Systematic study of real photon and Drell-Yan pair production in p+A (d+A) interactions

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Abstract

We investigate nuclear effects in production of Drell-Yan pairs and direct photons in p(d)-A collisions. For the first time, these effects are studied within the color dipole approach using path integral technique based on the Green function formalism which naturally incorporates the color transparency and quantum coherence effects. We found that the nuclear suppression is caused predominantly by effects of quantum coherence (shadowing corrections) and by the effective energy loss induced by multiple initial state interactions.

Color dipole approach

The DY process in the target rest frame can be treated as a radiation of a heavy photon/dilepton by a projectile quark. The transverse momentum p_T distribution of photon bremsstrahlung in quark-nucleon interactions reads [1]

$$\frac{d^3\sigma^{(qN\to\gamma^*X)}}{d\ln\alpha\; dp_T^2}=\frac{1}{(2\pi)^2}\int d^2\rho_1 d^2\rho_2 e^{i\vec{p}_T(\vec{\rho}_1-\vec{\rho}_2)}\Psi^*_{\gamma^*q}(\alpha,\vec{\rho}_2)\Psi_{\gamma^*q}(\alpha,\vec{\rho}_1)\Sigma(\alpha,\rho_1,\rho_2),$$

where $\Sigma(\alpha,\rho_1,\rho_2)=\sigma^N_{q\bar{q}}(\alpha\rho_1)+\sigma^N_{q\bar{q}}(\alpha\rho_2)-\sigma^N_{q\bar{q}}(\alpha|\rho_1-\rho_2|)$ and the light-cone (LC) wave functions of the projectile $|\gamma^*q\rangle$ fluctuation are presented in [1]. For the dipole cross section $\sigma^N_{q\bar{q}}(\rho)$ we used GBW [2], KST [3] and GBWnew [4] parametrizations.
The hadron cross section is given by convolution of the qN cross section with the corresponding parton distribution functions (PDFs) f_q and $f_{\bar{q}}$

$$\frac{d^3\sigma^{(pp\to llX)}}{dp_T^2 dx_F dM^2}=\sigma^{(\gamma^*\to ll)}\frac{x_1}{x_1+x_2}\int_{x_1}^{1}\frac{d\alpha}{\alpha^2}\sum_q Z_q\left(f_q\left(\frac{x_1}{\alpha}\right)+f_{\bar{q}}\left(\frac{x_1}{\alpha}\right)\right)\frac{d^3\sigma^{(qN\to\gamma^*X)}}{d\ln\alpha\; dp_T^2}$$

where Z_q is the fractional quark charge, PDFs f_q and $f_{\bar{q}}$ are used with the lowest order (LO) parametrization from [5] at the scale $Q^2=p_T^2+(1-\alpha)M^2$ and the factor $\sigma^{(\gamma^*\to ll)}=\alpha_{EM}/3\pi M^2$ accounts for decay of the photon into a dilepton. After integration over transverse momentum p_T we get

$$\frac{d^2\sigma^{(pp\to llX)}}{dx_F dM^2}=\sigma^{(\gamma^*\to ll)}\frac{x_1}{x_1+x_2}\int_{x_1}^{1}\frac{d\alpha}{\alpha^2}\sum_q Z_q\left(f_q\left(\frac{x_1}{\alpha}\right)+f_{\bar{q}}\left(\frac{x_1}{\alpha}\right)\right)\frac{d\sigma^{(qN\to\gamma^*X)}}{d\ln\alpha},$$

$$\frac{d\sigma^{(qN\to\gamma^*X)}}{d\ln\alpha}=\int d^2\rho\left|\Psi_{\gamma^*q}(\alpha,\vec{\rho},M^2)\right|^2\sigma^N_{q\bar{q}}(\alpha\vec{\rho},x).$$

Coherence length

The rest frame of the nucleus is very convenient for study of coherence effects. The dynamics of Drell-Yan (DY) process is regulated by the coherence length l_c, which controls the interference between amplitudes of the hard reaction occurring on different nucleons

$$l_c=\frac{1}{x_2 m_N}\frac{(M^2+p_T^2)(1-\alpha)}{\alpha(1-\alpha)M^2+\alpha^2 m_q^2+p_T^2},$$

where α is a fraction of the light-cone momentum of the quark carried out by the photon and $m_q=0.2$ GeV is an effective mass of quarks. Figs. 1 and 2 show the energy dependence of the mean coherence length separating long coherence length (LCL), $l_c>R_A$, and short coherence length (SCL) limit, $l_c\lesssim 1-2$ fm. For the transition region between both limits we used the Green function formalism as a general case with no restrictions for l_c.

