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Study of Drell-Yan pair production on nuclear targets

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Abstract. Drell-Yan pair production off nuclei is an ideal tool to test the cold nuclear effects occurring before a hard collision since no interaction in the final state is expected, neither energy loss or absorption. We present for the first time a comprehensive study of the nucleus-to-nucleon production ratio (the nuclear modification factor) within the color dipole approach using the Green function formalism which naturally incorporates for the color transparency and quantum coherence effects. We study a different onset of nuclear shadowing in various kinematical regions. At large values of the Feynman variable x_F and dilepton invariant mass M we include also a suppression factor due to restrictions caused by the energy conservation induced by multiple initial state interactions (ISI effects). We present a variety of predictions for the nuclear suppression as a function of x_F and M that can be verified by experiments at RHIC and LHC. The mixing of coherence effects with ISI effects can be eliminated going to large values of the dilepton invariant mass. Then predictions for the nuclear suppression is a direct manifestation for the onset of net ISI effects that can be verified by the future measurements.

1. Introduction

The aim of this contribution is to present a study of cold nuclear effects in proton-nucleus interactions at intermediate and low energies (RHIC energies and lower). For this purpose, we use the Drell-Yan (DY) pair production process representing a clean and precise tool for dynamics of the cold nuclear effects not only in proton-nucleus interactions but also in heavy-ion collisions. Moreover, besides no final state energy loss or absorption, the variability of the invariant mass of the dilepton pair allows to reach kinematical regions where the coherence or non-coherence effects are dominant [1].

The dynamics of the quantum coherence effects is controlled by the coherence length (CL) that corresponds to the lifetime of the lowest Fock component $|q\gamma^*\rangle$ for the production of the Drell-Yan dilepton pair in the light-cone formalism. Here, the coherence length for the DY process reads

$$l_c = \frac{1}{x_2 m_p} \frac{(M_{l\bar{l}}^2 + p_T^2)(1-\alpha)}{(1-\alpha)M_{l\bar{l}}^2 + \alpha^2 m_q^2 + p_T^2}\,, \tag{1}$$

where p_T is the transverse momentum of the dilepton pair, m_q is the quark effective mass, and α is the fraction of the light-cone momentum of the projectile quark carried out by the virtual photon.

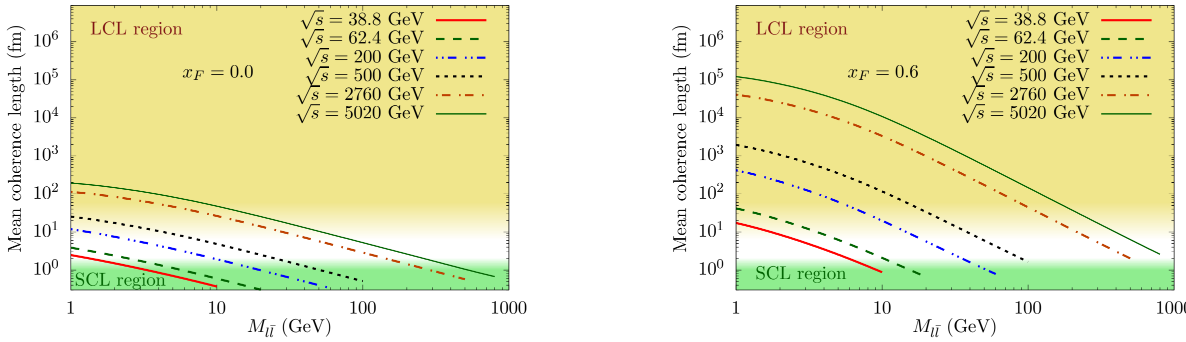

Figure 1. The mean CL as a function of the invariant dilepton mass for several values of the c.m. collision energy $\sqrt{s}$ and Feynman x_F variable. The LCL and SCL regions are highlighted by the yellow and green bands, respectively.

