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# Drell-Yan production at forward rapidities: a hybrid factorization approach

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## Abstract

We discuss the Drell-Yan production of dileptons at high energies in the forward rapidity region of proton-proton collisions in a hybrid high-energy approach. This approach uses unintegrated gluon distributions in one proton and collinear quark/antiquark distributions in the second proton.

We compute various distributions for the case of low-mass dilepton production and compare to the LHCb and ATLAS experimental data on dilepton mass distributions. In distinction to dipole approaches, we include four Drell-Yan structure functions as well as cuts at the level of lepton kinematics. The impact of the 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, but we see no clear hints of saturation even at small  $M_{ll}$ .

## 1 Introduction

Drell-Yan production in the forward direction is dominated by the quark-gluon fusion, where especially at not too large invariant masses of the dilepton system the gluon density is probed at low values of the longitudinal momentum fraction  $x$ . One might

therefore probe a kinematic range where gluon saturation effects are potentially large. Consequently the forward Drell-Yan process has been discussed in the Color-Glass Condensate approach in [1]. Recently much attention has also been paid to applications of the color dipole approach to the Drell-Yan process at the LHC (see e.g. [2, 3, 4, 5])

In this talk we instead present an alternative formulation in momentum space published recently in [6]. In particular, this approach includes all the four structure functions [7] of the Drell-Yan process and allows to put cuts on the momenta of individual leptons ( $e^+e^-$  or  $\mu^+\mu^-$ ). This is important if one wants to compare to existing experimental data.

The mechanisms considered are shown in the diagrams in Fig.1.

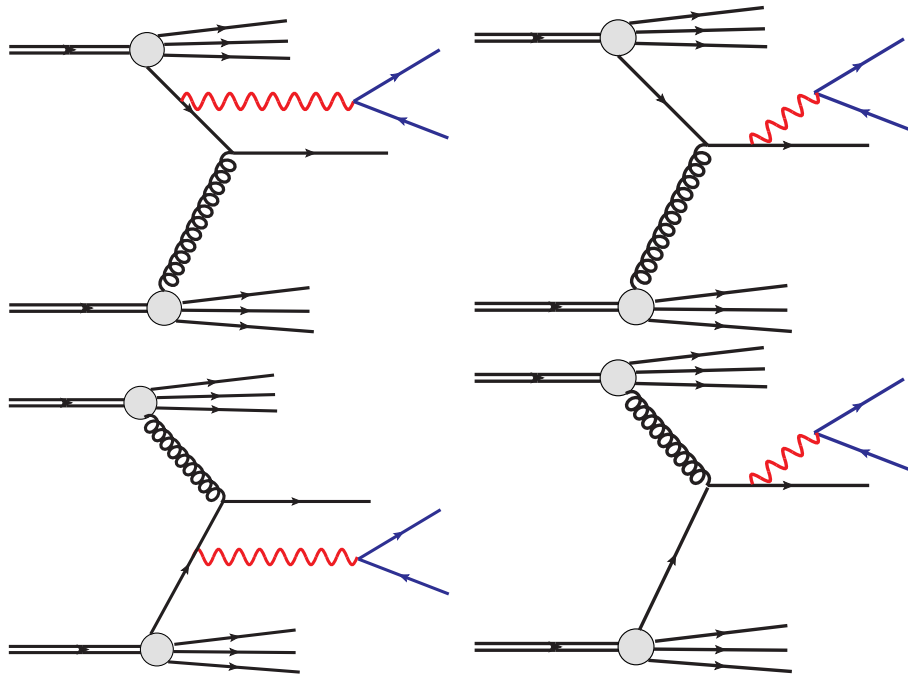


Figure 1: The diagrams relevant for forward and backward production of dilepton pairs.

