Pair correlations in D-meson production at the LHCb within the framework of Parton Reggeization Approach

A.V. Karpishkov, M.A. Nefedov, V.A. Saleev, A.V. Shipilova

Samara National Research University

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Motivation for k_T-factorization and PRA

- Heavy final states (Higgs bosons, $t\bar{t}$, ...) produced by large-$x \sim 10^{-1}$ initial partons $\leftarrow$ soft and collinear gluons
- Light final states (small-p_T quarkonia, single jets, prompt photons, ...) produced by small-$x \sim 10^{-3}$ initial partons $\leftarrow$ additional hard jets
- To obtain the agreement with experimental data one needs to perform the pQCD calculations in NLO and higher $\Rightarrow$ much time and computational resources are involved.

Motivation for k_T-factorization and PRA

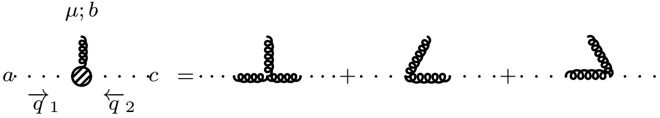
- In the region of small $x \sim \mu/\sqrt{S}$ most of the initial-state radiation is highly separated in rapidity from the central region, and can be factorized. In the small-x regime, initial-state partons carry the substantial transverse momentum (virtuality) $|\mathbf{q}_T| \sim x\sqrt{S}$, in contrast with the standard Collinear Parton Model (CPM), where $|\mathbf{q}_T| \ll x\sqrt{S}$, and can be neglected. This is the standard setup of the k_T*-factorization* [L. V. Gribov *et. al.* 1983; J. C. Collins *et. al.* 1991; S. Catani *et. al.* 1991].
  The old k_T-factorization approach contains a prescription for a polarization vector of initial-state gluon with 4-momentum $q = (q_0, \mathbf{q}_T, q_z)$:
  $\epsilon^\mu(q) = \frac{q_T^\mu}{|\mathbf{q}_T|} \Rightarrow$ no gauge invariance for 3- and 4-gluon vertices; no generally accepted prescription for the treatment of off-shell initial-state quarks.
- We need special conditions for a gauge-invariant description of the processes with the off-shell initial state partons. The Reggeization of the amplitudes in QCD solves this problem.

In present time, two methods to generate the gauge-invariant amplitudes for the k_T-factorization are proposed:

- The QCD in the Regge limit (see e. g. [B. Ioffe, V. S. Fadin, L. N. Lipatov, QCD – Perturbative and Nonperturbative aspects] and [L. N. Lipatov, Nucl. Phys. B**452** (1995) 369]).
- Methods based on the extraction of certain asymptotics of the amplitudes in the spinor-helicity representation (see e. g. [A. van Hameren *et. al.*, Phys.Lett. B727 226 (2013)]).

Effective Fadin-Kuraev-Lipatov vertex.

Using **Rg** and **Rgg** vertices, the Fadin-Kuraev-Lipatov $RR \to g$ vertex can be constructed:

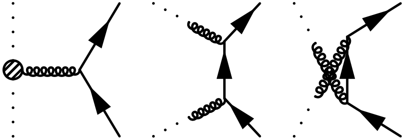


$$\Gamma^{-\mu+}_{abc}(q_1, q_2) = 2g_s f^{abc} \left[n^\mu_- \left(q_1^+ + \frac{q_1^2}{q_2^-} \right) - n^\mu_+ \left(q_2^- + \frac{q_2^2}{q_1^+} \right) + (q_2 - q_1)^\mu \right],$$

the effective vertex is gauge-invariant, even for the off-shell initial state partons ($q^2_{1,2} < 0$, $(q_1 + q_2)^2 = 0$):

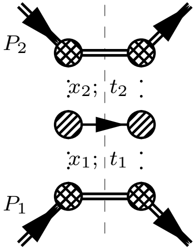
$$(q_1 + q_2)_\mu \Gamma^{-\mu+}_{abc}(q_1, q_2) = 0.$$

It contributes to the $RR \to c\bar{c}$ vertex:



Factorization of the cross section

Factorization:



Factorization formula:

$$d\sigma = \int \frac{d^2\mathbf{q}_{T1}}{\pi} \int \frac{dx_1}{x_1} \Phi(x_1, t_1, \mu_F) \times$$
$$\times \int \frac{d^2\mathbf{q}_{T2}}{\pi} \int \frac{dx_2}{x_2} \Phi(x_2, t_2, \mu_F) d\hat{\sigma}_{PRA}$$

Where Φ - Unintegrated PDFs.

