D-meson production at the Tevatron and LHC in the Parton Reggeization Approach.

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QCHS-XI
Saint-Petersburg, Russia
September 11, 2014

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Outline.

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Motivation for k_T-factorization and PRA.

- The class of processes, suitable for the study in k_T-factorization is the *central* production of the final state of interest by the *small-x* ($x \lesssim 10^{-2} - 10^{-3}$) partons in the $pp(\bar{p})$ or ep collisions.
- In this kinematics, 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 the gauge-invariant procedure to take into account the virtuality of the initial state parton (quark or gluon) in the amplitude of the hard scattering, is required.

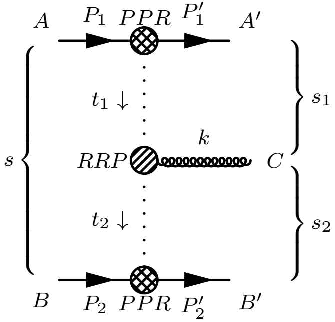
In present time, three methods proposed to solve the last problem:

- The standard k_T-factorization prescription gluons ($\varepsilon^\mu(k) = \frac{k_T^\mu}{|\mathbf{k}_T|}$).
- The parton Reggeization approach (PRA).
- 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 three 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:

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

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

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

$\gamma^R_{A'A}$ - 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.

Light-cone vectors:

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

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

Lagrangian of the effective theory $L = L_{kin} + \sum_y \left(L_{QCD} + L_{ind}\right)$, $v_\mu = v_\mu^a t^a$, $\left[t^a, t^b\right] = f^{abc}t^c$. 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 Reggeized gluons $(A_\pm = A_\pm^a t^a)$ with the kinetic term:

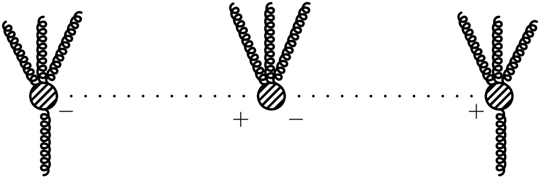
$$L_{kin} = -\partial_\mu A_+^a \partial^\mu A_-^a,$$

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*:

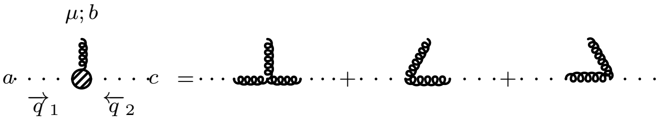
$$L_{ind} = - tr\left\{\frac{1}{g}\partial_+\left[P\exp\left(-\frac{g}{2}\int_{-\infty}^{x^-} dx'^- v_+(x')\right)\right]\cdot\partial_\sigma\partial^\sigma A_-(x) + \right.$$
$$\left. + \frac{1}{g}\partial_-\left[P\exp\left(-\frac{g}{2}\int_{-\infty}^{x^+} dx'^+ v_-(x')\right)\right]\cdot\partial_\sigma\partial^\sigma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

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

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

Fadin-Kuraev-Lipatov vertex and $RR \to q\bar{q}$ amplitude.

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

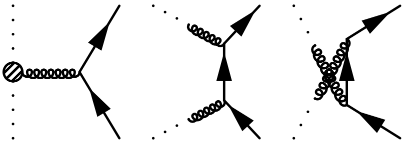


$$\Gamma^{-\mu+}_{abc}(q_1, q_2) = 2g_s f^{abc}\left[n^\mu_-\left(q_1^+ + \frac{q_1^2}{q_2^-}\right) - n^\mu_+\left(q_2^- + \frac{q_2^2}{q_1^+}\right) + (q_2 - q_1)^\mu\right],$$

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

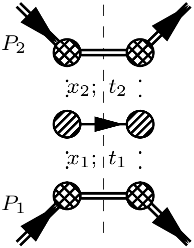
$$(q_1 + q_2)_\mu \Gamma^{-\mu+}_{abc}(q_1, q_2) = 0.$$

It contributes to the $RR \to q\bar{q}$ production amplitude:



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:

$$d\hat{\sigma}_{PRA} = \frac{(2\pi)^4}{2x_1 x_2 S} \overline{|\mathcal{M}|^2}_{PRA} \delta^{(4)}(P_{[i]} - P_{[f]}) \times$$
$$\times \prod_{j=[f]} \frac{d^3\mathbf{p}_j}{(2\pi)^3 2p_j^0},$$

Normalization of the unPDF:

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

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

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

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.*

Motivation for the present study.

