below 150 MeV/$c$ have been selected. The cut on the transverse momentum ensures that selected events have been coherently photoproduced.

As can be seen in Fig. 2 the transverse momentum distribution peaks at low $p_T$, typical for the coherent production. The Breit-Wigner gives a resonance mass of $1510\pm20$ MeV/$c^2$ and a width of $330\pm45$ MeV. The invariant mass distribution consist of approximately 100 candidates [14].

Previous fixed target experiments observed $\rho'$ as an enhancement in the $\rho' \rightarrow \pi^+\pi^-$ decay mode. STAR data show no significant enhancement around 1500 MeV/$c^2$ in the double pion decay mode.

### 3. Conclusions

Photoproduction of $\rho^0$ mesons has been measured in the STAR detector at RHIC in Au-Au collisions at $\sqrt{s_{NN}} = 62, 130, 200$ GeV. Coherent and incoherent $\rho^0$ photoproduction has been observed. The production of $\rho^0$ mesons is observed with and without accompanying Coulomb nuclear excitations.
Figure 2: Left plot shows invariant mass distribution for coherently produced $\pi^+\pi^-\pi^+\pi^-$ state. Right plot shows $p_T$ distribution of coherently produced $\pi^+\pi^-\pi^+\pi^-$. The hatched distribution histogram shows background distribution estimated with four charged tracks with total non zero net charge. Shaded histogram shows signal distribution obtained with simulation.

The differential cross section has been measured as the function of rapidity, invariant mass and $t_\perp$ which allowed to isolate the incoherent part of the $\rho^0$ production. The measured total production cross section has been compared to the available theoretical models.

The interference effect has been observed in the $\rho^0$ production and found to be at the level of $87 \pm 5$ (stat.) $\pm 8$ (syst.)% of the expectation. This proves that the final state wave function retains amplitudes for all possible decays, long after the decay occurs.

STAR also observed production of the $\pi^+\pi^-\pi^+\pi^-$ state which can be attributed to the overlap of the two separate states $\rho(1450)$ and $\rho(1700)$.

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