Partonic cross section:

$$d\hat{\sigma}_{PRA} = \frac{(2\pi)^4}{2x_1x_2S} \overline{|\mathcal{M}|^2}_{PRA} \delta^{(4)}(P_{[i]} - P_{[f]}) \times$$
$$\times \prod_{j=[f]} \frac{d^3\mathbf{p}_j}{(2\pi)^3 2p_j^0},$$

Normalization of the unPDF:

$$\int^{\mu^2} dt \Phi(x, t, \mu^2) \approx x f(x, \mu^2),$$

where $f(x, \mu^2)$ - collinear PDF, implies, that the *collinear limit* holds for the amplitude (at the *small* x):

$$\int \frac{d\phi_1 d\phi_2}{(2\pi)^2} \lim_{t_{1,2}\to 0} \overline{|\mathcal{M}|^2}_{PRA} \approx \overline{|\mathcal{M}|^2}_{CPM}$$

Fragmentation approach. Subprocesses in the LO PRA

In the fragmentation approach [B. Mele, P. Nason, 1991], the cross section of the inclusive production of D-meson is related with the parton cross section as follows:

$$\frac{d\sigma}{dp_T dy}(p+p\to D_i(p)+X)=\sum_a\int\limits_0^1\frac{dz}{z}D_i(z,\mu^2)\frac{d\sigma}{dq_T dy}(p+p\to a(p/z)+X)$$

where $D_i(z,\mu^2)$-fragmentation function for the meson D_i (which depends on μ-scale unlike the Peterson ansatz). In our calculations we use the LO set of FFs by [B. A. Kniehl, G. Kramer *et. al.*] fitted on the e^+e^- annihilation data.
We take into account the following parton subprocesses:

$$R(q_1)+R(q_2) \quad\to\quad g(q_3)\,[\to D(p)]\,, \qquad (1)$$
$$R(q_1)+R(q_2) \quad\to\quad c(q_3)\,[\to D(p)]+\bar{c}(q_4), \qquad (2)$$

where $q_1^2=-\mathbf{q}_{T1}^2=-t_1$, $q_2^2=-\mathbf{q}_{T2}^2=-t_2$. Subprocess (2) contains the collinear divergence, which is regularized by the finite m_c.

LHCb data, $2.0 < y < 4.5$, $\sqrt{S} = 7$ TeV.

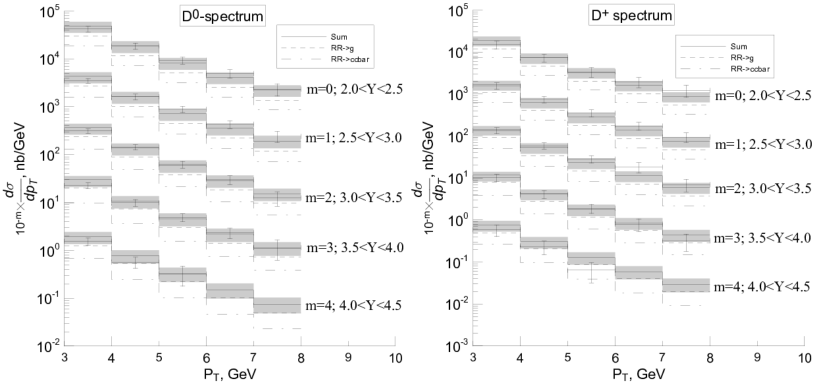


Figure 1: Transverse momentum distributions of D^0 and D^+ mesons in pp scattering with $\sqrt{S} = 7$ TeV and $2.0 < y < 4.5$. Dashed line represents the contribution of gluon fragmentation, dash-dotted line – the c-quark-fragmentation contribution, solid line is their sum. The LHCb data at the LHC are from the [LHCb Collaboration, R. Aaij *et al.*, Nucl.Phys. **B871**, 1-20 (2013)].

LHCb data, $2.0 < y < 4.5$, $\sqrt{S} = 7$ TeV.

