

Forward production of Drell-Yan dileptons at high energies and low dilepton invariant masses in a k_t -factorization approach: Do we see onset of saturation?

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We discuss Drell-Yan production of dileptons at high energies in forward rapidity region in a hybrid high-energy approach. This approach uses unintegrated gluon distributions in one proton and collinear quark/antiquark distributions in the second proton. Corresponding momentum-space formula for the differential cross sections in high-energy approximation has been derived. The relation to the commonly used dipole approach is discussed. We conclude and illustrate that some results of the dipole approaches are too approximate, as far as kinematics is considered, and in fact cannot be used for real experiments. We find that the dipole formula is valid only in very forward/backward rapidity regions ($|y| > 5$). Some differential cross sections for low-mass dilepton production are shown and compared to the LHCb and ATLAS experimental data. In distinction to dipole approaches, we include four Drell-Yan structure functions (the impact of interference structure functions is rather small for typical experimental cuts). We find that both side contributions (gq/\bar{q} and $q/\bar{q}g$) have to be included even for the LHCb rapidity coverage which is in contradiction with what is usually done in the dipole approach. We present results for different unintegrated gluon distributions from the literature (some of them include saturation effects). We see no clear hints of saturation even at small M_{ll} .

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1. Introduction

It was proposed some time ago that the Drell-Yan production of low invariant masses of dileptons in forward directions is a good place in searching for the onset of (gluon) saturation [1]. Recently a numbers of papers addressing the Drell-Yan process at the LHC appeared, which use the dipole approach (see e.g. [2, 3, 4, 5]) in which the main ingredient is the dipole-nucleon cross section parametrized as a function of dipole size (ρ) and collision energy or a similar equivalent kinematical variable.

In the dipole picture only global kinematic variables of the lepton pair (invariant mass, rapidity and transverse momentum of the pair) are used. In contrast, in real experiments one imposes cuts on pseudorapidities and transverse momenta of leptons. A real comparison of the theoretical predictions and experimental data is therefore not possible.

Here we present an alternative formulation in the momentum space proposed recently [6]. This approach allows for explicit treatment of momenta of individual leptons (e^+e^- or $\mu^+\mu^-$) and therefore a comparison to existing experimental data.

The mechanisms considered are shown in Fig.1.

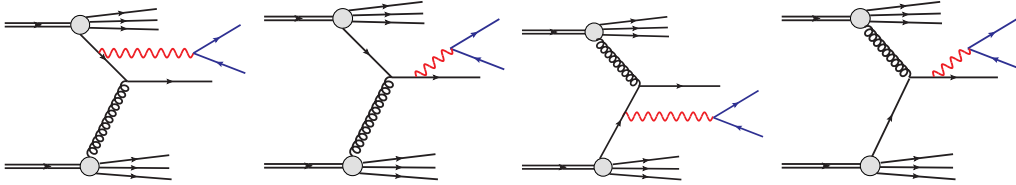


Figure 1: The diagrams relevant for forward and backward production of dilepton pairs.

2. Formalism and Results

The inclusive cross section for lepton pair production can be written in the form:

$$\begin{aligned}
 \frac{d\sigma(pp \rightarrow l^+l^-X)}{dx_+ dx_- d^2\mathbf{k}_+ d^2\mathbf{k}_-} &= \frac{\alpha_{\text{em}}}{(2\pi)^2 M^2} \frac{x_F}{x_+ x_-} \left\{ \Sigma_T(x_F, \mathbf{q}, M^2) D_T\left(\frac{x_+}{x_F}\right) + \Sigma_L(x_F, \mathbf{q}, M^2) D_L\left(\frac{x_+}{x_F}\right) \right. \\
 &+ \Sigma_\Delta(x_F, \mathbf{q}, M^2) D_\Delta\left(\frac{x_+}{x_F}\right) \left(\frac{\mathbf{l} \cdot \mathbf{q}}{|\mathbf{l}| |\mathbf{q}|} \right) \\
 &\left. + \Sigma_{\Delta\Delta}(x_F, \mathbf{q}, M^2) D_{\Delta\Delta}\left(\frac{x_+}{x_F}\right) \left(2 \left(\frac{\mathbf{l} \cdot \mathbf{q}}{|\mathbf{l}| |\mathbf{q}|} \right)^2 - 1 \right) \right\}. \quad (2.1)
 \end{aligned}$$

