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Improvements in the treatment of peripheral heavy ion collisions

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Dielectron production in peripheral heavy ion collisions was recently measured by the STAR Collaboration and a significant excess with respect to the hadronic cocktail was observed at low transverse momenta [1]. The excess occurs for pairs with transverse momenta $p_T < 150$ MeV/c and is most prominent in peripheral gold-gold and uranium-uranium collisions. A similar result has been obtained by the ALICE Collaboration in peripheral lead-lead collisions for dileptons from the J/Ψ decay [2]. In peripheral collisions we expect a dominance of hadronic processes so, usually, the dilepton production is studied with models based on hadronic cocktail contributions. However, these models are not able to describe the data, which has motivated the proposition of additional sources of dileptons. An alternative is the dilepton production by photon – photon interactions in heavy ion collisions. In this contribution, we estimate the rapidity and invariant mass distributions for the dielectron and dimuon production in peripheral heavy ion collisions at RHIC and LHC energies considering distinct centralities and different treatments for the nuclear form factor. We also present a procedure to improve the modelling of the dilepton production using the STARLight Monte Carlo, which allows us to derive more realistic predictions.

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1. Introduction

Dielectron production in peripheral Heavy-Ion Collisions (HICs) was recently measured by the STAR Collaboration [1] and a significant excess with respect to the hadronic cocktail was observed at low transverse momenta. The excess occurs for pairs with transverse momenta $p_T <$ 150 MeV/c. A similar result has been obtained by the ALICE Collaboration in peripheral lead-lead collisions for dileptons from the J/Ψ decay [2]. The description of these data sets is still a subject of intense debate. In peripheral collisions we expect a dominance of hadronic processes so, usually, the dilepton production is studied with models based on hadronic cocktail contributions. However, these models are not able to describe the data.

An alternative is the dilepton production by photon – photon interactions in heavy ion collisions [3], [4]. At ultrarelativistic energies, the heavy nuclei are sources of strong electromagnetic fields, which can be described in terms of an equivalent photon spectrum and the associated cross section for photon–photon interactions can be expressed in terms of the photon spectra of the incident nuclei and the cross section for the $\gamma\gamma \to l^+l^-$ subprocess [5].

In this contribution we estimate the rapidity and invariant mass distributions for the dimuon production in peripheral HICs at LHC energy considering the centrality of 20-40% and different treatments for the nuclear form factor. We present our predictions for the realistic and pointlike models and demonstrate that the pointlike approximation for the calculation of the photon spectra, present in the STARLight Monte Carlo, underestimate the number of dileptons produced in peripheral HICs for this centrality and all others. We present a procedure to improve the modelling of the dilepton production using the STARLight Monte Carlo, which allows us to derive more realistic predictions. Our results indicate the dilepton production by photon–photon interactions in peripheral HICs are not negligible and must be considered in order to describe the recent data.

2. Formalism

2.1 Equivalent photon approximation

At the high energy limit where charged nuclei emit strong electromagnetic fields, the equivalent photon approximation allows us to consider the effect of the electromagnetic field as a cloud of virtual photons.

In practice, we can factorize the total cross section of the event into the photoproduction cross section and the equivalent photon flux [5]

$$\sigma\left(H_1H_2 \to X + l^+l^-; s\right) = \int d^2r_1 d^2r_2 d\omega_1 d\omega_2 \sigma_{\gamma\gamma\to l^+l^-}(W) N(\omega_1, r_1) N(\omega_2, r_2) S^2_{abs}(b), \quad (1)$$

where, $\sqrt{s}$ is the center-of-mass energy of the H_1H_2 collision, $W = \sqrt{4\omega_1\omega_2}$ is the center-of-mass energy of the $\gamma\gamma$ system and X characterizes the break of the nuclei after the collision. $\sigma_{\gamma\gamma\to l^+l^-}$ is the cross section of photon-production. Moreover, $N(\omega_i, r_i)$ is the equivalent photon spectrum of photons with energy ω_i. The spectrum can be expressed in terms of the charge form factor $F(q)$ as follows

$$N(\omega, r) = \frac{Z^2\alpha_{em}}{\pi^2\omega}\left|\int_0^\infty dk_\perp k_\perp^2 \frac{F\left(\vec{k}_\perp^2 + \frac{\omega^2}{\gamma^2}\right)}{\vec{k}_\perp^2 + \frac{\omega^2}{\gamma^2}} J_1(rk_\perp)\right|^2, \quad (2)$$

where, Z is the nuclear charge, $k_\perp$ is the transverse momentum and J_1 is the Bessel function of the first kind.