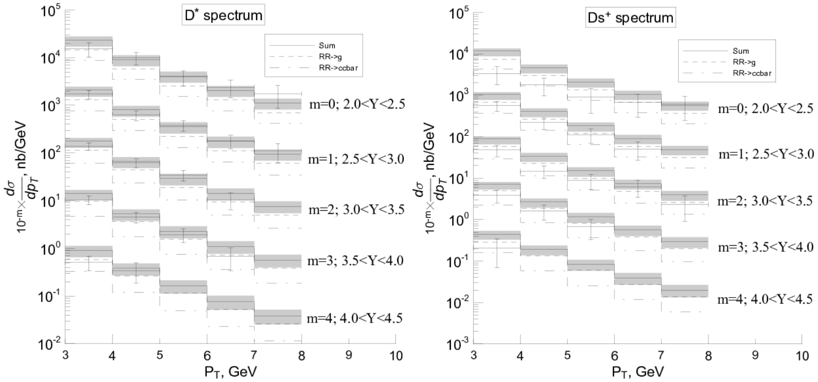


Figure 2: Transverse momentum distributions of $D^{\star +}$ and D_s^+ mesons in pp scattering with $\sqrt{S} = 7$ TeV and $2.0 < y < 4.5$.

Fragmentation approach (pair production). Subprocesses in the LO PRA.

In case of pair D-meson production we can write down the cross section of the inclusive pair production of D-mesons in the following form:

$$\frac{d\sigma}{dp_{TD}\,dy_D\,dp_{T\overline{D}}\,dy_{\overline{D}}}\left(p+p\to D_i(p_D)+\overline{D}_j(p_{\overline{D}})+X\right)=$$
$$=\sum_{ab}\int\limits_0^1\frac{dz_1}{z_1}D_i(z_1,\mu^2)\int\limits_0^1\frac{dz_2}{z_2}D_j(z_2,\mu^2)\frac{d\sigma}{dq_{3T}\,dy_3\,dq_{4T}\,dy_4}\left(p+p\to a(\frac{p_D}{z_1})+b(\frac{p_{\overline{D}}}{z_2})+X\right)$$

We take into account the following partonic subprocesses:

$$R(q_1)+R(q_2)\quad\to\quad g(q_3)\,[\to D(p_D)]+g(q_4)\,\left[\to \overline{D}(p_{\overline{D}})\right], \tag{3}$$
$$R(q_1)+R(q_2)\quad\to\quad c(q_3)\,[\to D(p_D)]+\bar{c}(q_4)\,\left[\to \overline{D}(p_{\overline{D}})\right], \tag{4}$$

where $q_1^2=-\mathbf{q}_{T1}^2=-t_1$, $q_2^2=-\mathbf{q}_{T2}^2=-t_2$. Subprocesses (3) and (4) contains the collinear divergence, which is regularized by the finite m_c.

$D^0\overline{D^0}$ spectra

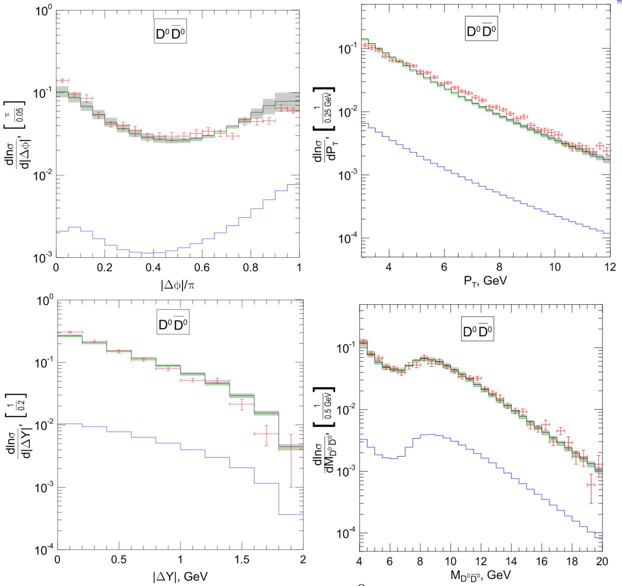


Figure 3: $\Delta\phi$, p_T, Y, and $M_{D\bar{D}}$ spectra for $D^0\overline{D}^0$ pair. LHCb data from the [LHCb Collab. R. Aaij *et al.*, JHEP **1206**, 141 (2012)].

