Physics Letters B 781 (2018) 182–186

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Coherent lepton pair production in hadronic heavy ion collisions

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ARTICLE INFO

Article history:
Received 14 January 2018
Received in revised form 11 March 2018
Accepted 3 April 2018
Available online 6 April 2018
Editor: W. Haxton

ABSTRACT

Recently, significant enhancements of e^+e^- pair production at very low transverse momentum ($p_T <$ 0.15 GeV/c) were observed by the STAR collaboration in peripheral hadronic A+A collisions. This excesses can not be described by the QGP thermal radiation and ρ in-medium broadening calculations. This is a sign of coherent photon–photon interactions, which were conventionally studied only in ultra-peripheral collisions. In this article, we present calculations of lepton pair (e^+e^- and $\mu^+\mu^-$) production from coherent photon–photon interactions in hadronic A+A collisions at RHIC and LHC energies within the STAR and ALICE acceptance.

The major scientific goal of relativistic heavy-ion collisions carried out at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) is to study the properties of the deconfined state of partonic matter – Quark–Gluon Plasma (QGP) [1]. Dileptons has been suggested as "penetrating probes" for the hot and dense medium created in heavy-ion collisions [2], because they are produced during the whole evolution and not subject to the violent strong interactions in the medium. Various dilepton measurements have been performed since the early days of heavy-ion collisions [3–14]. Of particular interest, a clear enhancement in the low ($M_{ll} < M_\phi$) and intermediate mass ($M_\phi < M_{ll} < M_{J/\psi}$) region [15] has been observed when compared to known hadronic source. The enhancement in the low mass region is consistent with in-medium broadening of the ρ mass spectrum [16–21], while the excess in the intermediate mass region is believed to be originated from the QGP thermal radiation [22].

Dileptons can also be produced by the collision of the two intense electromagnetic fields which accompany the relativistic heavy ions [23]. The electromagnetic field of a relativistic charge particle can be viewed as a spectrum of equivalent photons. The photon flux is proportional to Z^2, where Z is the charge of the particle. The dilepton production from the electromagnetic interactions can be represented as $\gamma + \gamma \rightarrow l^+ + l^-$. The equivalent two-photon luminosity is proportional to Z^4. The strong dependence on Z results in copiously produced dileptons in relativistic heavy-ion collisions. Conventionally, the two-photon process was only studied without background from hadronic processes, *i.e.* in the so-called Ultra-Peripheral Collisions (UPCs) [24–29]. In these collisions, the impact parameter (b) is larger than twice the nuclear radium (R_A).

Recently, significant excesses of J/ψ yield at very low transverse momentum ($p_T <$ 0.3 GeV/c) have been observed by the ALICE [30] and STAR [31] collaborations in peripheral Hadronic Heavy-Ion Collisions (HHICs). These excesses cannot be explained by the hadronic J/ψ production with currently known cold and hot medium effects taken into account, however, could be qualitatively described by coherent photonuclear production mechanism [32–34]. Assuming that the coherent photonuclear production is response for the observed J/ψ excess, the coherent two-photon process should be there and contribute to the dilepton production in HHICs. Recently, STAR made measurements of e^+e^- pair production at very low p_T, and indeed, a significant excess with respect to hadronic cocktails in peripheral HHICs was observed in the preliminary results [35], which points to evidence of coherent photon–photon interactions in HHICs. There are plenty of theoretical calculations on lepton pair production from coherent photon–photon interactions in UPCs [23,24,36–42], however, the calculations in HHICs are absent on the market to constrain the origin of the excess at present. In this article, we report calculations of lepton pair (e^+e^- and $\mu^+\mu^-$) production from coherent photon–photon interactions in hadronic A+A collisions at RHIC and LHC energies within the STAR and ALICE acceptance. The centrality and pair mass dependence of lepton pair production at $p_T <$ 0.15 GeV/c in Au+Au collisions at $\sqrt{s_{NN}} =$ 200 GeV and Pb+Pb collisions at $\sqrt{s_{NN}} =$ 2.76 TeV are presented. We also compare the

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https://doi.org/10.1016/j.physletb.2018.04.006

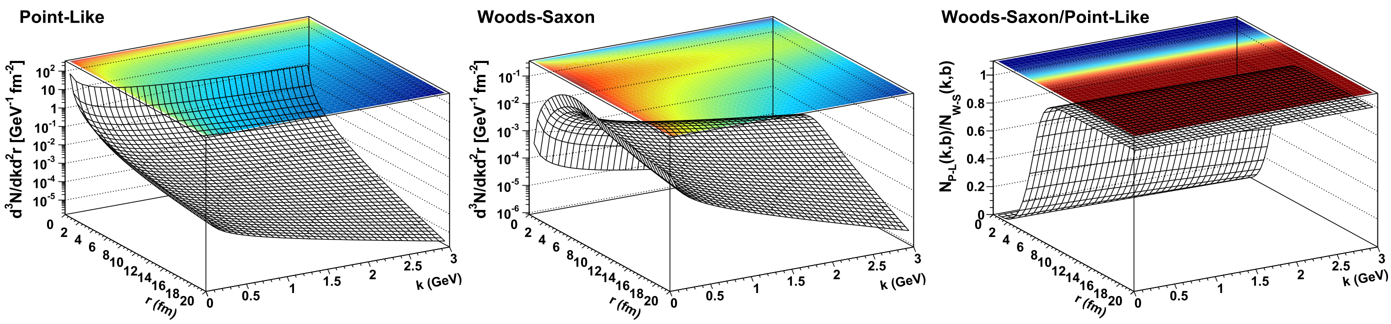

Fig. 1. Two-dimensional distributions of the photon flux in the distant r and in the energy of photon k for point-like (left panel) and Woods–Saxon (middle panel) form factors in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The right panel shows the ratio of the differential photon fluxes with Woods–Saxon form factor to those with point-like form factor.

calculated results with the contributions from hadronic cocktails, QGP thermal radiation, and in-medium ρ broadening in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV within STAR acceptance.