In order to obtain an accurate prediction, it is necessary a suitable treatment of the nuclear form factor. In this work, we are interested at point like and realistic form factor. The point like form factor [$F\left(q^2\right) = 1$] assumes the nuclei as particles without internal structure, consequently the flux with this form factor diverges in small distances. Therefore, this model is not suitable to describe hadron collisions when small distances are important to analysis.

The real form factor can be written as [6]

$$F(q^2) = \frac{4\pi\rho_0}{Aq^3}\left[\sin(qR) - qR\sin(qR)\right]\left[\frac{1}{q^2a^2}\right]. \quad (3)$$

Unlike the point like form factor, the realistic does not diverge for small distances.

2.2 Absorptive factor

The factor $S^2_{abs}(b)$ present in Eq. (1) depends on the impact parameter b of the ions collision and is denoted the absorptive factor. In this work, our interest are peripheral collisions. To consider these collisions, is necessary a treatment of the ion-ion impact parameter range constrained to match a desired centrality bin: $b_{min} < |b| < b_{max}$. This can be made with the function below [4]

$$S^2_{abs}(b) = \theta(b_{min} < |b| < b_{max}). \quad (4)$$

To make a correspondence between the collision centrality with the impact parameter we use the tables for different centrality classes available in Ref. [7]

3. Results

The distribution on rapidity Y and invariant mass W of the produced final state can be directly computed from Eq.(1), by using: $Y = (1/2)(y_{l^+} + y_{l^-})$, $\omega_1 = (W/2)(e^Y)$ e $\omega_2 = (W/2)(e^{-Y})$. Explicitly, the rapidity distribution is given by

$$\frac{d\sigma\left(H_1H_2 \to X + l^+l^-; s\right)}{dY} = \int d^2r_1 d^2r_2 dW \frac{W}{2} N(\omega_1, r_1) N(\omega_2, r_2) \sigma(\gamma\gamma \to l^+l^-; W) S^2_{abs}(b). \quad (5)$$

For invariant mass distribution, we also find a form similar to Eq. (5), but the integration is carried out at the rapidity. In our results, we present predictions for the realistic and point like models.

In Fig. 1 we present our predictions for the invariant mass (left panel) and rapidity distribution (right panel) for the photo-production of $\mu^+\mu^-$ in Pb-Pb peripheral collisions of 20-40% centrality at $\sqrt{s} = 5.02$ TeV. We obtain that the point like approximation (black dotted curve) for the calculation of the photon spectra, present in the STARLight Monte Carlo, underestimate the number of dileptons produced in peripheral heavy ion collisions in this centrality. We find the same pattern for other centralities, too. The red and green dotted curves demonstrate the divergence of point like as we reduce the lower limit of integration in r. This reaffirms the deficiency of this approximation when regions close to the radius of the nucleus are important.

In order to Improve the treatment of peripheral heavy ion collisions, we propose a modification in the point like model in order to make its predictions more realistic, as Tab. 1.

Centrality	**Realistic**
20-40%	Ra/1.438
40-60%	Ra/1.392
60-80%	Ra/1.385

Table 1: Values for the lower limit of r integration using point like suitable to reproduce the differential cross section distributions with realistic form factor.