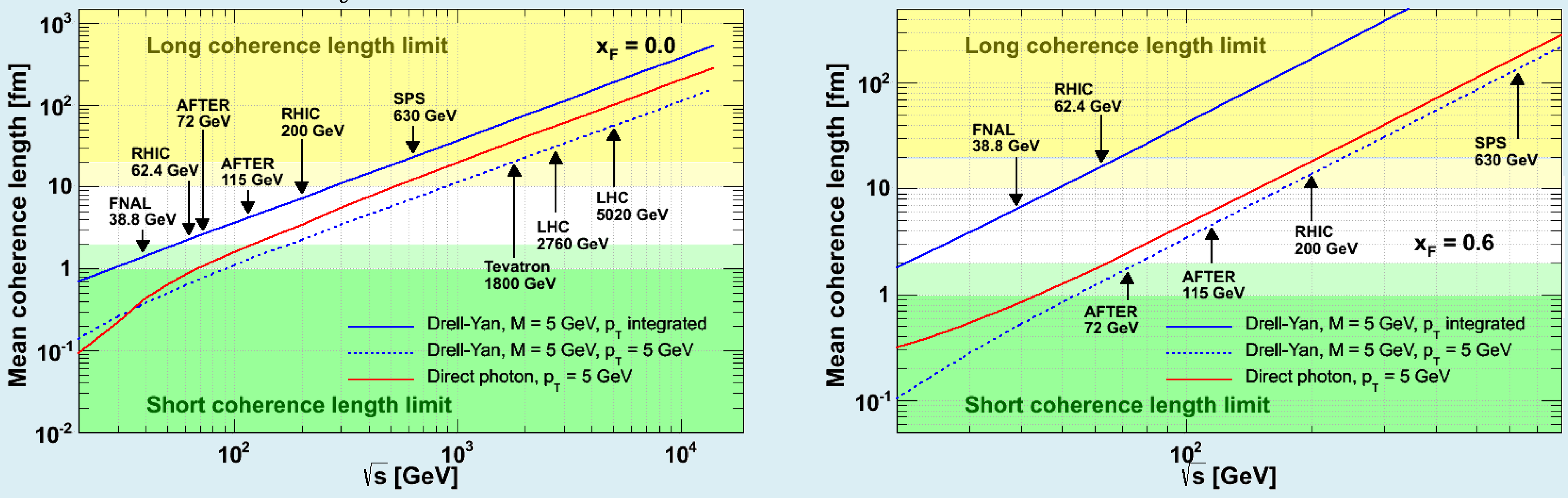

Fig. 1,2: The mean coherence length for Drell-Yan and direct photons for $x_F=0.0$ and $x_F=0.6$.

