EXPLORING DOUBLE-PARTON SCATTERING EFFECTS FOR JETS WITH LARGE RAPIDITY SEPARATION AND IN FOUR-JET PRODUCTION AT THE LHC*

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We present an estimation of the contribution of double parton scattering (DPS) for jets widely separated in rapidity and for four-jet sample. In the case of four-jet production, we calculate cross section for both single-parton scattering (SPS) using the code ALPGEN as well as for DPS in LO collinear approach. The DPS contribution is calculated within the so-called factorized Ansatz and each step of DPS is calculated in the LO collinear approximation. We show that the relative (with respect to SPS dijets and to the BFKL Mueller–Navelet (MN) jets) contribution of DPS is growing at large rapidity distance between jets. The calculated differential cross sections as a function of rapidity distance between the most remote in rapidity jets are compared with recent results of LL and NLL BFKL calculations for the Mueller–Navelet jet production at $\sqrt{s} = 7$ TeV. Our results for four-jet sample are compared with experimental data obtained recently by the CMS Collaboration and a rather good agreement is achieved. We propose to impose different cuts in order to enhance the relative DPS contribution. The relative DPS contribution increases when decreasing the lower cut on the jet transverse momenta as well as when a lower cut on the rapidity distance between the most remote jets is imposed.

1. Introduction

Many years ago, Mueller and Navelet predicted strong decorrelation in relative azimuthal angle [1] of jets with large rapidity separation due to exchange of the BFKL ladder between quarks (see left panel of Fig. 1). Since

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then, both leading-logarithmic and higher-order BFKL effects were calculated and discussed. The effect of the NLL correction is large and leads to significant lowering of the cross section. The LHC opens a new possibility to study the decorrelation in azimuthal angle. First experimental data measured at $\sqrt{s} = 7$ TeV are expected soon [2]. Also double parton scattering (DPS) can be important in this context (for diagrammatic representation of DPS, see the right panel of Fig. 1). We discussed recently how important is the contribution of DPS in the case of the jets widely separated in rapidity [3] and for four-jet sample [4].
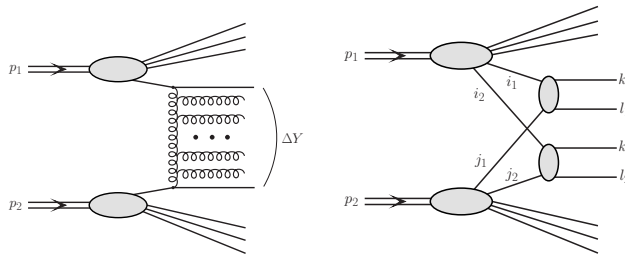

Fig. 1. A diagrammatic representation of the Mueller–Navelet jet production (left diagram) and of the double parton scattering mechanism (right diagram).

Four-jet production was already discussed in the context of double parton scattering. Actually, it was a first process where the DPS was claimed to be observed experimentally [5]. However, in most of the past as well as current analyses, the DPS contribution to four-jet production is relatively small and single parton scattering (SPS) driven by the $2 \to 4$ partonic processes dominates.

On the theoretical side, the DPS effects in four-jet production were discussed in Refs. [6–11]. A first theoretical estimate of SPS four-jet production, including only some partonic subprocesses, and its comparison to DPS contribution was presented in Ref. [8] for Tevatron. Some new kinematical variables useful for identification of DPS were proposed in Ref. [10]. The presence of perturbative parton splitting mechanism was discussed in Ref. [11].

In our recent studies, we have shown how big can be the contribution of DPS for jets widely separated in rapidity [3]. Understanding of this contribution is important in the context of searching for BFKL effects or in general QCD higher-order effects [12].

In the present letter, we wish to discuss also exclusive four-jet sample where the situation in the context of searching for DPS is even better [4]. In Ref. [4], we showed how to maximize the DPS contribution by selecting relevant kinematical cuts. Here, we shall show only some examples.

2. DPS mechanism

Partonic cross sections used to calculate DPS are calculated only in leading order. Then, the cross section for dijet production can be written as

$$\frac{d\sigma(ij \to kl)}{dy_1 dy_2 d^2 p_t} = \frac{1}{16\pi^2 \hat{s}^2} \sum_{i,j} x_1 f_i\left(x_1, \mu^2\right) \ x_2 f_j\left(x_2, \mu^2\right) \ \overline{|\mathcal{M}_{ij \to kl}|^2}. \qquad (1)$$

In our calculations, we include all leading-order $ij \to kl$ partonic subprocesses. The K-factor for dijet production is rather small, of the order of 1.1–1.3. It was shown in Ref. [3] that already the leading-order approach gives results in sufficiently reasonable agreement with recent ATLAS and CMS inclusive jet data.