Studying the kinematical dependence of the CL we can distinguish two limits. First, the short coherence length (SCL) limit, where the CL is too short, $\langle l_c\rangle \leq 1 \div 2$ fm, and excludes any coherence effects. This regime corresponds to the so-called Bethe-Heitler regime [3]. Second, for the long coherence length (LCL) limit, $\langle l_c\rangle \gg R_A$ where R_A is the nuclear radius, coherence effects, i.e. nuclear shadowing, are maximal. LCL limit is analogy of the so-called Landau-Pomeranchuk-Migdal effect [4] in QED. For both limits, the formalism for calculation of cross sections on nuclear targets are well-known, see Refs. [5, 1] for the LCL and Ref. [6] for the SCL limit.

In Fig. 1, the mean coherence length is shown for several CMS energies and for two values of Feynman $x_F = 0.0, 0.6$ where regions of SCL and LCL are highlighted by the green and yellow bands, respectively. Especially for $x_F = 0.0$ (mid-rapidity), one can see that the most common measured values of the dilepton pair mass occurs in the white band between these limits. Here, the more general and rigorous Green function formalism that treats the CL exactly has to be used.

The Green function formalism was formulated in Ref. [7] and exact numerical solution was provided in Ref. [8] for nuclear DIS and in Ref. [2] for proton-nucleus collisions. This formalism describes the propagation of $q\gamma^*$ fluctuation through the nucleus where the transverse separation of the fluctuation is varied and interacts with the local bounded nucleons via the dipole cross section as is illustrated in Fig. 2. The Green function effectively resums over all possible trajectories of the $q\gamma^*$ fluctuation. For more details, see Ref. [2].

The considered Green function formalism includes the exact quark shadowing only due to $|q\gamma^*\rangle$ Fock state. At CMS energies, where we use this formalism, the gluon shadowing is very small to negligible. Despite, we include the gluon shadowing in the same way as in Ref. [1].

Besides the coherence effects, we also study the effective energy loss induced by the ISI effects. The latter are expected to cause a significant suppression of the nuclear DY cross section when

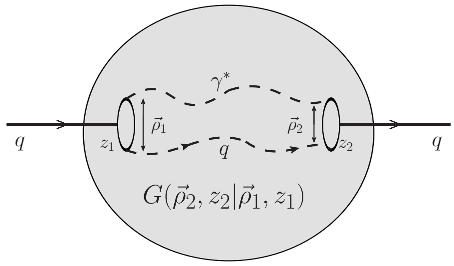

Figure 2. An illustration of propagation of the $q\gamma^*$ fluctuation through a nucleus is described by the Green function $G(\vec{\rho}_2, z_2|\vec{\rho}_1, z_1)$ as a result of summation over different paths of the $q\gamma^*$ state in the medium.

reaching the kinematical limits, $x_L = 2p_L/\sqrt{s} \to 1$ and/or $x_T = 2p_T/\sqrt{s} \to 1$, and were analyzed in Ref. [9]. The ISI effects explain the nuclear suppression at large p_T as well as at forward rapidities in fixed-target experiments where the coherence effects are not allowed due to a low collision energy. For more details, see Ref. [1].

2. Results

In Fig. 3 we present predictions for the future fixed-target experiment AFTER@LHC as functions of $M_{l\bar{l}}$. In the left part one can see that the variation of dilepton mass covers the whole space between LCL and SCL limits. The middle part compares the calculations with different dipole cross sections, and the right part compares the results with quark shadowing (red solid line), quark + gluon shadowing (blue dashed line) and shadowing in combination with ISI (green dashed line). Here, the coherence effects (nuclear shadowing) dominate at small values of $M_{l\bar{l}}$ while the non-coherence (ISI) effects dominate at large values of $M_{l\bar{l}}$.