Here x_\pm are longitudinal (lightcone-) momentum fractions of leptons, \mathbf{k}_\pm are their transverse momenta. The heavy virtual photon carries the longitudinal momentum fraction $x_F = x_+ + x_-$ and transverse momentum $\mathbf{q} = \mathbf{k}_+ + \mathbf{k}_-$. There also appears the light-front relative transverse momentum of l^+ and l^- :

$$\mathbf{l} = \frac{x_+}{x_F} \mathbf{k}_- - \frac{x_-}{x_F} \mathbf{k}_+. \quad (2.2)$$

The functions $\Sigma_i(x_F, \mathbf{q}, M^2)$, $i = T, L, \Delta, \Delta\Delta$ correspond to the four helicity structure functions [7] of inclusive lepton pair production. They contain all information of strong dynamics in the production

of the virtual photon. The functions D_i and the momentum structures in brackets represent the density matrix of decay of the massive photon into l^+l^- . See [6] for explicit expressions. Let us concentrate on, say the first two diagrams of Fig. 1. Then we are dealing with a process where a fast quark from one proton radiates a virtual photon interacting with a small- x gluon of the other proton. It is therefore natural to adopt a factorization which involves the collinear quark distribution from one side and the k_T -dependent unintegrated gluon distribution from the other side. We can write for the functions Σ_i :

$$\begin{aligned}\Sigma_i(x_F, \mathbf{q}, M) &= \sum_f \int dx_1 dz \delta(x_F - zx_1) \left[q_f(x_1, \mu^2) + \bar{q}_f(x_1, \mu^2) \right] \hat{\Sigma}_i(z, \mathbf{q}, M^2). \\ &= \sum_f \frac{e_f^2 \alpha_{\text{em}}}{2N_c} \int_{x_F}^1 dx_1 \left[q_f(x_1, \mu^2) + \bar{q}_f(x_1, \mu^2) \right] \int \frac{d^2\kappa}{\pi\kappa^4} \mathcal{F}(x_2, \kappa^2) \alpha_S(\bar{q}^2) I_i\left(\frac{x_F}{x_1}, \mathbf{q}, \kappa\right).\end{aligned}\quad (2.3)$$

Here we have introduced the parton-level functions $\hat{\Sigma}_i$ which correspond to the process $qp \rightarrow q\gamma^* p$. In the last line we have given their impact-factor representation in terms of the unintegrated gluon distribution $\mathcal{F}(x_2, \kappa^2)$ and impact factors I_i which can be found in [6].

An important comment on the longitudinal momentum fractions x_1, x_2 is in order. They must be obtained from the full l^+l^-q final state:

$$\begin{aligned}x_1 &= \sqrt{\frac{\mathbf{k}_+^2}{S}} e^{y_+} + \sqrt{\frac{\mathbf{k}_-^2}{S}} e^{y_-} + \sqrt{\frac{\mathbf{k}_q^2}{S}} e^{y_q}, \\ x_2 &= \sqrt{\frac{\mathbf{k}_+^2}{S}} e^{-y_+} + \sqrt{\frac{\mathbf{k}_-^2}{S}} e^{-y_-} + \sqrt{\frac{\mathbf{k}_q^2}{S}} e^{-y_q}.\end{aligned}\quad (2.4)$$

Here the contribution from the final state (anti-)quark must not be neglected!

