D and $D\bar{D}$ pair production at the LHCb in the Parton Reggeization Approach

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3. $D\overline{D}$ pair production
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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.
- Even that not all the observables are successfully described in the framework of collinear parton model (CPM), such as azimuthal angle distributions in pair production of particles.

At small x the logarithms $\ln^n(1/x)$ can be resummed in all orders n by the BFKL-approach based on the property of gluon Reggeization.

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.

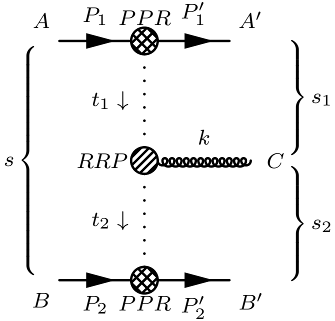
In present time, two methods to generate the gauge-invariant amplitudes for the k_T-factorization are proposed:

- 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)]).

There is, in fact, a chain of succession between these methods.

Reggeization of amplitudes in QCD.

PRA is based on the Reggeization of amplitudes in gauge theories (QED, QCD, Gravity). The *high energy asymptotics* of the $2 \to 2+n$ amplitude is dominated by the diagram with t-channel exchange of the effective (Reggeized) particle and Multi-Regge (MRK) or Quasi-Multi-Regge Kinematics (QMRK) of final state.



In the limit $s \to \infty$, $s_{1,2} \to \infty$, $-t_1 \ll s_1$, $-t_2 \ll s_2$ (Regge limit), $2 \to 3$ amplitude has the form:

$$\mathcal{A}_{AB}^{A'B'C} = 2s\gamma_{A'A}^{R_1} \left(\frac{s_1}{s_0}\right)^{\omega(t_1)} \frac{1}{t_1} \times$$

$$\times \Gamma_{R_1R_2}^{C}(q_1, q_2) \times \frac{1}{t_2} \left(\frac{s_2}{s_0}\right)^{\omega(t_2)} \gamma_{B'B}^{R_2}$$

$\Gamma_{R_1R_2}^{C}(q_1, q_2)$ - RRP effective production vertex,

$\gamma_{A'A}^{R}$ - PPR effective scattering vertex,

$\omega(t)$ - Regge trajectory.

Two approaches to obtain this asymptotics:

- BFKL-approach (Unitarity, renormalizability and gauge invariance), see [B. Ioffe, V. S. Fadin, L. N. Lipatov, QCD – Perturbative and Nonperturbative aspects].
- Effective action approach [L. N. Lipatov, Nucl. Phys. B**452** (1995) 369].

The field content of the effective theory.

To produce the amplitudes for the arbitrary QMRK processes, the effective-action approach is very useful. Light-cone coordinates and derivatives:

$$n^+ = \frac{2P_2}{\sqrt{S}},\ n^- = \frac{2P_1}{\sqrt{S}},\ n^+n^- = 2$$

$$x^\pm = n^\pm x = x^0 \pm x^3,\ \partial_\pm = 2\frac{\partial}{\partial x^\mp}$$

Lagrangian of the effective theory $L = L_{kin} + \sum_y \left(L_{QCD} + L_{ind}\right)$, $v_\mu = v_\mu^a t^a$, $\left[t^a, t^b\right] = f^{abc}t^c$. The rapidity space is sliced into the subintervals, corresponding to the groups of final-state particles, close in rapidity. Each subinterval in rapidity $(1 \ll \eta \ll Y)$ has it's own set of QCD fields:

$$L_{QCD} = -\frac{1}{2}tr\left[G_{\mu\nu}^2\right],\ G_{\mu\nu} = \partial_\mu v_\nu - \partial_\nu v_\mu + g\left[v_\mu, v_\nu\right].$$

Different rapidity intervals communicate via the gauge-invariant fields of Reggeized gluons ($A_\pm = A_\pm^a t^a$) with the kinetic term:

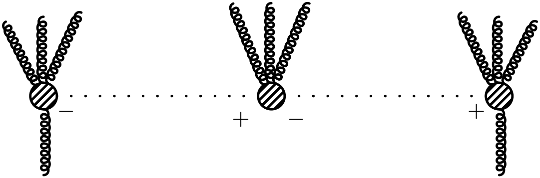
$$L_{kin} = -\partial_\mu A_+^a \partial^\mu A_-^a,$$

and the kinematical constraint:

$$\partial_- A_+ = \partial_+ A_- = 0 \Rightarrow$$

$$A_+ \text{ has } k_- = 0 \text{ and } A_- \text{ has } k_+ = 0.$$

The effective action for high energy processes in QCD.