## 2 Results

We start by defining the relevant kinematical variables. Below,  $x_{\pm}$  will denote the longitudinal (lightcone-) momentum fractions of leptons, while  $\mathbf{k}_{\pm}$  are their transverse momenta. The heavy virtual photon of mass  $M^2$  then carries the longitudinal momentum fraction  $x_F = x_+ + x_-$  and transverse momentum  $\mathbf{q} = \mathbf{k}_+ + \mathbf{k}_-$ . It is useful to introduce also the light-front relative transverse momentum of  $l^+$  and  $l^-$ :

$$\mathbf{l} = \frac{x_+}{x_F} \mathbf{k}_- - \frac{x_-}{x_F} \mathbf{k}_+. \quad (1)$$

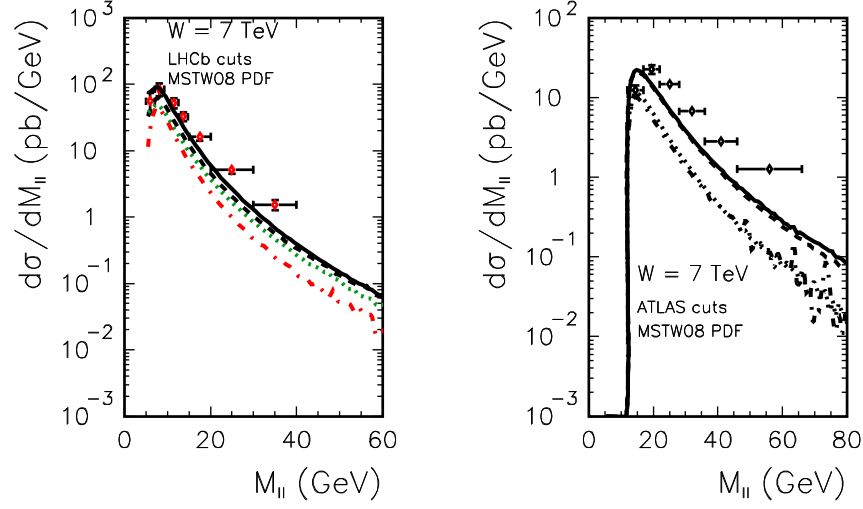


Figure 2: Left panel: Invariant mass distribution (only the dominant component) for the LHCb cuts:  $2 < y_+, y_- < 4.5$ ,  $k_{T+}, k_{T-} > 3$  GeV for different UGDFs: KMR (solid), Kutak-Stasto (dashed), AAMS (dotted) and GBW (dash-dotted). Right panel: the same for the ATLAS kinematics:  $-2.4 <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

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

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

The functions  $\Sigma_i(x_F, \mathbf{q}, M^2)$ ,  $i = T, L, \Delta, \Delta\Delta$  are in a one-to-one correspondence with the four helicity structure functions [7] of inclusive lepton pair production in a Gottfried-Jackson frame. 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  $l^+l^-$ . For explicit expressions, see [6].

Let us concentrate now on one of the partonic subprocesses, where a fast quark from one proton radiates a virtual photon while interacting with a small- $x$  gluon of the other proton. (E.g. the top two diagrams in Fig. 1.) Naturally the large- $x$  quark is described by the collinear quark distribution, while for the low- $x$  gluon it is more appropriate to use the  $k_T$ -dependent unintegrated gluon distribution.