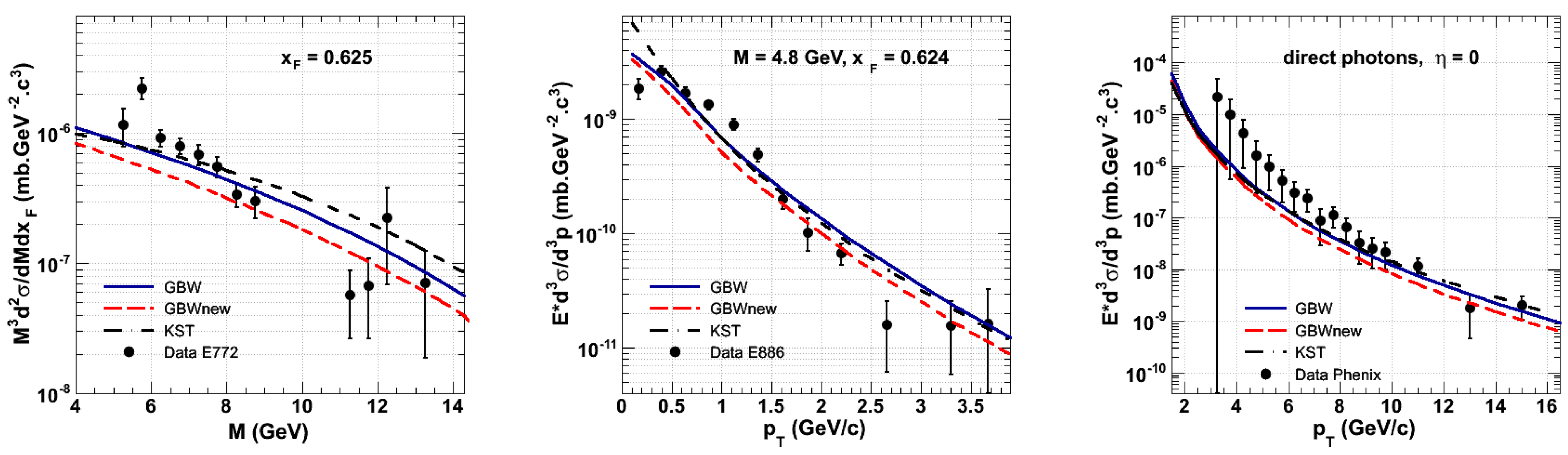

Fig. 3,4,5: Differential dilepton and direct photon cross sections in pp collisions vs E772 [9], E886 [10] and Phenix [11] data.

Transition to nuclear target

Using Green function formalism the quark-nucleus cross section for DY productions on nuclear targets reads [1]

$$\frac{d\sigma^{(qA\to\gamma^*X)}}{d\ln\alpha}=A\frac{d\sigma^{(qN\to\gamma^*X)}}{d\ln\alpha}-\frac{1}{2}Re\int_{-\infty}^{\infty}dz_1\int_{z_1}^{\infty}dz_2\int d^2b\, d^2\rho_1 d^2\rho_2$$
$$\times\Psi^*_{\gamma^*q}(\alpha,\vec{\rho}_2)\rho_A(b,z_2)\sigma^N_{q\bar{q}}(\alpha\rho_2)G(\vec{\rho}_2,z_2|\vec{\rho}_1,z_1)\rho_A(b,z_1)\sigma^N_{q\bar{q}}(\alpha\rho_1)\Psi_{\gamma^*q}(\alpha,\vec{\rho}_1),$$

where the Green function $G(\vec{\rho}_2,z_2|\vec{\rho}_1,z_1)$ describes a propagation of $|\gamma^*q\rangle$ Fock state from longitudinal position z_1 to z_2 through the nucleus with initial and final separations $\vec{\rho}_1$ and $\vec{\rho}_2$. $G(\vec{\rho}_2,z_2|\vec{\rho}_1,z_1)$ satisfies 2D time-dependent Schroedinger equation (z_2 plays the role of time)

$$\left[i\frac{\partial}{\partial z_2}+\frac{\Delta_T(\vec{\rho}_2)-\eta^2}{2E_q\alpha(1-\alpha)}-V(z_2,\vec{\rho}_2,\alpha)\right]G(\vec{\rho}_2,z_2|\vec{\rho}_1,z_1)=0$$

with a boundary condition $G(\vec{\rho}_2,z_2|\vec{\rho}_1,z_1)|_{z_1=z_2}=\delta^2(\vec{\rho}_2-\vec{\rho}_1)$. The imaginary part of the potential $V(z_2,\vec{\rho}_2,\alpha)$ describes an absorption of the dipole in a nuclear medium and reads

$$V(z_2,\vec{\rho}_2,\alpha)=-\frac{i}{2}\rho_A(b,z_2)\sigma^N_{q\bar{q}}(\alpha\vec{\rho}_2,x).$$

For p_T-dependent DY production cross section we solved the Schroedinger equation analytically which is possible for quadratic $\sigma^N_{q\bar{q}}(\rho)=C\rho^2$ and uniform nuclear density. For p_T-integrated DY production cross section we solved the Schroedinger equation numerically using an algorithm from [7].