D^0D^- spectra

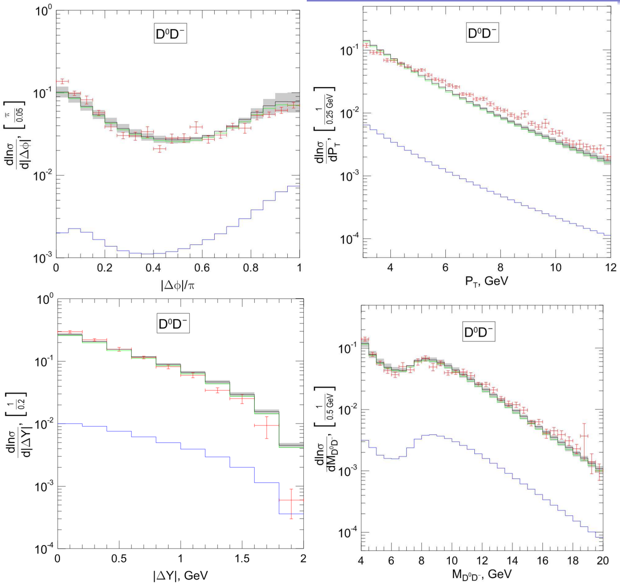


Figure 4: $\Delta\phi$, p_T, Y, and $M_{D\bar{D}}$ spectra for D^0D^- pair. LHCb data from the [LHCb Collab. R. Aaij *et al.*, JHEP **1206**, 141 (2012)].

$D^0 D_s^-$ spectra

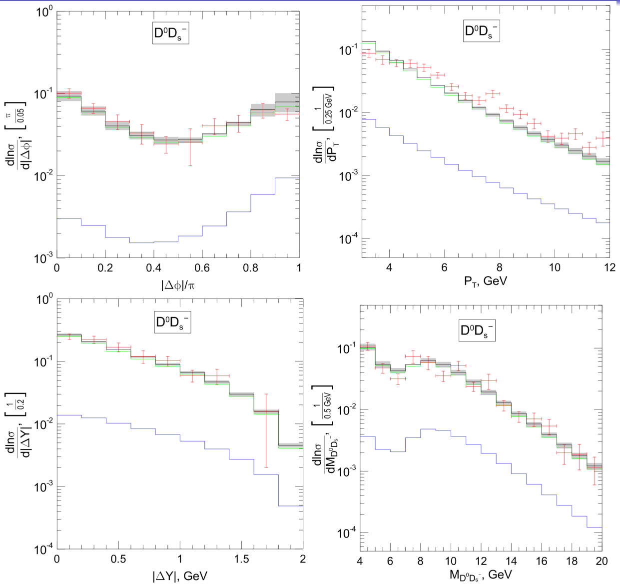


Figure 5: $\Delta\phi$, p_T, Y, and $M_{D\bar{D}}$ spectra for $D^0 D_s^-$ pair. LHCb data from the [LHCb Collab. R. Aaij *et al.*, JHEP **1206**, 141 (2012)].

D^+D^- spectra

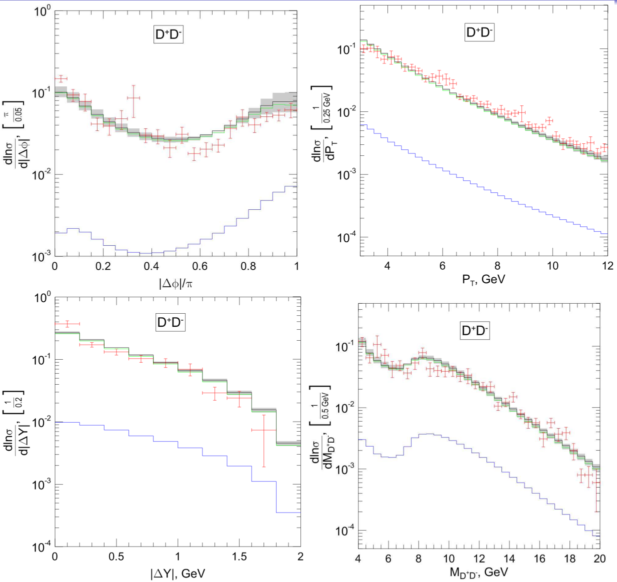


Figure 6: $\Delta\phi$, p_T, Y, and $M_{D\bar{D}}$ spectra for D^+D^- pair. LHCb data from the [LHCb Collab. R. Aaij *et al.*, JHEP **1206**, 141 (2012)].