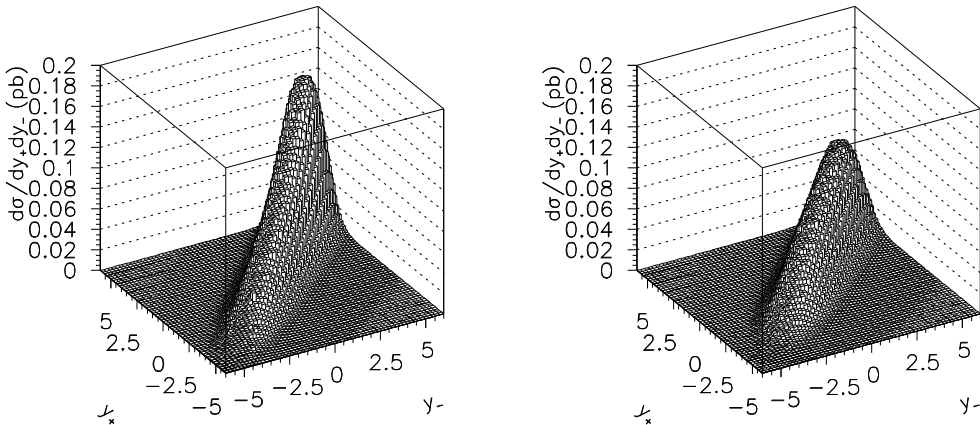


Figure 2: Two-dimensional (y_+, y_-) distribution for $\sqrt{s} = 7$ TeV and $k_{T+}, k_{T-} > 3$ GeV for MSTW08 PDF and KMR (left) and KS (right) UGDFs.

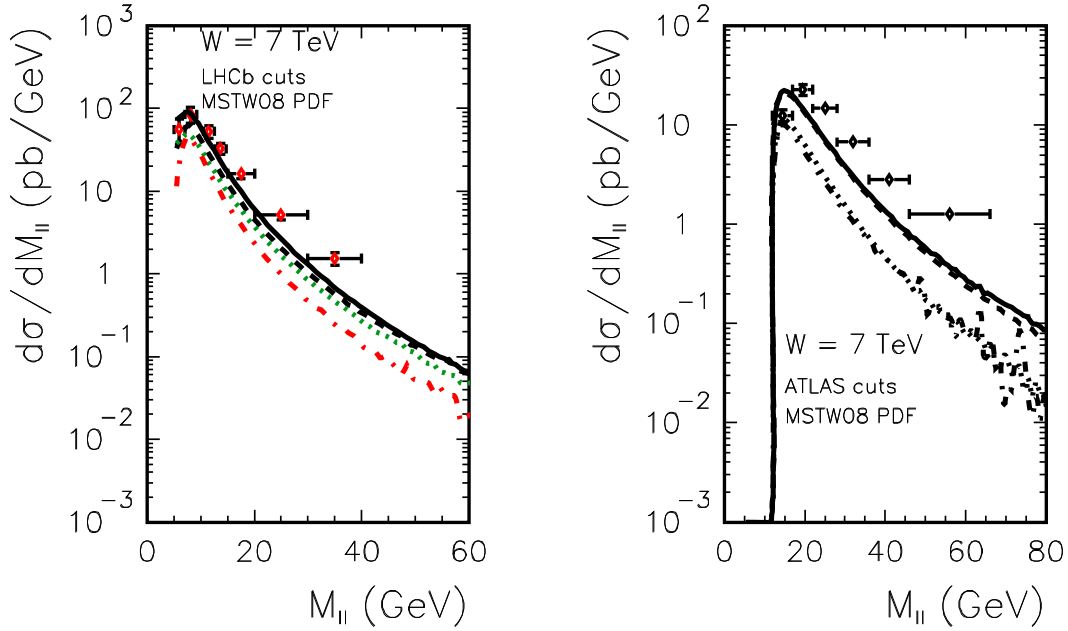


Figure 3: Left panel: Invariant mass distribution (only the dominant component) for the LHCb cuts: $2 < y_+, y_- < 4.5$, $k_{T+}, k_{T-} > 3$ GeV for different UGDs: KMR (solid), Kutak-Stasto (dashed), AAMS (dotted) and GBW (dash-dotted). Right panel: the same for the ATLAS kinematics: $-2.4 < y_+, y_- < 2.4$, $k_{T+}, k_{T-} > 6$ GeV. Here both gq/\bar{q} and $q/\bar{q}g$ contributions have been included.

We come to a selection of results presented in [6]. In Fig. 2 we show a map of the (y_+, y_-) rapidity plane of leptons for two different unintegrated gluon distributions. We see a strong correlation along the diagonal, which is a property of the $\gamma^* \rightarrow l^+ l^-$ “decay”. Notice the peak in the forward rapidity region – still there is a nonnegligible amount of radiation into negative rapidities. The presence of such radiation in the “backward” region makes it necessary to include all of the diagrams of Fig. 1.

