Nuclear effects in Drell-Yan production at the LHC

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Abstract

Using the color dipole formalism we study production of Drell-Yan (DY) pairs in proton-nucleus interactions in the kinematic region corresponding to LHC experiments. Lepton pairs produced in a hard scattering are not accompanied with any final state interaction, either energy loss or absorption. Consequently, dileptons may serve as more efficient and cleaner probes for the onset of nuclear effects than inclusive hadron production.
We present a systematic analysis of these effects in production of Drell-Yan pairs in *pPb* interaction at the LHC. We perform predictions for nuclear suppression as a function of p_T, rapidity and dilepton invariant mass that can be verified by the LHC experiments. We found that a strong nuclear suppression can be interpreted as an effective energy loss proportional to the initial energy universally induced by multiple initial state interactions. We include and analyze also a contribution of coherent effects associated with gluon shadowing affecting the observables predominantly at small and medium-high p_T.

Proton-nucleus interactions

The dynamics of DY production on nuclear targets is controlled by the mean coherence length

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

where M is a dilepton mass, m_q is the mass of a projectile quark and α is a fraction of the light-cone momentum of the quark carried out by the gauge boson. The condition for the onset of shadowing is that the coherence length exceeds the nuclear radius R_A, $l_c \gtrsim R_A$. In the LHC kinematic region this long coherence length (LCL) limit can be safely used as is demonstrated in Fig. 3. This allows to incorporate shadowing effects via eikonalization of $\sigma^N_{q\bar q}$ [10]

$$\sigma^N_{q\bar q}(\alpha\rho) \to \sigma^A_{q\bar q}(\alpha\rho) = 2\int d^2b\left(1-\exp\left[-\tfrac{1}{2}\sigma^N_{q\bar q}(\alpha\rho)T_A(b)\right]\right), \qquad (*)$$

where $T_A(b)$ is the nuclear thickness function. Fig. 4 demonstrates a good agreement of our calculations for DY production in *pPb* collisions with data from ATLAS experiment [11]. Fig. 5 shows predictions for nuclear modification factor R_{pPb} as function of p_T for production of DY pairs at rapidities $y = 0, 3$ and dilepton invariant masses $66 < M < 122$ GeV typical for the ATLAS experiment. GS and ISI effects are irrelevant at $y = 0$. However, we expect a strong nuclear suppression especially at $y = 3$ and large p_T caused by ISI effects. Here GS effects give a small contribution to nuclear suppression only at $p_T < 15 \div 20$ GeV.

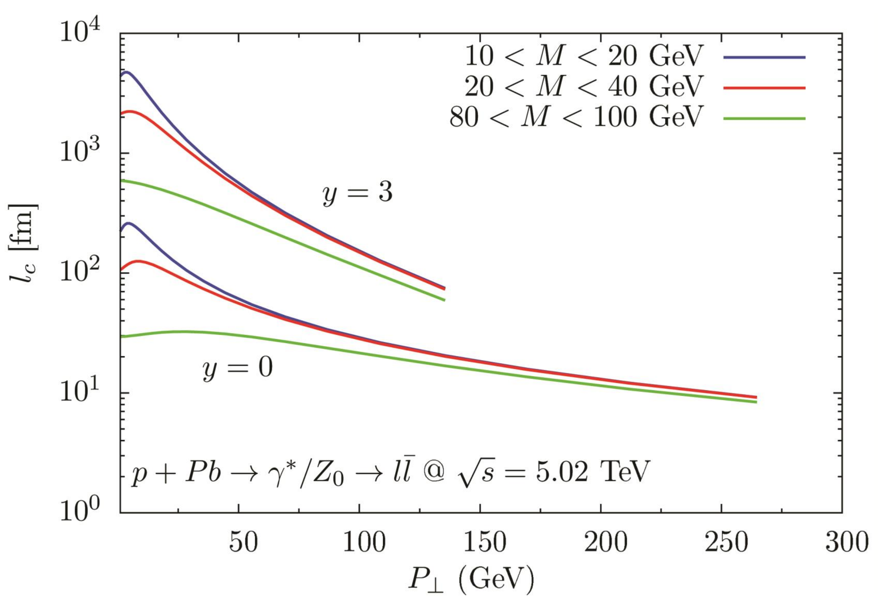

Fig. 3: Mean coherence length.