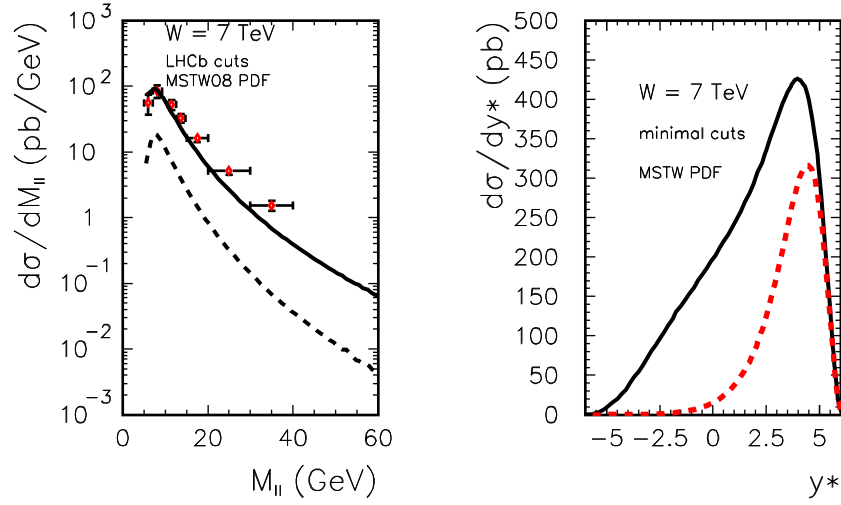


Figure 3: Left Panel: By the dashed line, we show the contributions of the second-side component for the LHCb kinematics:  $2 < y_+, y_- < 4.5$ ,  $k_{T+}, k_{T-} > 3$  GeV. KMR UGDF was used here. Right panel: Distribution in rapidity of the dileptons for  $\sqrt{s} = 7$  TeV and  $k_{T+}, k_{T-} >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

We can then write for the functions  $\Sigma_i$  an impact-factor representation typical of the  $k_\perp$ -factorization:

$$\begin{aligned} \Sigma_i(x_F, \mathbf{q}, M) &= \sum_f \frac{e_f^2 \alpha_{em}}{2N_c} \int_{x_F}^1 dx_1 \left[ q_f(x_1, \mu^2) + \bar{q}_f(x_1, \mu^2) \right] \\ &\times \int \frac{d^2 \kappa}{\pi \kappa^4} \mathcal{F}(x_2, \kappa^2) \alpha_S(\bar{q}^2) I_i\left(\frac{x_F}{x_1}, \mathbf{q}, \kappa\right). \end{aligned} \quad (3)$$

Here appears the unintegrated gluon distribution

$$\mathcal{F}(x_2, \kappa^2) \propto \frac{\partial x_2 g(x_2, \kappa^2)}{\partial \log(\kappa^2)}. \quad (4)$$

The impact factors  $I_i$  can be found in [6].

Here 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:

$$\begin{aligned} x_1 &= \sqrt{\frac{\mathbf{k}_+^2}{S}} e^{y_+} + \sqrt{\frac{\mathbf{k}_-^2}{S}} e^{y_-} + \sqrt{\frac{\mathbf{k}_q^2}{S}} e^{y_q}, \\ x_2 &= \sqrt{\frac{\mathbf{k}_+^2}{S}} e^{-y_+} + \sqrt{\frac{\mathbf{k}_-^2}{S}} e^{-y_-} + \sqrt{\frac{\mathbf{k}_q^2}{S}} e^{-y_q}. \end{aligned} \quad (5)$$

Neglecting the contribution from the final state (anti-)quark leads to a systematic underestimation of  $x$ -values, which may artificially enhance saturation effects.

In Fig. 2 we compare our results to recent experimental data. In the left panel we compare our results for the dilepton invariant mass distribution to the data from the LHCb collaboration [8], which cover the forward rapidity region. Here a reasonable description of data can be obtained by an unintegrated gluon distribution constructed by the KMR prescription. Other gluon distributions which include gluon saturation effects do not lead to such a good agreement. In the right panel, we compare our results to the ATLAS data [9]. These data were obtained in the central rapidity region. This kinematical domain is strictly speaking beyond the region of applicability of our approach. The asymmetrical treatment of collinear quarks and  $k_T$ -dependent gluons is not warranted here. And indeed, we do not describe the ATLAS data well, especially at large invariant masses.

The results shown in Fig. 3 were obtained in the LHCb kinematics. In the left panel we show by the dashed line the contribution from dileptons emitted from the “other side” proton. As we observe, such a spillover of dileptons emitted into the forward region of “the other” proton is not negligible. It seems to have been 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 Summary

In this talk at the Low- $x$  meeting, we have presented the main results from our recent paper [6] on the Drell-Yan production of dileptons in the forward rapidity region in a hybrid factorization approach. Here the large- $x$  parton participating in the hard process is described by a collinear parton distribution, while for the low- $x$  parton an unintegrated parton distribution is taken.

We have compared the results of our calculations to recent experimental data for low-mass dilepton production from the LHCb and ATLAS experiments.

Going beyond on previous work in the literature, we have found that emissions from both protons have to be included even for the LHCb configuration.

We find that LHCb data do not require gluon saturation effects at small  $M_{ll}$ .

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