In Fig. 3 we compare our results to experimental data on so-called “low-mass” Drell-Yan. In the left panel we compare our results to the data from the LHCb collaboration [8], which cover the forward rapidity region. We see that a reasonable description of data can be obtained by an unintegrated gluon distribution constructed by the KMR prescription. Gluon distributions which include gluon saturation effects do not lead to a good agreement, certainly there is no trace that gluon saturation would be required by the data. In the right panel, we compare our results to the ATLAS data [9]. These are obtained in the central rapidity region, and we see that we are underpredicting the cross section at larger masses. This is a sign that the approach used here is in fact not adequate for the central rapidity region. For example, here one should also include transverse momenta of quarks in a consistent manner.

In Fig. 4 we return to the LHCb kinematics. In the left panel we show again the distribution in dilepton invariant mass. Here by the dashed line we show the contribution from the “other side” proton. We see that such a spillover of dileptons emitted into the forward region of “the other”

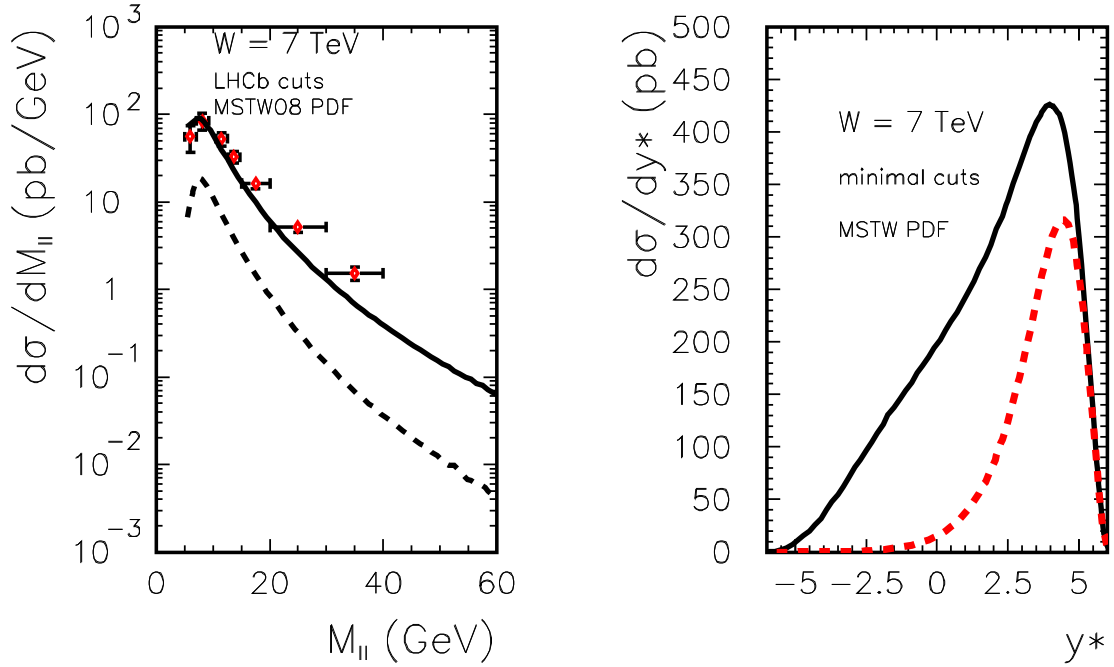


Figure 4: Contributions of the second-side component for the LHCb kinematics: $2 < y_+, y_- < 4.5$, $k_{T+}, k_{T-} > 3$ GeV. KMR UGDF was used here. Right panel: Distribution in rapidity of the dileptons for $\sqrt{s} = 7$ TeV and $k_{T+}, k_{T-} > 3$ GeV for MSTW08 valence quark distributions and KMR UGDFs. The dashed line is the contribution from valence quarks only.

proton is not negligible. It seems to be generally neglected in dipole model calculations. In the right panel we show the rapidity distribution of the virtual photon. By the red dashed line we show the contribution from valence quarks of the “forward” proton only. We see that within the rapidity coverage of LHCb sea quarks are important.

3. Conclusions

In our recent paper [6] we have considered Drell-Yan production of dileptons in the forward rapidity region in a hybrid high-energy approach. Corresponding formula for matrix element in the high-energy approximation has been derived and presented in our recent paper.

Here we have shown some examples of differential cross sections corresponding to recent experimental data for low-mass dilepton production relevant for the LHCb and ATLAS experiments. Different UGDFs have been used in our calculations.

In contrast what was done in the literature, we have found that both side contributions have to be included even for the LHCb configuration.

We do not see clear hints of saturation at small M_{II} .

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