Particles and Reggeons interact via *induced interactions*:

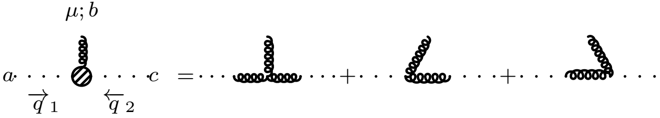
$$L_{ind} = - tr\left\{\frac{1}{g}\partial_+\left[P\exp\left(-\frac{g}{2}\int\limits_{-\infty}^{x^-}dx'^- v_+(x')\right)\right]\cdot\partial_\sigma\partial^\sigma A_-(x) + \right.$$
$$\left. + \frac{1}{g}\partial_-\left[P\exp\left(-\frac{g}{2}\int\limits_{-\infty}^{x^+}dx'^+ v_-(x')\right)\right]\cdot\partial_\sigma\partial^\sigma A_+(x)\right\}$$

Wilson lines lead to the infinite chain of the induced vertices:

$$L_{ind} = tr\left\{\left[v_+ - gv_+\partial_+^{-1}v_+ + g^2v_+\partial_+^{-1}v_+\partial_+^{-1}v_+ - ...\right]\partial_\sigma\partial^\sigma A_- + \right.$$
$$\left. + \left[v_- - gv_-\partial_-^{-1}v_- + g^2v_-\partial_-^{-1}v_-\partial_-^{-1}v_- - ...\right]\partial_\sigma\partial^\sigma A_+\right\}$$

Effective Fadin-Kuraev-Lipatov vertex.

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

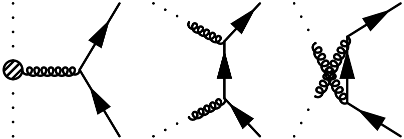


$$\Gamma^{-\mu+}_{abc}(q_1, q_2) = 2g_s f^{abc}\left[n^\mu_-\left(q_1^+ + \frac{q_1^2}{q_2^-}\right) - n^\mu_+\left(q_2^- + \frac{q_2^2}{q_1^+}\right) + (q_2 - q_1)^\mu\right],$$

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

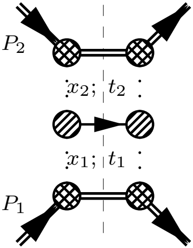
$$(q_1 + q_2)_\mu \Gamma^{-\mu+}_{abc}(q_1, q_2) = 0.$$

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):

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

The Kimber-Martin-Ryskin unPDF.

Kimber M. A. , Martin A. D. , Ryskin M. G., Phys. Rev. D **63**, 114027, (2001), [arXiv:hep-ph/0101348]

KMR prescription to obtain unintegrated PDF from collinear one is based on the mechanism of last step parton k_T-dependent radiation and the assumption of strong angular ordering:

$$\Phi_g(x, k_T^2, \mu^2) = T_g(k_T, \mu)\frac{\alpha_s(k_T^2)}{2\pi} \int\limits_x^{1-\Delta} dz \int^{k_T^2} \frac{dq_T^2}{q_T^2} \times \\ \times \left[P_{gg}(z) f_g\left(\frac{x}{z}, q_T^2\right) + P_{gq}(z) f_q\left(\frac{x}{z}, q_T^2\right)\right].$$

Where $P_{gg}(z)$, $P_{gq}(z)$- DGLAP splitting functions, $T_g(k_T, \mu)$- Sudakov formfactor:

$$T_g(k_T, \mu) = exp\left\{-\int\limits_{k_T^2}^{\mu^2} \frac{dq_T^2}{q_T^2}\frac{\alpha_s(q_T^2)}{2\pi}\sum_{a'}\int\limits_{\Delta}^{1-\Delta} P_{ga'}(z')dz'\right\}$$

where $\Delta = \frac{k_T}{\mu + k_T}$ ensures the **rapidity ordering of the last emission and particles produced in the hard subprocess**.

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:

$$\frac{d\sigma}{dp_T dy}(p+p \to D_i(p)+X) = \sum_a \int_0^1 \frac{dz}{z} D_i(z,\mu^2) \frac{d\sigma}{dq_T dy}(p+p \to a(p/z)+X)$$

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:

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

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.