According to the equivalent photon approximation method, a two-photon reaction can be factorized into a semiclassical part and a quantum part. The semiclassical part deals with distribution of massless photons swarming about the colliding ions, while the quantum part usually involves the description of the interaction between the two emitted photons. The cross section to produce a lepton pair with pair mass W can be written as [37]:

$$\sigma(A+A \to A+A+l^+l^-) = \int dk_1 dk_2 \frac{n(k_1)}{k_1}\frac{n(k_2)}{k_2}\sigma[\gamma\gamma \to l^+l^-(W)], \quad (1)$$

where k_1 and k_2 are the two photon energies and $n(k)$ is the photon flux at energy k. The two photon energies k_1 and k_2 determine the pair mass W and rapidity y:

$$k_{1,2} = \frac{W}{2}e^{\pm y} \quad (2)$$

and

$$y = \frac{1}{2}\ln\frac{k_1}{k_2}. \quad (3)$$

The photon flux induced by nucleus can be modelled using the Weizsäcker–Williams method [43]. For the point-like charge distribution, the photon flux is given by the simple formula

$$n(k,r) = \frac{d^3N}{dkd^2r} = \frac{Z^2\alpha}{\pi^2 kr^2}x^2 K_1^2(x), \quad (4)$$

where $n(k,r)$ is the flux of photons with energy k at distant r from the center of nucleus, α is the electromagnetic coupling constant, $x = kr/\gamma$, and γ is Lorentz factor. Here, K_1 is a modified Bessel function. For realistic case, the charge distribution in nucleus should be take into account for the estimation of photon flux. A generic formula for any charge distribution can be written as [41]:

$$n(k,r) = \frac{4Z^2\alpha}{k}\left|\int \frac{d^2q_\perp}{(2\pi)^2}q_\perp \frac{F(q)}{q^2}e^{iq_\perp \cdot r}\right|^2, \quad q = (q_\perp, \frac{k}{\gamma}), \quad (5)$$

where the form factor $F(q)$ is Fourier transform of the charge distribution in nucleus. In our calculations, we use two-parameter Fermi distribution (called equivalently Woods–Saxon distribution) for charge distribution in nucleus

$$\rho_A(r) = \frac{\rho^0}{1+\exp[(r-R_{\rm WS})/d]} \quad (6)$$

where the radius $R_{\rm WS}$ (Au: 6.38 fm, Pb: 6.62 fm) and skin depth d (Au: 0.535 fm, Pb: 0.546 fm) are based on fits to electron scattering data [44,45], and ρ^0 is the normalization factor.

Fig. 1 shows the two-dimensional distributions of the photon flux induced by Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV as a function of distant r and energy k for point-like (left panel) and Woods–Saxon (middle panel) form factors. The right panel of Fig. 1 shows the ratio of the differential photon fluxes with Woods–Saxon form factor to those with point-like form factor. One can observe that the difference between photon fluxes obtained with point-like form factor and the result for Woods–Saxon photon source is huge inside the nucleus ($r < R_{WS}$). For $r \gg R_{WS}$, the difference is negligible. In this calculation, for $r < 10$ fm, we use the photon flux calculated with Woods–Saxon form factor; while at $r > 10$ fm, the result with point-like assumption is employed.

The elementary cross-section to produce a pair of leptons with lepton mass m and pair invariant mass W can be determined by the Breit–Wheeler formula [46]

$$\sigma(\gamma\gamma \to l^+l^-) = \frac{4\pi\alpha^2}{W^2}[(2+\frac{8m^2}{W^2}-\frac{16m^4}{W^4})\ln(\frac{W+\sqrt{W^2-4m^2}}{2m}) - \sqrt{1-\frac{4m^2}{W^2}}(1+\frac{4m^2}{W^2})]. \quad (7)$$

The angular distribution of these lepton pairs is given by

$$G(\theta) = 2+4(1-\frac{4m^2}{W^2})\frac{(1-\frac{4m^2}{W^2})\sin^2(\theta)\cos^2(\theta)+\frac{4m^2}{W^2}}{(1-(1-\frac{4m^2}{W^2})\cos^2(\theta))^2}, \quad (8)$$

where θ is the angle between the beam direction and one of the leptons in the lepton–lepton center of mass frame. Here, we neglect the effect of the photon p_T on the angular distribution.

The approach used in this calculation is very similar to that of the STARlight Monte Carlo [37], which is popular for UPCs. STARlight has been extensively compared with UPC data, with good agreement found for $\gamma+\gamma \to l^+ + l^-$, with data from STAR [25], ATLAS [26], ALICE [27] and CMS [28] collaboration. In STARlight, a point-like charge distribution for photon flux is employed and the production for transverse positions within the nucleus is neglected. This approximation is proper for UPCs, because the production inside the nucleus is small. However, comes to the hadronic heavy-ion collision, when the two colliding nuclei are very close to each other, the charge distribution and the production inside the nucleus can not be neglected. In this calculation,