$D^+D_s^-$ spectra

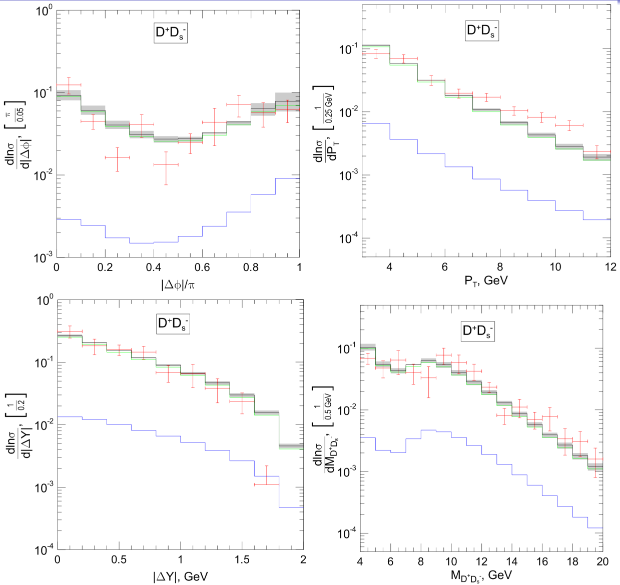


Figure 7: $\Delta\phi$, p_T, Y, and $M_{D\bar{D}}$ spectra for $D^+D_s^-$ pair. LHCb data from the [LHCb Collab. R. Aaij *et al.*, JHEP **1206**, 141 (2012)].

Summary of $D\overline{D}$ production

- We can see that the $RR \to c\bar{c}$ contribution lies upper than $RR \to gg$. This subprocesses have the same order of α_S but the probability of fragmentation of c-quark into D meson is higher than the gluon one.

$D^0 D^0$ spectra

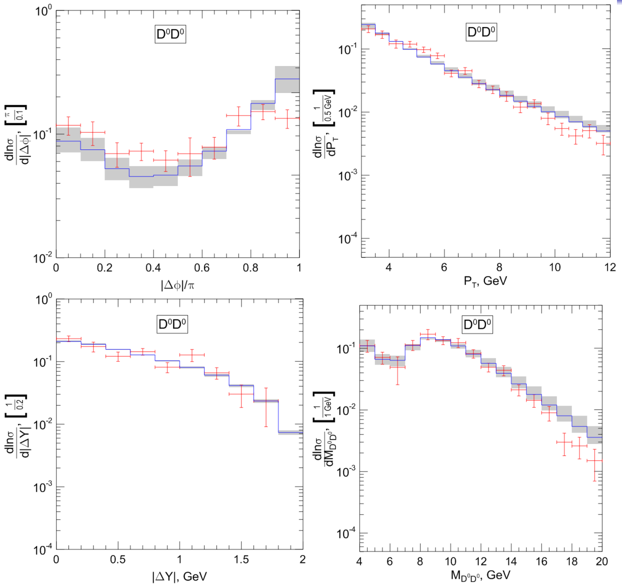


Figure 8: $\Delta\phi$, p_T, Y, and M_{DD} spectra for $D^0 D^0$ pair. LHCb data from the [LHCb Collab. R. Aaij *et al.*, JHEP **1206**, 141 (2012)].