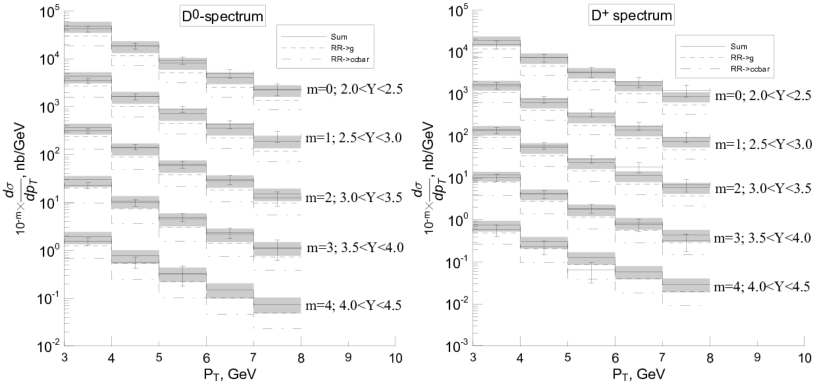


Figure 1: Transverse momentum distributions of D^0 and D^+ mesons in pp scattering with $\sqrt{S} = 7$ TeV and $2.0 < y < 4.5$. Dashed line represents the contribution of gluon fragmentation, dash-dotted line – the c-quark-fragmentation contribution, solid line is their sum. The LHCb data at the LHC 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.

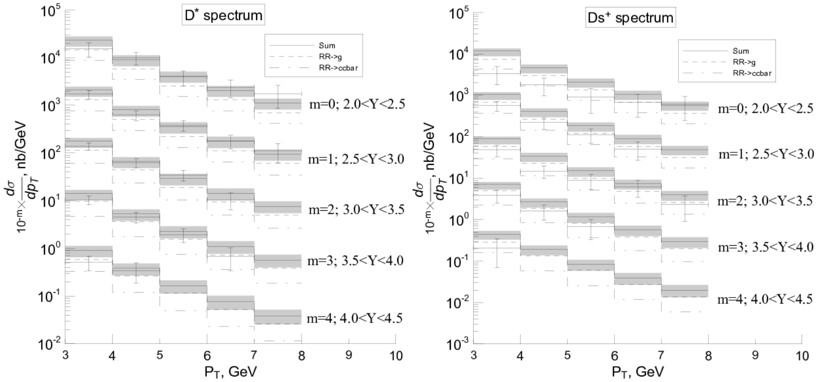


Figure 2: Transverse momentum distributions of $D^{\star +}$ and D_s^+ mesons in pp scattering with $\sqrt{S} = 7$ TeV and $2.0 < y < 4.5$.

ALICE data, $|y| < 0.5$, $\sqrt{S} = 7$ TeV.

Published result:

- Karpishkov A. V., Nefedov M. A., Saleev V. A., Shipilova A. V., Phys. Rev. D **91**, 054009

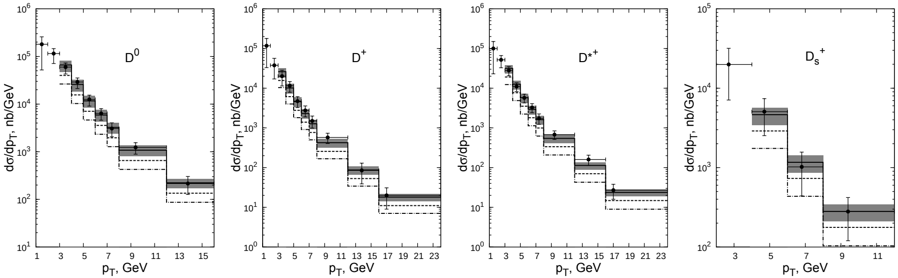


Figure 3: Transverse momentum distributions of D^0, D^+, $D^{\star+}$, and D_s^+ mesons in pp scattering with $\sqrt{S} = 7$ TeV and $|y| < 0.5$. The notations as in the Fig. 1. The ALICE data at the LHC are from the [ALICE Collaboration, B. Abelev *et al.*, JHEP **1207**, 191 (2012)].