This simplified leading-order approach can be, however, used easily in calculating DPS differential cross sections. The multi-dimensional differential cross section can be written as

$$\frac{d\sigma^{\mathrm{DPS}}(pp \to 4\mathrm{jets}\ X)}{dy_1 dy_2 d^2 p_{1\mathrm{t}} dy_3 dy_4 d^2 p_{2\mathrm{t}}} = \sum_{i_1,j_1,k_1,l_1;i_2,j_2,k_2,l_2} \frac{\mathcal{C}}{\sigma_{\mathrm{eff}}} \frac{d\sigma(i_1 j_1 \to k_1 l_1)}{dy_1 dy_2 d^2 p_{1\mathrm{t}}} \frac{d\sigma(i_2 j_2 \to k_2 l_2)}{dy_3 dy_4 d^2 p_{2\mathrm{t}}},$$
$$(2)$$

where $\mathcal{C} = \left\{ \begin{array}{ll} \frac{1}{2} & \text{if } i_1 j_1 = i_2 j_2 \wedge k_1 l_1 = k_2 l_2 \\ 1 & \text{if } i_1 j_1 \neq i_2 j_2 \vee k_1 l_1 \neq k_2 l_2 \end{array} \right\}$ and partons $j, k, l, m = g, u, d, s, \bar{u}, \bar{d}, \bar{s}$. The combinatorial factors include identity of the two subprocesses. Each step of DPS is calculated in the leading-order approach (see Eq. (1)).

In the calculations, we have taken in most cases $\sigma_{\mathrm{eff}} = 15$ mb. Phenomenological studies of σ_{eff} summarized *e.g.* in [13] give a similar value.

3. DPS and jets with large rapidity separation

In Fig. 2, we show distribution in the rapidity distance between two jets in LO collinear calculation and between the most distant jets in rapidity in the case of four DPS jets. In this calculation, we have included cuts for the CMS experiment [2]: $y_1, y_2 \in (-4.7, 4.7)$, $p_{1\mathrm{t}}, p_{2\mathrm{t}} \in (35$ GeV, 60 GeV$)$. For comparison, we show also results for the BFKL calculation from Ref. [14]. For this kinematics, the DPS jets give relatively sizeable contribution only at large rapidity distance. The NLL BFKL cross section (long-dashed line) is smaller than that for the LO collinear approach (short-dashed line).

In Fig. 3, we show rapidity-difference distribution for even smaller lowest transverse momenta of the jet. A measurement of such jets may be, however, difficult. Now the DPS contribution may even exceed the standard SPS dijet contribution, especially at the nominal LHC energy. One could also try to measure correlations of semihard ($p_t \sim 10$ GeV) neutral pions with the help of so-called zero-degree calorimeters (ZDC) [3].