A few points to motivate the study of inclusive D-meson hadroproduction in PRA:

- The successful description in the CPM exists, in the FONLL [Cacciari *et. al.*] and GM-VFNS [Kniehl *et. al.*] approaches, but NLO corrections to the inclusive p_T-spectra are large (factor 2-3) so the resummations are required.
- The typical values of $x \sim 10^{-3}$ at the Tavatron and LHC, so k_T-factorization should be applicable. Can the LO computation in the k_T-factorization do a good job?
- Existing studies in k_T-factorization [Szczurek *et. al.*, 2012-2014](see e. g. the talk by R. Maciula, given on the QCD@LHC-2014 conference) do not take into account $g \to D_i$ fragmentation, only $c \to D_i$, because of the gauge-invariance issues. $\Rightarrow$ Undershooting the inclusive spectra by a factor $1.5 - 2$ at the LHC.
- Claims where made by this authors, that the process $p + p \to D^0 + D^0 + X$ is the sensitive probe to the double-parton scattering, but, as it will be shown below, contribution of the $g \to D^0$ fragmentation is sizeable.

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 partonic cross-section as follows:

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

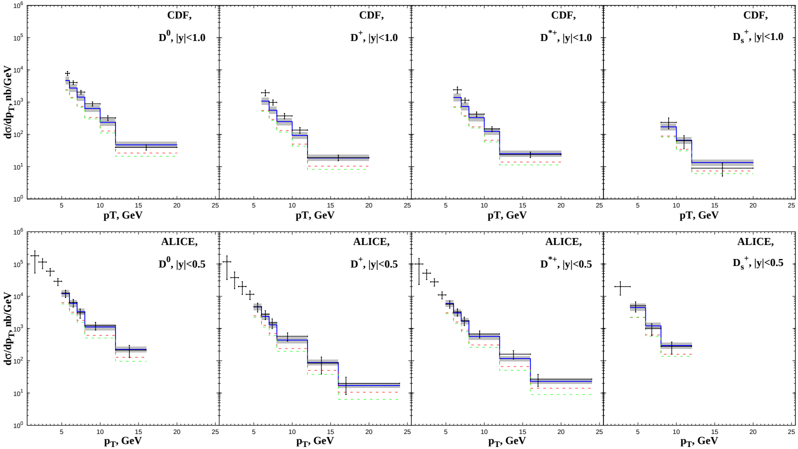
where $D_i(z,\mu^2)$-fragmentation function for the meson D_i. In our calculations we use the LO set of FFs by [B. A. Kniehl, G. Kramer *et. al.*] fitted on the e^+e^- annihilation data.
We take into account the following partonic subprocesses:

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

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

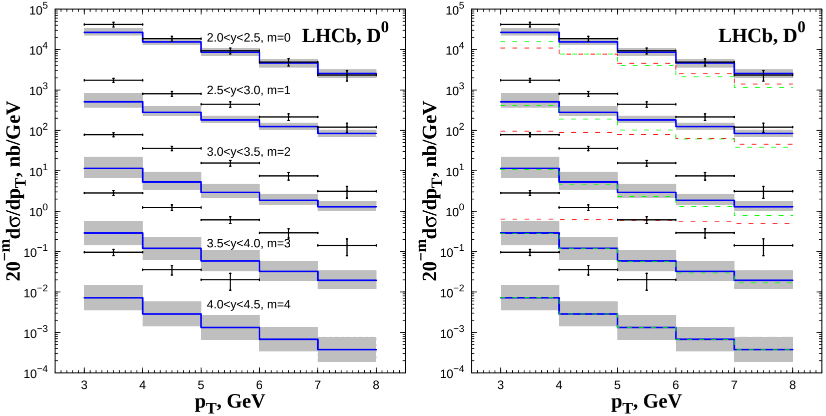
where $q_1^2=-\mathbf{q}_{T1}^2=-t_1$, $q_2^2=-\mathbf{q}_{T2}^2=-t_2$. Subprocess (2) contains the collinear divergence, which is regularized by the finite m_c.

Numerical results. Central production.



Upper panel – CDF data ($\sqrt{S} = 1.96$ TeV), lower panel – ALICE data ($\sqrt{S} = 7$ TeV). Red line – subprocess $RR \to g$ (1), green line – subprocess $RR \to c\bar{c}$ (2), **blue** line – their sum, Gray band – scale uncertainty: $\mu_F = \mu_R = 2^{\pm 1}\sqrt{p_T^2 + m_D^2}$.

LHCb data, non-central production.



LHCb data combine small and large values of x: $\langle x_{1,2}\rangle \sim \langle p_T\rangle e^{\pm y}/\sqrt{S}$, $\langle p_T\rangle/\sqrt{S} \sim 10^{-3}$, $e^3 \simeq 20$. Non QMRK corrections (additional radiation non separated in rapidity) are important.

Conclusions.

- The quality of the description of data on central production of D-mesons in the LO PRA is comparable with the NLO CPM results.
- Outside the central region ($y > 2.5$) the cross-section is decreasing too fast, due to the absence of higher-order non-QMRK corrections, as expected.
- The contribution of the $RR \to g\,[\to D]$ subprocess is found to be significant.

Future prospects:

- More careful treatment of the double-counting of the log-enchanced contributions between $RR \to c\bar{c}$ and $RR \to g$ contributions.
- Include the fragmentation of the light quarks.
- Add the processes with Reggeized quarks.

Thank you for your attention!