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:

$$\frac{d\sigma}{dp_{TD}dy_D dp_{T\overline{D}}dy_{\overline{D}}}\left(p+p\to D_i(p_D)+\overline{D}_j(p_{\overline{D}})+X\right)=$$

$$=\sum_{ab}\int_0^1\frac{dz_1}{z_1}D_i(z_1,\mu^2)\int_0^1\frac{dz_2}{z_2}D_j(z_2,\mu^2)\frac{d\sigma}{dq_{3T}dy_3dq_{4T}dy_4}\left(p+p\to a(\frac{p_D}{z_1})+b(\frac{p_{\overline{D}}}{z_2})+X\right)$$

We take into account the following partonic subprocesses:

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

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

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.

LHCb data, $2 < y < 4$, $\sqrt{S} = 7$ TeV.

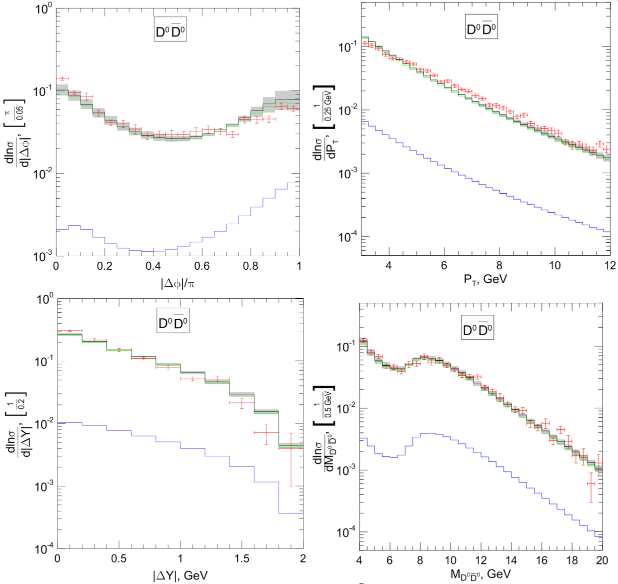


Figure 4: $\Delta\phi$, p_T, Y, and $M_{D\bar{D}}$ spectra for $D^0\overline{D}^0$ pair. LHCb data from the [LHCb Collab. R. Aaij *et al.*, JHEP **1206**, 141 (2012)].

LHCb data, $2 < y < 4$, $\sqrt{S} = 7$ TeV.

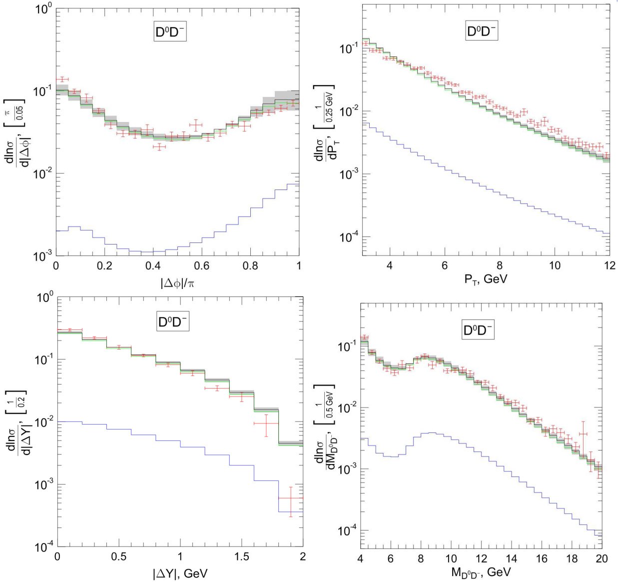


Figure 5: $\Delta\phi$, p_T, Y, and $M_{D\bar{D}}$ spectra for D^0D^- pair. LHCb data from the [LHCb Collab. R. Aaij *et al.*, JHEP **1206**, 141 (2012)].

LHCb data, $2 < y < 4$, $\sqrt{S} = 7$ TeV.