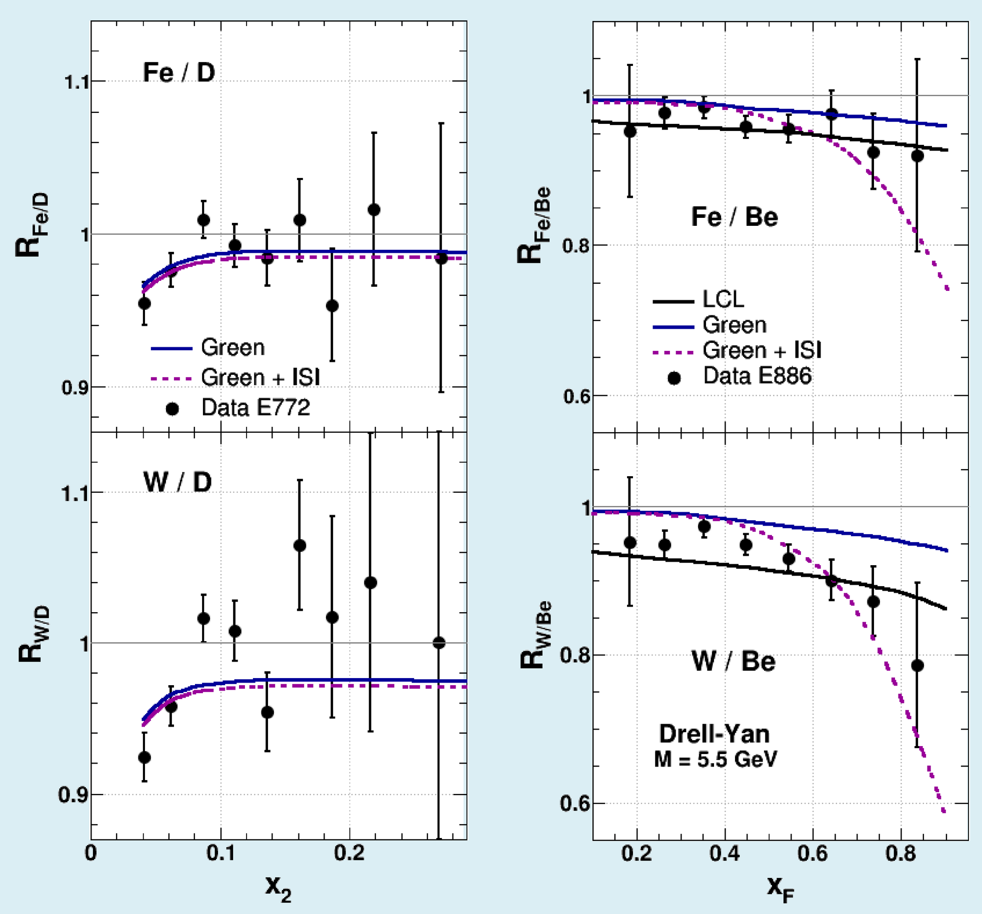

Fig. 6,7: Comparison with data at $\sqrt{s}=38.8$ GeV [9,10].

In LCL limit the Green function formalism naturally leads to simple modification of the dipole cross section: $\sigma^N_{q\bar{q}}(\alpha\rho)\to\sigma^A_{q\bar{q}}(\alpha\rho)=2\int d^2b\left(1-\exp\left[-\frac{1}{2}\sigma^N_{q\bar{q}}(\alpha\rho)T_A(b)\right]\right)$.
In Figs. 6 and 7 we compare our calculations for $R_{A/B}(x_2)$ and $R_{A/B}(x_F)$ with E772 and E886 data where GS is not expected. However, we obtain reasonable agreement with E886 data including ISI effects. In Fig. 8 we present our predictions for nuclear suppression of DY pairs expected in planned experiment AFTER@LHC demonstrating a different contributions of GS and ISI effects. Fig. 9 shows a difference between calculations using Green function formalism and LCL limit within RHIC kinematics for production of direct photons and DY at midrapidity. The RHIC data [11] indicate a strong large-p_T suppression that can be explained only by ISI effects.

