Open charm production in the parton model at $\sqrt{S} = 20 - 30$ GeV

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Sketch of the Parton Reggeization Approach (PRA)

Model process and Sudakov's decomposition

We can derive the factorization formula in PRA, considering the following auxilliary hard subprocess:

$$g(p_1) + g(p_2) \to g(k_1) + \mathcal{Y}(P_{\mathcal{A}}) + g(k_2), \tag{1}$$

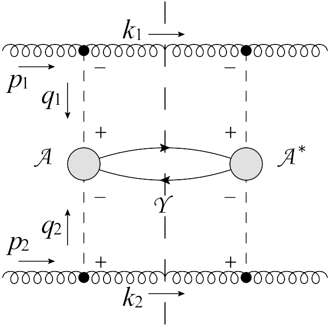
where $p_1^2 = p_2^2 = k_1^2 = k_2^2 = 0$, $M_{\mathcal{A}}^2 = P_{\mathcal{A}}^2$.
We use the Sudakov (light-cone) components of any four-momentum k:

$$k^\mu = \frac{1}{2}\left(k^+ n_-^\mu + k^- n_+^\mu\right) + k_T^\mu,$$

where $n_\pm^\mu = \left(n^\pm\right)^\mu = (1, 0, 0, \mp 1)^\mu$, $n_\pm^2 = 0$, $n_+ n^- = 2$, $k^\pm = k_\pm = (n_\pm k) = k^0 \pm k^3$, $n_\pm k_T = 0$, so that $p_1^- = p_2^+ = 0$ and $s = (p_1 + p_2)^2 = p_1^+ p_2^- > 0$. Then the dot-product of two four-vectors k and q in this notation is equal to:

$$(kq) = \frac{1}{2}\left(k^+ q_- + k^- q_+\right) - \mathbf{k}_T \mathbf{q}_T.$$

Multi-Regge Kinematics (MRK)



The limit of **Multi-Regge Kinematics** (MRK) for the subprocess (1) is defined as:

$$\Delta y_1 = y(k_1) - y(P_{\mathcal{A}}) \gg 1, \; \Delta y_2 = y(P_{\mathcal{A}}) - y(k_2) \gg 1, \quad (2)$$

$$\mathbf{k}_{T1}^2 \sim \mathbf{k}_{T2}^2 \sim M_{T\mathcal{A}}^2 \sim \mu^2 \ll s, \quad (3)$$

where rapidity for the four-momentum k is equal to $y(k) = \log\left(k^+/k^-\right)/2$.
MRK limit of QCD amplitudes can be obtained using **Lipatov's EFT for MRK processes in QCD** [L. N. Lipatov, Nucl. Phys. B **452**, 369 (1995)].

The field content of the effective theory.

Light-cone derivatives:

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

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:

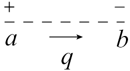
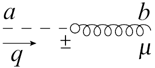
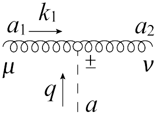
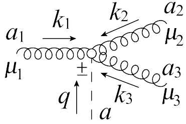
$$L_{kin} = -\partial_\mu A_+^a \partial^\mu A_-^a,$$

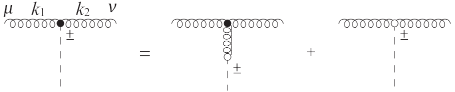
and the kinematical constraint:

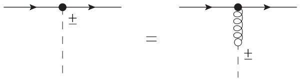
$$\partial_- A_+ = \partial_+ A_- = 0 \Rightarrow$$

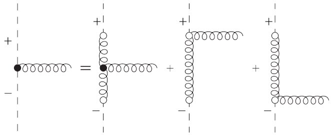
$$A_+ \text{ has } k_- = 0 \text{ and } A_- \text{ has } k_+ = 0.$$