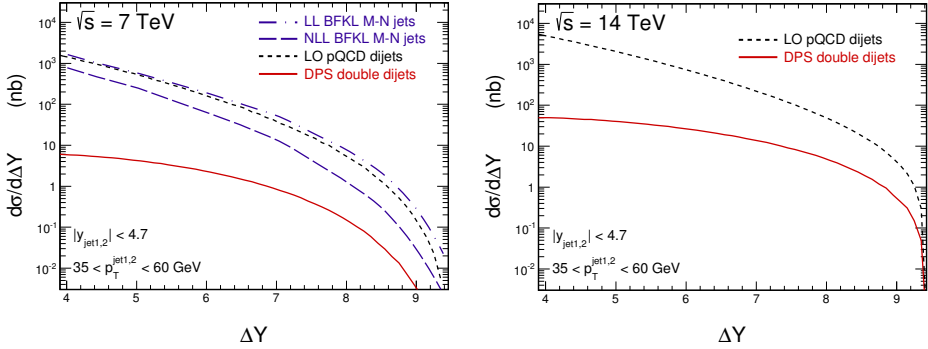Fig. 2. Distribution in rapidity distance between jets (35 GeV $< p_t <$ 60 GeV). The collinear pQCD result is shown by the short-dashed line and the DPS result by the solid line for $\sqrt{s} = 7$ TeV (left panel) and $\sqrt{s} = 14$ TeV (right panel). For comparison, we show also results for the BFKL Mueller–Navelet jets in leading-logarithm and next-to-leading-order logarithm approaches from Ref. [14].
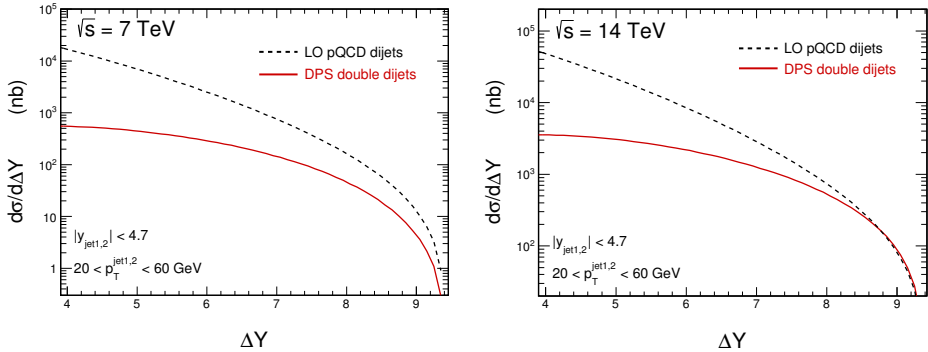

Fig. 3. The same as in the previous figure but now for smaller lower cut on jet transverse momentum.

4. In search for optimal conditions for DPS contribution in four-jet sample

First, we wish to demonstrate how reliable our SPS four-jet calculation is. In Fig. 4, we compare the results of calculation with the leading-order code ALPGEN [15] with recent CMS experimental data [12]. In this analysis the CMS Collaboration imposed different transverse momentum cuts on the leading, subleading, 3rd and 4th jets. In this calculation, we have used an extra K-factor to effectively include higher-order effects [16]. We get relatively good description of both transverse momentum and pseudorapidity distributions of each of the four (ordered in transverse momentum) jets. Therefore, we conclude that the calculation with the ALPGEN generator can be a reliable SPS reference point for an exploration of the DPS effects.
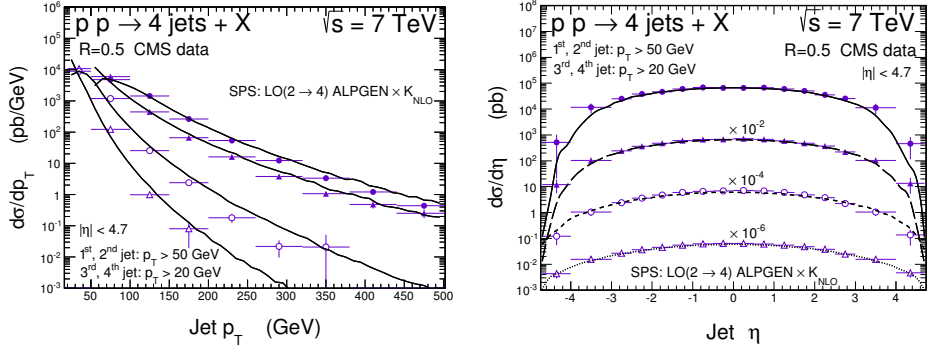
Fig. 4. Transverse momentum (left panel) and rapidity (right panel) distributions of each of the four-jets (ordered in transverse momentum) in the four-jet sample together with the CMS experimental data [12]. The calculations were performed with the code ALPGEN [15]. Here, kinematical cuts relevant for the experiment were applied to allow for a comparison.
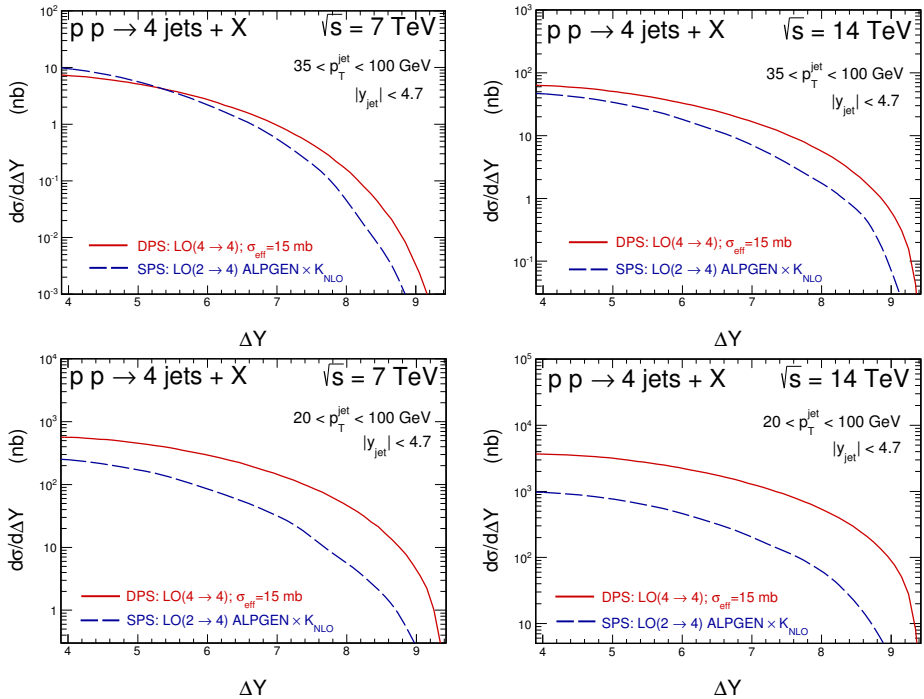