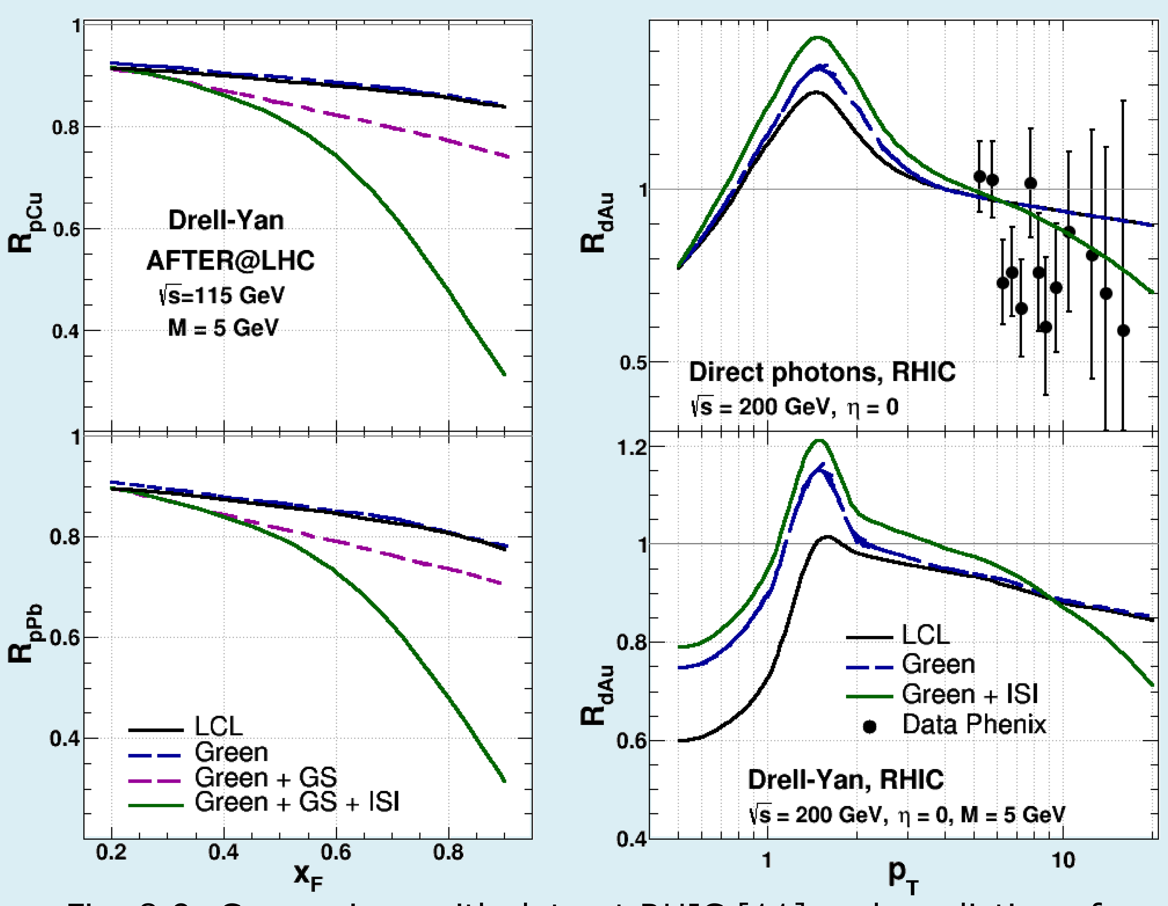

Fig. 8,9: Comparison with data at RHIC [11] and prediction of DY for experiment AFTER@LHC and RHIC.

Gluon shadowing

Higher Fock components containing gluons $|\gamma^*qG\rangle,|\gamma^*q2G\rangle$,... lead to additional corrections, called gluon shadowing (GS). The corresponding suppression factor R_G [7], calculated as the correction to the total γ^*A cross section for the longitudinal photon, $R_G(x,Q^2,b)\approx 1-\frac{\Delta\sigma_L^{(\gamma^*A)}}{A\sigma_{tot}^{(\gamma^*p)}}$, was included in calculations replacing $\sigma^N_{q\bar{q}}(\vec{\rho},x)\to\sigma^N_{q\bar{q}}(\vec{\rho},x)R_G(x,Q^2,b)$.

Effective energy loss

The initial state energy loss (ISI effects) is expected to essentially suppress the nuclear cross section reaching towards kinematical limits, $x_L=\frac{2p_L}{\sqrt{s}}\to 1$ and $x_T=\frac{2p_T}{\sqrt{s}}\to 1$. Correspondingly, the proper variable which controls this effect is $\xi=\sqrt{x_T^2+x_L^2}$.
The magnitude of suppression was evaluated in [8]. It was found within the Glauber approximation that each interaction in the nucleus leads to a suppression factor $S(\xi)\approx 1-\xi$. Summing up over the multiple initial state interactions in a pA collision with impact parameter b, one arrives at a nuclear ISI-modified PDF

$$f_{a/p}(x,Q^2)\Rightarrow f^A_{a/p}(x,Q^2,b)$$
$$=C_v f_{a/p}(x,Q^2)\frac{e^{-\xi\sigma_{eff}T_A(b)}-e^{-\sigma_{eff}T_A(b)}}{(1-\xi)(1-e^{-\sigma_{eff}T_A(b)})}.$$

Conclusions

We use for the first time the color dipole approach based on the Green function formalism for description of DY and direct photon production on nuclear targets in the kinematic regions, where SCL and LCL should not be used. We demonstrate that GS and ISI energy loss cause a significant nuclear suppression. Whereas GS dominates at large energies and x_F, ISI effects are important at large p_T and/or x_F. Our predictions are in a good agreement with FNAL E772 and E886 data as well as with data from the Phenix collaboration. Finally we predict a strong suppression due to ISI effects that can be verified in the future by planned experiment AFTER@LHC.

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