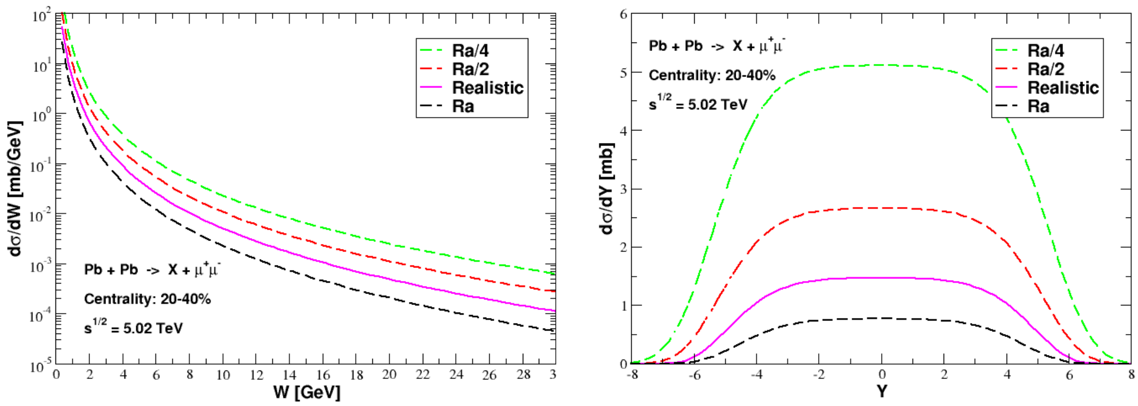

Figure 1: Invariant mass (left panel) and rapidity distribution (right panel) for the photo-production of $\mu^+\mu^-$ in Pb-Pb peripheral collisions of 20-40% centrality at $\sqrt{s}$ = 5.02 TeV.

The modification consists of replacing the lower limit of r integration by the values shown in the table, according to the specified centrality ranges. The Fig. 2 (left panel), shows the point like adjusted to reproduce the realistic form factor, according to the value presented in Tab. 1 for the centrality of 20-40% at $\sqrt{s}$ = 5.02 TeV.

Even better results are found as the collision center of mass increases, as shown in Fig. 2 (right panel). This figure shows the ratio of the rapidity distribution with point like form factor to those with realistic form factor for the photo-production of $\mu^+\mu^-$ in Pb-Pb peripheral collisions of 20-40% centrality at different energies. As we can see, our procedures have good accuracy in central rapidity.

4. Conclusion

We have demonstrated – using the equivalent photon approximation method – that the correct treatments of the nuclear form factor have a significant impact on the predictions of the distributions at rapidity and invariant mass, showing that the predictions are considerably distinct for the point like approximation compared the realistic model. Moreover, we propose an improvement to the point like model the dilepton production used in STARLight Monte Carlo. Our main conclusion is that an adequate treatment of the nuclear form factor is essential to provide accurate predictions.

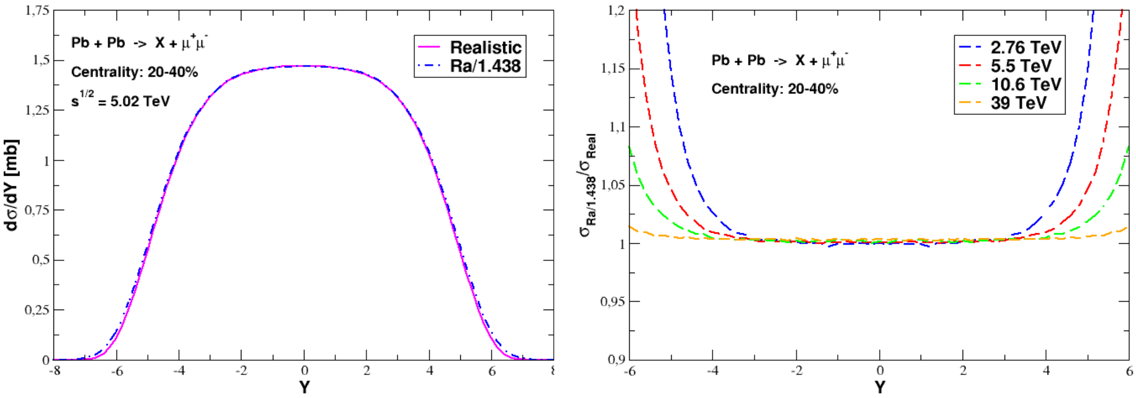

Figure 2: Rapidity distribution considering realistic and adjusted point like form factor (left panel) and ratio of the rapidity distribution with point like form factor to those with realistic form factor (right panel) for the photo-production of $\mu^+\mu^-$ in Pb-Pb peripheral collisions of 20-40% centrality at $\sqrt{s} = 5.02$ TeV.

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