$D^0 D^+$ spectra

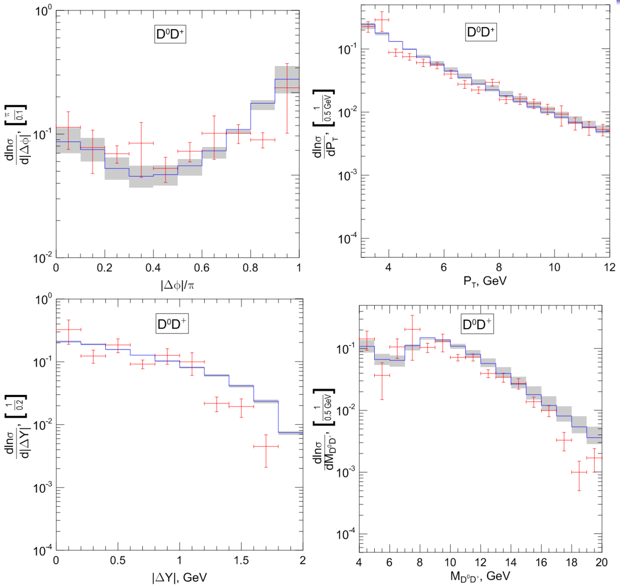


Figure 9: $\Delta\phi$, p_T, Y, and M_{DD} spectra for $D^0 D^+$ pair. LHCb data from the [LHCb Collab. R. Aaij *et al.*, JHEP **1206**, 141 (2012)].

$D^0 D_s^+$, $D^+ D^+$, and $D^+ D_s^+$ spectra

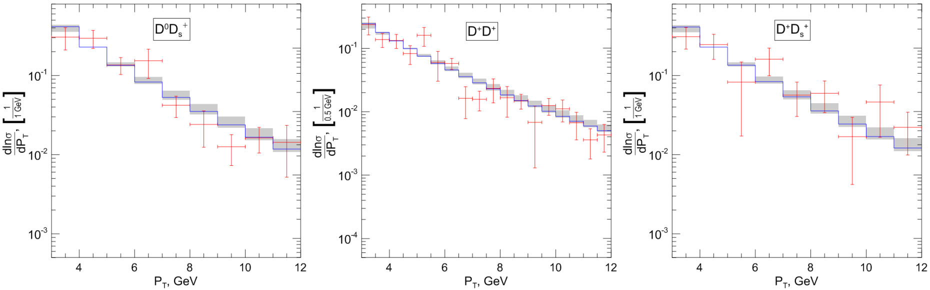


Figure 10: p_T spectra for $D^0 D_s^+$, $D^+ D^+$, and $D^+ D_s^+$ pairs. LHCb data from the [LHCb Collab. R. Aaij *et al.*, JHEP **1206**, 141 (2012)].

Double Parton Scattering approach

$$d\sigma^{DSP} = \frac{1}{2\sigma_{eff}} d\sigma^{SPS} * d\sigma^{SPS}, \ \sigma_{eff} = 15\ mb \quad (5)$$

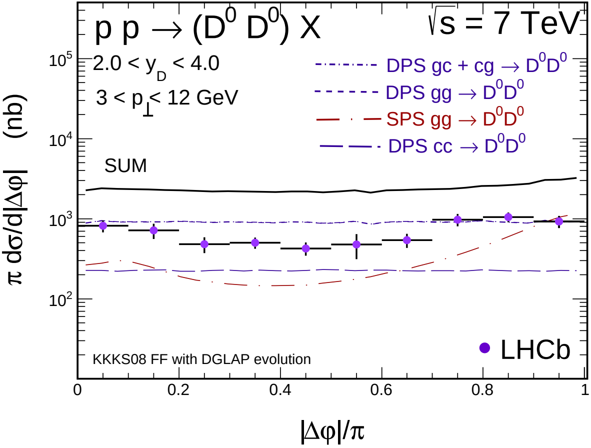


Figure 11: The result of calculation in the double parton scattering approach: the $RR \to gg$ contribution to the $\Delta\phi$ spectra for $D^0 D^0$ from [Rafal Maciula, Vladimir A. Saleev, Alexandra V. Shipilova, Antoni Szczurek, arXiv:1601.06981 (2016)].

Conclusions

- In the single D-meson production the contribution of the $RR \to g\,[\to D]$ subprocess has been found to be significant. There is not such contribution in the Collinear Parton Model.
- We have described the inclusive pair production of $D\overline{D}$ mesons in the Parton Reggeization Approach within uncertainties and without any free parameters.
- In case of $D\overline{D}$ production we can see that the $RR \to c\bar{c}$ contribution lies upper than $RR \to gg$. This subprocesses have the same order of α_S but the probability of fragmentation of c-quark into D meson is higher than the gluon one.
- The $RR \to gg[\to D^0 D^0]$ contribution calculated in the PRA lies very close to the experimental data. Using ReggeQCD module for FeynArts we can obtain the $RR \to c + \bar{c} + g$ amplitude to calculate this contribution in DD production cross section. We estimate that it would be possible to describe the DD pair production without involving of the double parton scattering approach.

Thank you for your attention!