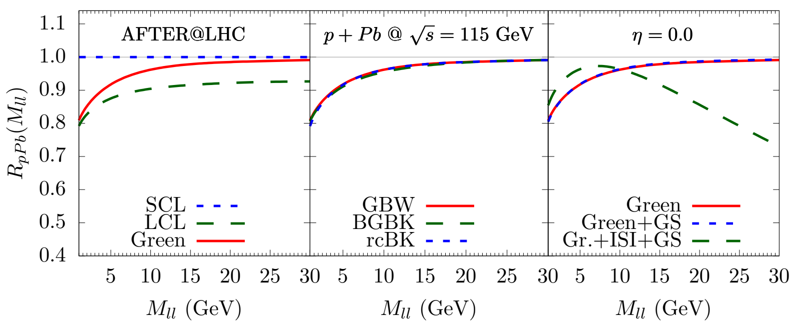

Figure 3. The dilepton mass dependence at midrapidity of the lead-to-proton ratio R_{pPb} at the AFTER@LHC c.m. collision energy $\sqrt{s} = 115$ GeV.

Fig. 4 includes predictions for the LHCb-gas experiment where four different nuclei were tested. In the left part, the quark shadowing is counted only (the gluon shadowing is neglected), and the right part includes both, the quark shadowing and ISI effects together. Here, it is demonstrated that the suppression R_pA as a function of rapidity is a superposition of the coherence and ISI effects whereas R_pA as a function of dilepton mass allows to separate the coherence and ISI effects.

3. Conclusions

In this paper, we have considered the Drell-Yan process as an ideal tool for study of nuclear effects occurring before a hard collision. We showed that the coherence effects (nuclear shadowing) are

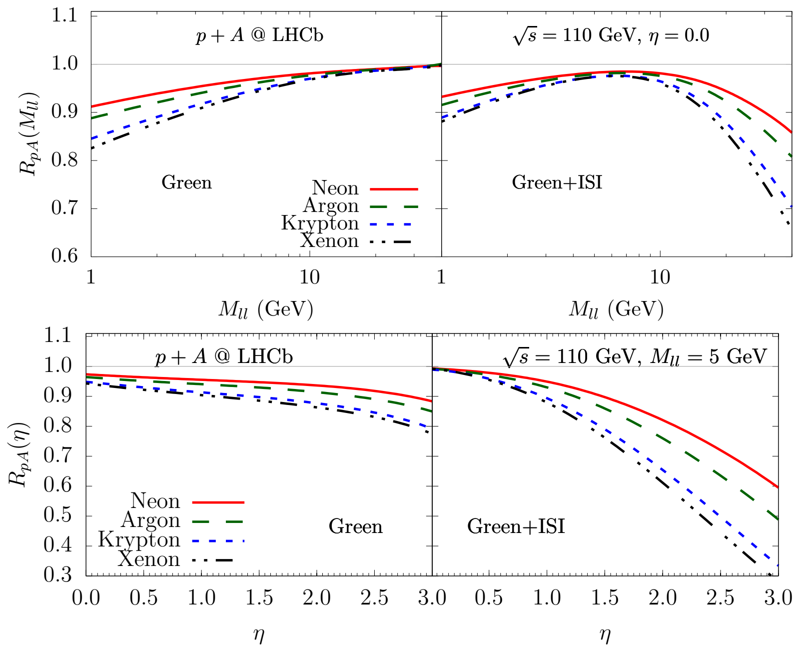

Figure 4. The dilepton invariant mass (upper panels) and pseudorapidity (lower panels) dependences of the nucleus-to-proton ratio R_{pA} at LHCb fixed-target c.m. collision energy $\sqrt{s} = 110$ GeV for several different nuclear targets.

controlled by the coherence length which depends on energy, rapidity and dilepton invariant mass. Also, we demonstrated the necessity of the Green function formalism for RHIC energies and lower where the coherence length corresponds to the transition region between LCL and SCL limits. Using this formalism, the predictions for the future experiment AFTER@LHC and current LHCb-gas experiment were presented. We advice to study the nuclear modification factor as function of $M_{l\bar{l}}$ that is a good probe for both the coherence and non-coherence sources of suppression allowing to reduce or eliminate the shadowing-ISI mixing.

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