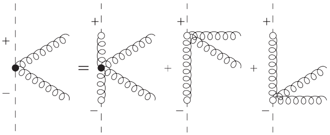
Feynman rules

 $= \frac{-i\delta_{ab}}{2q^2}$	 $= (-iq^2)n^{\mp}_{\mu}\delta_{ab}$
	$g_s f_{aa_1a_2}\left(n^{\mp}_{\mu}n^{\mp}_{\nu}\right)\frac{q^2}{k_1^{\mp}}$
	$ig_s^2\left(n^{\mp}_{\mu_1}n^{\mp}_{\mu_2}n^{\mp}_{\mu_3}\right)\frac{q^2}{k_3^{\mp}}\left[\frac{f_{aba_1}f_{ba_2a_3}}{k_1^{\mp}} + \frac{f_{aba_2}f_{ba_1a_3}}{k_2^{\mp}}\right]$

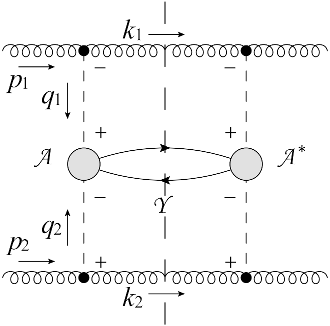








Factorization formula for the PRA



In the MRK-limit we obtained the following formula in k_T**-factorized form** [A. V. Karpishkov, M. A. Nefedov, V. A. Saleev, Phys. Rev. D **96** (2017) 096019]:

$$d\sigma = \int\limits_0^1 \frac{dx_1}{x_1} \int \frac{d^2\mathbf{q}_{T1}}{\pi} \Phi_g(x_1, t_1, \mu^2) \int\limits_0^1 \frac{dx_2}{x_2} \int \frac{d^2\mathbf{q}_{T2}}{\pi} \Phi_g(x_2, t_2, \mu^2) \cdot d\hat{\sigma}_{\rm PRA},$$

where the partonic cross-section in PRA is given by:

$$d\hat{\sigma}_{\rm PRA} = \frac{\overline{|\mathcal{A}_{PRA}|^2}}{2Sx_1x_2} \cdot (2\pi)^4 \delta\left(\frac{1}{2}\left(q_1^+ n_- + q_2^- n_+\right) + q_{T1} + q_{T2} - P_{\mathcal{A}}\right) d\Phi_{\mathcal{A}}.$$

Nonintegrated Parton Distribution Functions (nPDFs)

The tree-level "unintegrated PDFs" (unPDFs) are:

$$\tilde{\Phi}_g(x, t, \mu^2) = \frac{1}{t}\frac{\alpha_s}{2\pi}\int\limits_x^1 dz\ P_{gg}(z)\frac{x}{z} f_g\left(\frac{x}{z}, \mu^2\right),$$

which have the collinear divergence at $t_{1,2} \to 0$ and infrared (IR) divergence at $z_{1,2} \to 1$. It regularizes at $z_{1,2} < 1 - \Delta_{KMR}(t_{1,2}, \mu^2)$, where $\Delta_{KMR}(t, \mu^2) = \sqrt{t}/(\sqrt{\mu^2} + \sqrt{t})$, and $\mu^2 \sim M_{T\mathcal{A}}^2$.
The collinear singularity is regularized by the Sudakov formfactor:

$$T_i(t, \mu^2) = \exp\left[-\int\limits_t^{\mu^2} \frac{dt'}{t'}\frac{\alpha_s(t')}{2\pi}\sum_{j=q,\bar{q},g}\int\limits_0^1 dz\ z \cdot P_{ji}(z)\theta\left(1 - \Delta_{KMR}(t', \mu^2) - z\right)\right].$$

The final form of our unPDF is:

$$\Phi_i(x, t, \mu^2) = T_i(t, \mu^2)\frac{\alpha_s(t)}{2\pi}\sum_{j=q,\bar{q},g}\int\limits_x^1 dz\ P_{ij}(z)\frac{x}{z} f_j\left(\frac{x}{z}, \mu^2\right)\theta\left(1 - \Delta_{KMR}(t, \mu^2) - z\right).$$