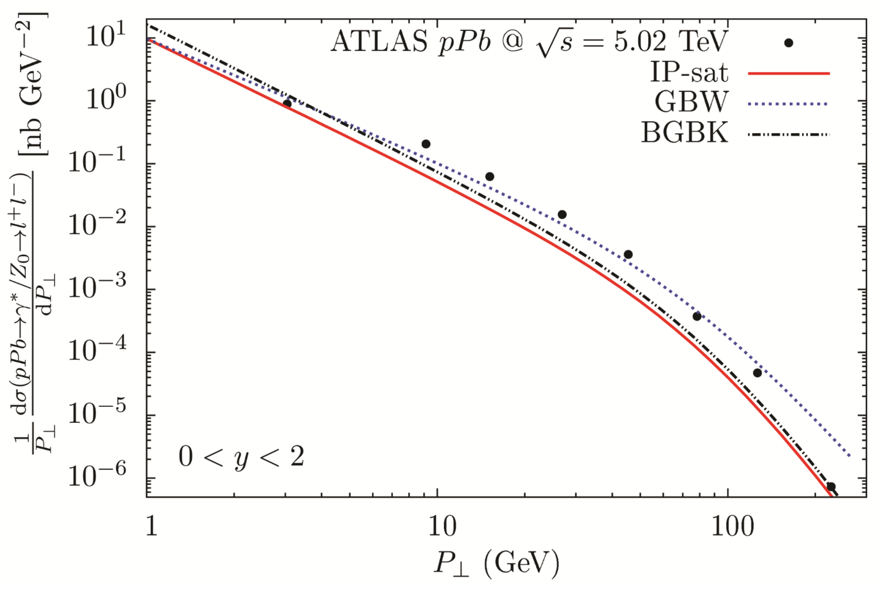

Fig. 4: DY dilepton p_T distribution in *pPb* collisions vs. ATLAST data [11].

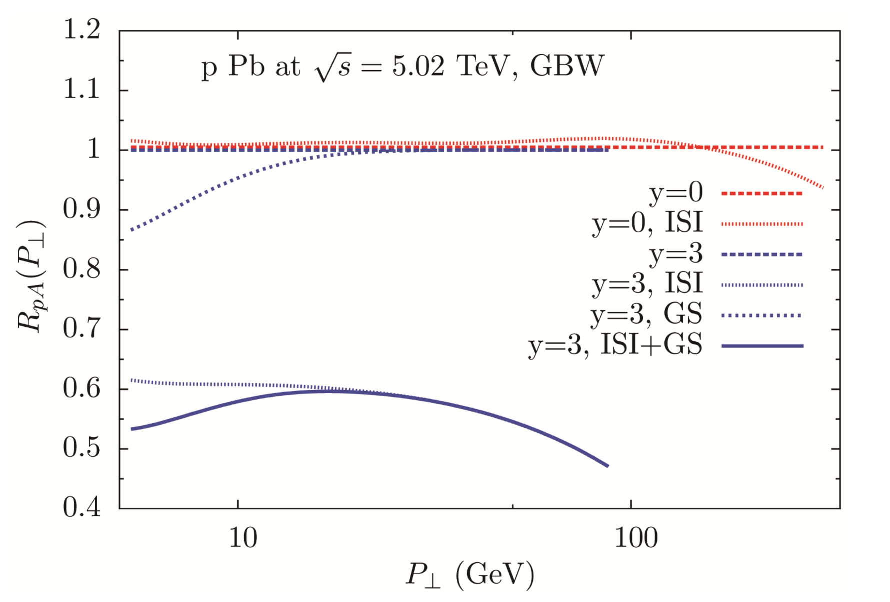

Fig. 5: Predictions for nuclear modification factor R_{pPb}.