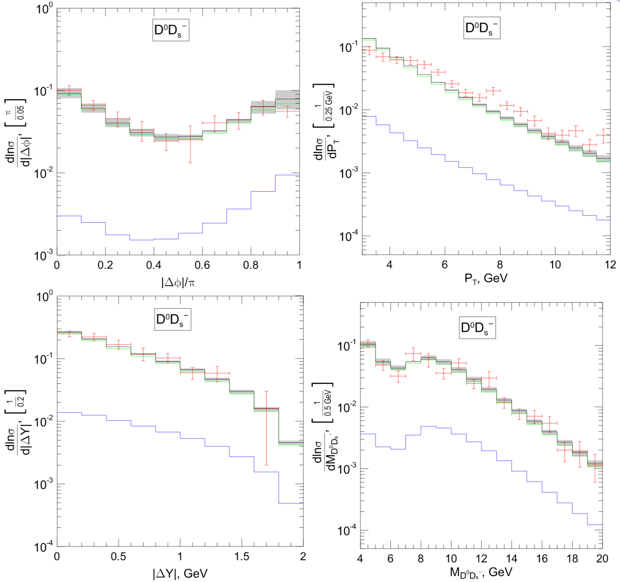


Figure 6: $\Delta\phi$, p_T, Y, and $M_{D\bar{D}}$ spectra for $D^0 D_s^-$ pair. LHCb data from the [LHCb Collab. R. Aaij *et al.*, JHEP **1206**, 141 (2012)].

LHCb data, $2 < y < 4$, $\sqrt{S} = 7$ TeV.

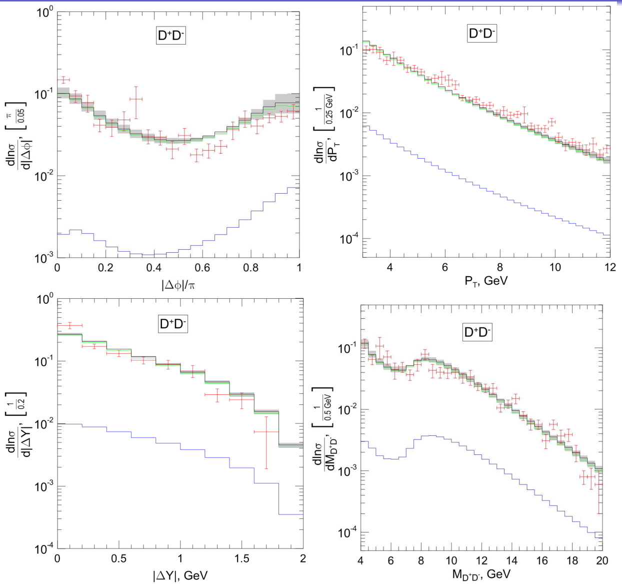


Figure 7: $\Delta\phi$, p_T, Y, and $M_{D\bar{D}}$ spectra for D^+D^- pair. LHCb data from the [LHCb Collab. R. Aaij *et al.*, JHEP **1206**, 141 (2012)].

LHCb data, $2 < y < 4$, $\sqrt{S} = 7$ TeV.

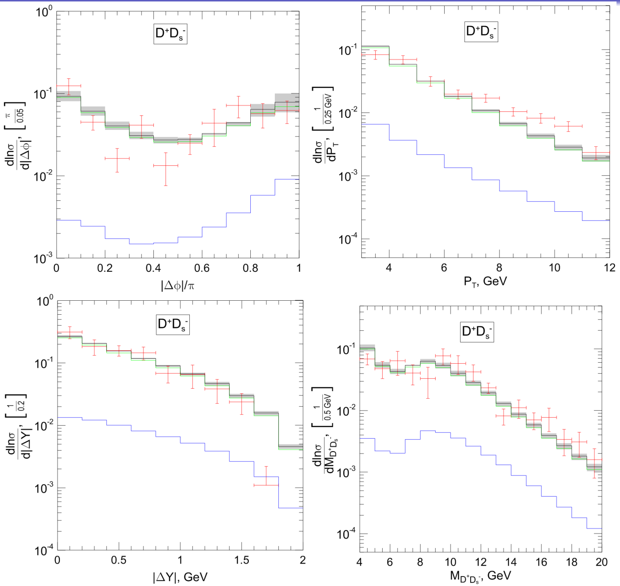


Figure 8: $\Delta\phi$, p_T, Y, and $M_{D\bar{D}}$ spectra for $D^+D_s^-$ pair. LHCb data from the [LHCb Collab. R. Aaij *et al.*, JHEP **1206**, 141 (2012)].

Conclusions

- In the single D-meson production the contribution of the $RR \to g\,[\to D]$ subprocess has been found to be significant.
- We have described the inclusive pair production of $D\overline{D}$ mesons in the Parton Reggeization Approach within uncertainties and without 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.

DD pair production at the LHCb will be discussed in the next talk by Prof. Szczurek.

Thank you for your attention!