The KMR unPDF satisfies the following normalization condition:

$$\int\limits_0^{\mu^2} dt\ \Phi_i(x, t, \mu^2) = x f_i(x, \mu^2).$$

Ingredients of the parton Reggeization approach

1. Factorization formula in the Regge limit of QCD:

$$d\sigma = \int_0^1 \frac{dx_1}{x_1} \int \frac{d^2\mathbf{q}_{T1}}{\pi} \Phi_g(x_1, t_1, \mu^2) \int_0^1 \frac{dx_2}{x_2} \int \frac{d^2\mathbf{q}_{T2}}{\pi} \Phi_g(x_2, t_2, \mu^2) \cdot d\hat{\sigma}_{\mathrm{PRA}}.$$

2. Unintegrated parton distribution functions in KMR model:

$$\Phi_i(x, t, \mu^2) = T_i(t, \mu^2) \frac{\alpha_s(t)}{2\pi} \sum_{j=q,\bar{q},g} \int_x^1 dz\, P_{ij}(z) \frac{x}{z} f_j\left(\frac{x}{z}, \mu^2\right) \theta\left(1 - \Delta_{KMR}(t, \mu^2) - z\right).$$

3. Partonic amplitudes with initial-state reggeized quarks and gluons in the Lipatov's EFT:

$$L = L_{kin} + \sum_y \left(L_{QCD} + L_{ind}\right).$$

Production of D mesons at LHC and LEBC-EHS

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:

$$\frac{d\sigma}{dp_T dy}(p + p \to D_i(p) + X) = \sum_a \int_0^1 \frac{dz}{z} D_i(z, \mu^2) \frac{d\sigma}{dq_T dy}(p + p \to a(p/z) + X) \quad (4)$$

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:

$$R(q_1) + R(q_2) \to c(q_3)\,[\to D(p)] + \bar{c}(q_4), \quad (5)$$

$$Q(q_1) + \bar{Q}(q_2) \to c(q_3)\,[\to D(p)] + \bar{c}(q_4), \quad (6)$$

where $q_1^2 = -\mathbf{q}_{T1}^2 = -t_1$, $q_2^2 = -\mathbf{q}_{T2}^2 = -t_2$. Subprocess (5) and (6) contains the collinear divergence, which is regularized by the finite m_c.

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

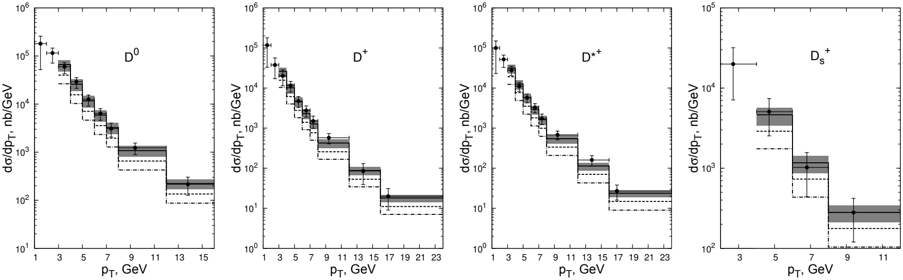


Figure 1 : Transverse momentum distributions of D^0, D^+, $D^{\star +}$, and D_s^+ mesons in pp scattering with $\sqrt{S} = 7$ TeV and $|y| < 0.5$. The notations as in the Fig. 4. The ALICE data at the LHC are from the [ALICE Collaboration, B. Abelev *et al.*, JHEP **1207**, 191 (2012)].

LEBC-EHS data, $2 < y < 4$, $\sqrt{S} = 27.4$ GeV.