Fig. 5. Distribution in rapidity distance of the most remote jets for the four-jet sample for $\sqrt{s} = 7$ TeV (left column) and $\sqrt{s} = 14$ TeV (right column) for different cuts on jet transverse momenta (identical for all four jets).

Having shown that our approach is consistent with existing LHC four-jet data, we wish to discuss how to find optimal conditions for "observing" the DPS effects. As shown in our previous paper [3] on dijets widely separated in rapidity, the distribution in rapidity separation of such jets seems a very good observable for observing the DPS. In Fig. 5, we show some examples of such distributions for different cuts on the jet transverse momenta for two collision energies $\sqrt{s} = 7$ TeV and $\sqrt{s} = 14$ TeV obtained with the condition of the four-jet observation. We focus only on the distance between the most remote jets and do not check what happens in between. The higher collision energy or the smaller the lower transverse momentum cut, the bigger the relative DPS contribution. Here, the relative DPS contribution is much bigger than for jets widely separated in rapidity (compare with Figs. 2 and 3). In such a case, one can therefore expect a considerable deficit when only SPS four jets are included. Such cases would be therefore useful to "extract" the σ_{eff} parameter. Any deviation from the "canonical" value of 15 mb would, therefore, shed new light on the underlying dynamics. For example, a two-component model discussed in Refs. [17, 18] strongly suggests such dependences.

5. Conclusion

We have discussed how the double-parton scattering effects may contribute to large-rapidity-distance dijet correlations. As an example, we have shown distributions in rapidity distance between the most-distant jets in rapidity. The relative contribution of the DPS mechanism increases with increasing distance in rapidity between jets. We have also shown some predictions of the Mueller–Navelet jets in the LL and NLL BFKL framework. For the CMS configuration, our DPS contribution is smaller than the dijet SPS contribution, but only slightly smaller than that for the NLL BFKL calculation. We have shown that the relative effect of DPS can be increased by lowering the jet transverse momenta.

In this presentation, we have also discussed how to enhance the relative contribution of double-parton scattering for four-jet production. First, we have confronted results of our calculations with those obtained at the LHC by the CMS collaborations. The comparison indicates some evidence of DPS at large pseudorapidities of the leading jet.

We have shown that imposing a lower cut on transverse momenta and rapidity distance between the most remote jets improves the situation considerably enhancing the relative contribution of DPS. A dedicated analysis of the DPS effect is possible already with the existing data sample at $\sqrt{s} = 7$ TeV. The situation at larger energies, relevant for the LHC Run 2, should be even better. As a consequence, we predict that azimuthal cor-

relation between jets widely separated in rapidity should disappear in the considered kinematical domain [4]. We have found that in some corners of the phase space the DPS contribution can go even above 80% [4].

In this presentation, we have presented the detailed predictions. Once such cross sections are measured, one could try to extract the σ_{eff} parameter from the four-jet sample and try to obtain its dependence on kinematical variables. Such dependence can be expected due to several reasons such as parton–parton correlations, hot spots, perturbative parton splitting.

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