Color dipole picture

In the color dipole picture, the production mechanism of DY pairs looks like a radiation of a gauge boson $G^* = \gamma^*, Z^0, W^\pm$ by a quark (diquark)[1,2]. Then the quark–nucleus differential cross section reads [1-3]

$$\frac{d\sigma^f_{T,L}(qN\to qG^*X)}{d\ln\alpha\, d^2P_\perp} = \frac{1}{(2\pi)^2}\int d^2\rho_1 d^2\rho_2\, e^{i\vec q_\perp\cdot(\vec\rho_1-\vec\rho_2)}\Psi^{V-A}_{T,L}(\alpha,\vec\rho_1)\Psi^{V-A,*}_{T,L}(\alpha,\vec\rho_2)\Sigma(\alpha,\rho_1,\rho_2),$$

where $\Sigma(\alpha,\rho_1,\rho_2) = \frac{1}{2}\left(\sigma^N_{q\bar q}(\alpha\rho_1)+\sigma^N_{q\bar q}(\alpha\rho_2)-\sigma^N_{q\bar q}(\alpha|\rho_1-\rho_2|)\right)$ and $P_\perp$ is the transverse momentum of the outgoing gauge boson. The vector and axial-vector wave functions are decorrelated in the simplest case of an unpolarized incoming quark [2]. In this work we take into account the presence of $G^* = \gamma^*$ and Z^0. The corresponding wave functions $\Psi^{V-A}_{T,L}(\alpha,\vec\rho)$ can be found in [2]. The cross section for inclusive production of a G^* in *pp* collisions is expressed as [1],

$$\frac{d\sigma_{L,T}(pp\to G^*X)}{d^2P_\perp d\eta\, dM^2} = J(\eta,P_\perp)\frac{x_1}{x_1+x_2}\sum_f\int_{x_1}^1\frac{d\alpha}{\alpha^2}\left(q_f(x_q,\mu^2)+\bar q_f(x_q,\mu^2)\right)\frac{d\sigma^f_{T,L}(qN\to qG^*X)}{d\ln\alpha\, d^2P_\perp},$$

where $J(\eta,P_\perp) = \frac{2}{\sqrt{s}}\sqrt{M^2+P_\perp^2}\cosh\eta$ is the Jacobian of the transformation between $x_F = x_1 - x_2$ and the pseudorapidity η, $x_q = x_1/\alpha$ with x_1 representing the momentum fraction of G^* from the projectile proton and $q_f, \bar q_f$ denote PDFs [4]. In order to estimate the DY cross section one should add the factor accounting for the decay of $G^*\to l^+l^-$ [2]. In calculations we use several parametrizations of dipole cross sections; GBW [5], BGBK [6] and IP-Sat [7].