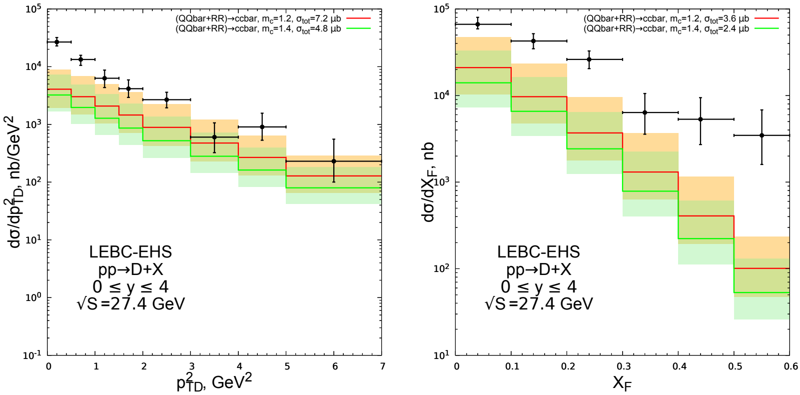


Figure 2 : p_T and x_F distributions of D mesons and leading processes of PRA in pp scattering with $\sqrt{S} = 27.4$ GeV and $0 < y < 4$. The LEBC-EHS data are from the [LEBC-EHS Collaboration, M.Aguilar-Benitez *et al.*, Phys. Lett. B **189**, 476-482 (1987)].

LEBC-EHS data, $2 < y < 4$, $\sqrt{S} = 27.4$ GeV.

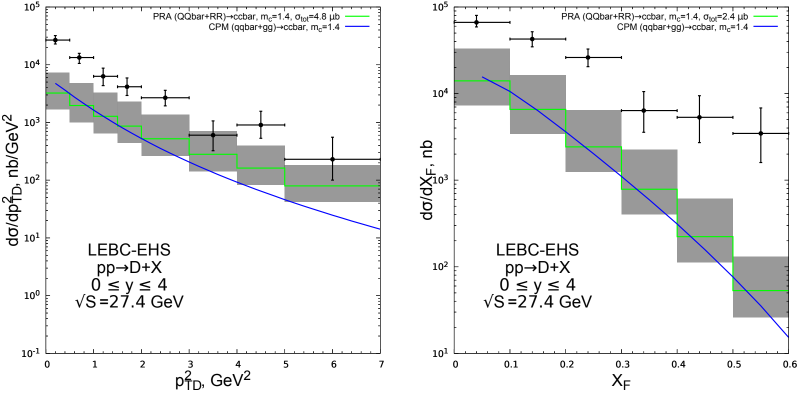


Figure 3 : p_T and x_F distributions of D mesons in pp scattering with $\sqrt{S} = 27.4$ GeV and $0 < y < 4$ and leading processes of PRA in comparison with LO CPM (massive amplitudes). The LEBC-EHS data are from the [LEBC-EHS Collaboration, M.Aguilar-Benitez *et al.*, Phys. Lett. B **189**, 476-482 (1987)].

LEBC-EHS data, $2 < y < 4$, $\sqrt{S} = 27.4$ GeV.

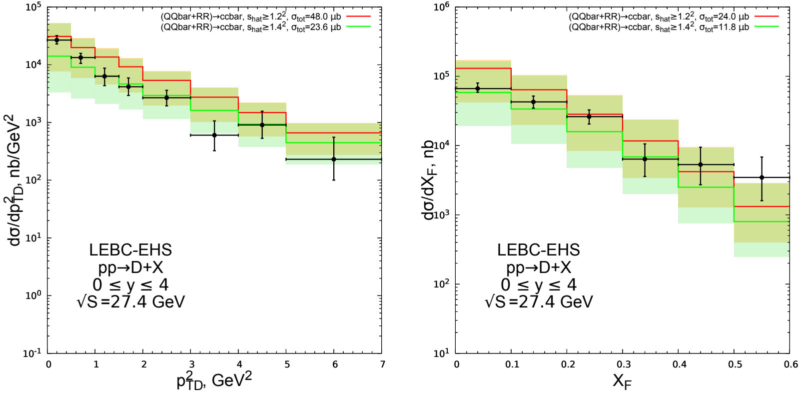


Figure 4 : p_T and x_F distributions of D mesons in pp scattering with $\sqrt{S} = 27.4$ GeV and $0 < y < 4$ and leading processes of PRA in comparison with LO CPM (massless amplitudes). The LEBC-EHS data are from the [LEBC-EHS Collaboration, M.Aguilar-Benitez *et al.*, Phys. Lett. B **189**, 476-482 (1987)].

Thank you for your attention!