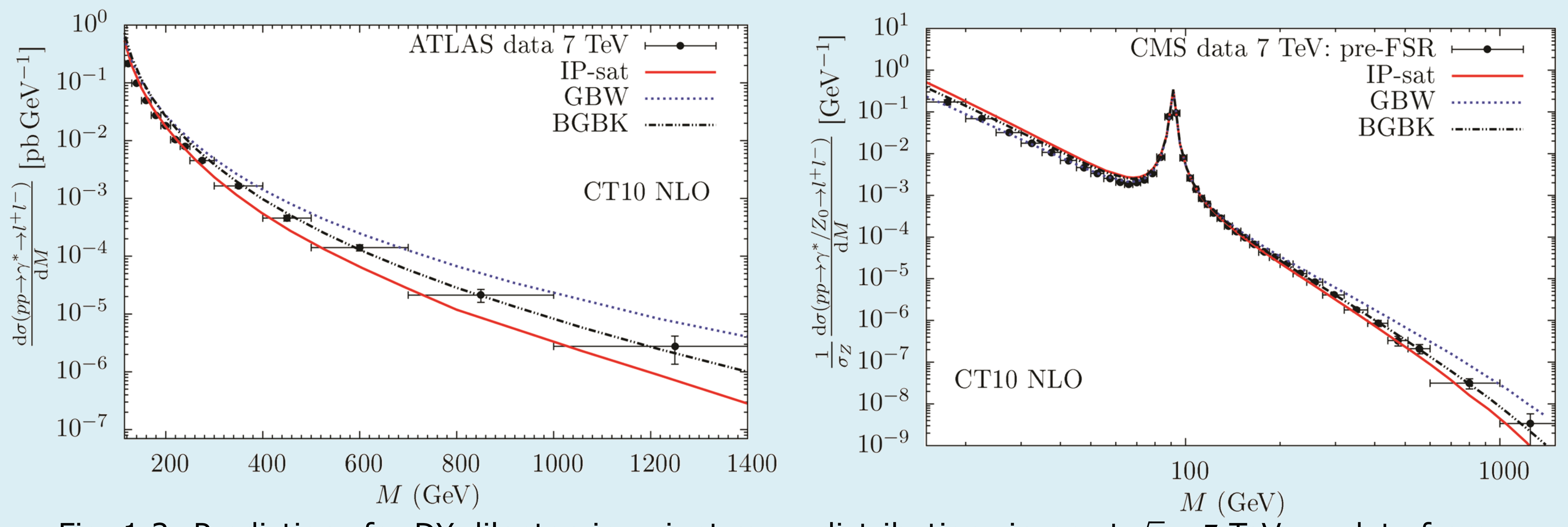

Fig. 1,2: Predictions for DY dilepton invariant mass distributions in *pp* at $\sqrt{s} = 7$ TeV vs. data from ATLAS [8] and CMS [9].

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 [12], calculated as the correction to the total $\gamma^* A$ 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 [13]. 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 p-A collision with impact parameter b, one arrives at a nuclear ISI-modified PDF

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

Drell-Yan - Hadron correlations

The correlation function $C(\Delta\phi)$ depends on the azimuthal angle difference $\Delta\phi$ between the trigger and associate particles. Azimuthal correlations are investigated through a coincidence probability defined in terms of a trigger particle, which could be either the gauge boson or the hadron. If we assume the former as trigger particle then the correlation function is written as [1]

$$C(\Delta\phi) = \frac{2\pi\int_{p_\perp^{G^*},p_\perp^h > p_\perp^{cut}} dP_\perp^{G^*} P_\perp^{G^*} dP_\perp^h P_\perp^h \frac{d\sigma(pp\to hGX)}{d^2P_\perp^h d\eta^h d^2P_\perp^{G^*} d\eta^{G^*} d^2b}}{\int_{p_\perp^{G^*} > p_\perp^{cut}} dP_\perp^{G^*} P_\perp^{G^*}\frac{d\sigma(pp\to GX)}{d^2P_\perp^{G^*} d\eta^{G^*} d^2b}}$$

where $\Delta\phi$ is the angle formed between the gauge boson and the hadron. Differential cross sections for G^* and G^*h production in momentum representation can be found in [1].
Fig. 6 demonstrates that a double peak structure is predicted around $\Delta\phi = \pi$ in *pp* collisions considering that the photon and the pion are produced at forward rapidities, close to the limit of the phase space.
Using eikonalisation (*) in LCL limit we calculated correlation functions for proton-lead collisions as is shown in Fig. 7, where we expect again unique double peak structure at forward rapidity $y = 4$.

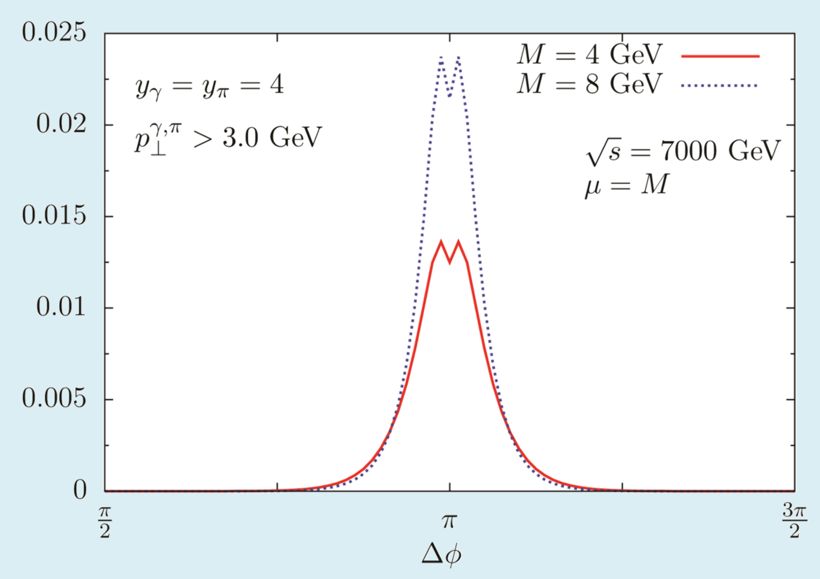

Fig. 6: Correlation function for the DY – pion Production in *pp* collisions.

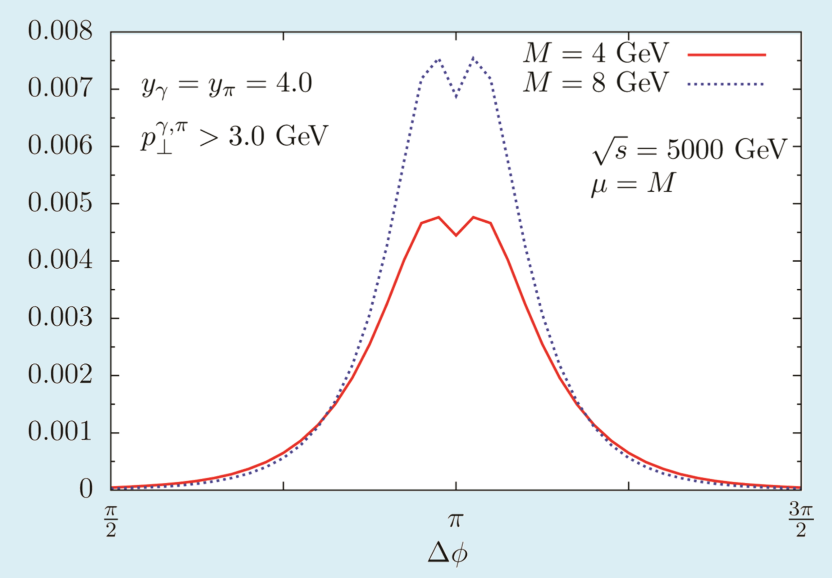

Fig. 7: Correlation function for the DY – pion Production in *pPp* collisions.

Conclusions

Within the color dipole picture we analyzed the DY production from the gauge boson $G^* = \gamma$ and Z^0. For *pp* collisions we found a good agreement of the invariant cross sections as function of dilepton invariant mass with ATLAS and CMS data. We demonstrate that for production of DY pairs on nuclear targets LCL limit can be safely used in the LHC kinematic region. Our calculations of differential cross section for DY production in *pPb* collisions were successfully compared with ATLAS data. We showed that the main source of a strong nuclear suppression especially at forward rapidities expected at LHC comes from ISI corrections. Small onset of GS is visible only at $y = 3$ for $p_T < 15 \div 20$ GeV. Investigating correlation function corresponding to G^* and pion production we found an unique double peak structure around $\Delta\phi = \pi$ not only for *pp* but also for *pPb* collisions.

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