DD-pair production in the Parton Reggeization Approach within SPS and DPS scenarios

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Introduction

- Open-charm production constitutes a stringent test of next-to-leading-order (NLO) pQCD ($\alpha_S(m_c) \ll 1$)
- Single parton scattering (SPS) calculations alone fail to reproduce the measured DD production
- Description may also include either gluon to charm-quark fragmentation or double parton scattering (DPS) contributions [Maciuła, Saleev, Shipilova, Szczurek 2016]
- The usage of gluon-to-charm fragmentation, however, includes double-counting issues and the limited range of validity of the gluon fragmentation function [Karpishkov, Nefedov, Saleev, Shipilova 2016]
- We study pair-D^0D^0 production in the Parton Reggeization Approach (PRA). The charm-quark mass $c \to D^0$ effects in fragmentation are taken into account.

High-energy factorization

Parton Reggeization approach (PRA) is a scheme of k_T-factorization, which is based on the modified multi-Regge kinematics (mMRK) approximation of the QCD $\Lambda_{QCD} \ll \mu \ll \sqrt{s}$. [Nefedov, Saleev, Shipilova 2013] [Karpishkov, Nefedov, Saleev 2017] [Nefedov, Saleev 2020]

The cross section is written as a convolution:

$$d\sigma^{PRA}(pp \to D^0 D^0) = \sum_{a,b} \int \frac{dx_1}{x_1} \frac{d^2 q_{1T}}{\pi} \int \frac{dx_2}{x_2} \frac{d^2 q_{2T}}{\pi} \Phi_a(x_1, q_{1T}^2, \mu^2) \Phi_b(x_2, q_{2T}^2, \mu^2) \times$$
$$\times d\hat{\sigma}^{PRA}(ab \to D^0 D^0)$$

$$q_{1,2}^{\mu} = x_{1,2} P_{1,2}^{\mu} + q_{1,2T}^{\mu}, \quad q_{1,2T}^2 = -\vec{q}_{1,2T}^{\,2} \neq 0$$

where a, b denotes the parton types $R, Q, \bar{Q}$ in the partonic subprocesses.

$\Phi_{a,b}(x, q_T^2, \mu^2)$ is modified Kimber-Martin-Ryskin-Watt (mKMRW) PDFs with exact normalization:

$$\int_0^{\mu^2} dq_T^2 \Phi_a(x, q_T^2, \mu^2) = x f_a(x, \mu^2)$$

KMR modification

The exact normalization condition is equivalent to:

$$\Phi_a(x, t, \mu^2) = \frac{d}{dt}\left[T_a(t, \mu^2, x)\tilde{f}_a(x, t)\right],$$

where $\tilde{f}_a(x,t) = xf_a(x,t)$, $T_a(t,\mu^2,x)$ is usually referred to as Sudacov form-factor, satisfying the boundary conditions $T_a(t=0,\mu^2,x) = 0$ and $T_a(t=\mu^2,\mu^2,x) = 1$, $t = q_T^2$ is negative initial parton mass.

By obtaining uPDF through the factorization and requiring equality with KMR prescription, the $T_a(t,\mu^2,x)$ solution can be derived:

$$T_a(t,\mu^2,x) = \exp\left[-\int_t^{\mu^2} \frac{dt'}{t'}\frac{\alpha_S(t')}{2\pi}\left(\tau_a(t',\mu^2) + \Delta\tau_a(t',\mu^2,x)\right)\right]$$

$$\text{with } \tau_a(t,\mu^2) = \sum_b \int_0^1 dz\, zP_{ba}(z)\theta(\Delta(t,\mu^2) - z), \qquad \Delta(t,\mu) = \frac{\mu}{\mu+\sqrt{t}}$$

$$\text{and with } \Delta\tau_a(t,\mu^2,x) = \sum_b \int_0^1 dz\, \theta(z - \Delta(t,\mu^2))\left[zP_{ba}(z) - \frac{\tilde{f}_b(\frac{x}{z},t)}{\tilde{f}_a(x,t)}P_{ab}(z)\theta(z-x)\right]$$

PRA advantages

The Reggeized parton amplitudes are described by Lipatov's gauge-invariant effective field theory (EFT) [Lipatov 1995]. There is an exact collinear limit:

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

The PRA smoothly interpolates between small and large p_T and coincides with the CSS approach at $p_T \ll \mu$.

Advantages of mMRK uPDFs over KMRW uPDFs:

- The Sudacov form-factor depends on x
- KMRW is only for gluons, mMRK includes gluons and quarks
- Due to the elimination of certain discrepancies, the condition $x \ll 1$ becomes less strict.

The PRA has demonstrated its effectiveness in describing various single– and pair–production processes with D-mesons.

- Inclusive D^0, D^+, D^{*+}, D_s^+ production [Karpishkov, Nefedov, Saleev, Shipilova 2015]
- $J/\psi(\Upsilon)$ and D [Saleev, Chernyshev 2024][2024]

Fragmentation mechanism

Hadronization is described using fragmentation functions (FFs):

$$d\hat{\sigma}(ab \to D^0 D^0) = P^2_{c\to D^0} \times \int\limits_{z_1^{min}}^{1} dz_1 D_{c\to D^0}(z_1) \int\limits_{z_2^{min}}^{1} dz_2 D_{c\to D^0}(z_2) d\sigma(ab \to ccX)$$

with $z_{1,2}^{min} = m_{D^0}/(E_c + |\vec{p}|_c)$.

$$z = \frac{E_{D^0} + |\vec{p}|_{D^0}}{E_c + |\vec{p}|_c}$$

z provides a link between quark and hadron momenta, $P_{c\to D^0} = 0.542$ is fragmentation probability [H1 and ZEUS 1999].

The fragmentation approach works fairly well at $p_T \gg 1$ GeV, but has difficulty at $p_T \sim m_c$. We use FF with Peterson parametrization:

$$D_{c\to D^0}(z) = \frac{N}{z(1 - \frac{1}{z} - \frac{\epsilon}{1-z})^2}$$

where N is a normalization factor (to unity), and with $\epsilon = 0.06$.

SPS open charm production

Combining the formulas for cross-section factorization and the fragmentation approach:

$$d\sigma^{SPS}(pp \to D^0 D^0) = P^2_{c \to D^0} \times D_{c \to D^0}(z_1) \otimes D_{c \to D^0}(z_2) \otimes \sum_{a,b} \Phi_a \otimes \Phi_b \otimes d\hat{\sigma}^{PRA}(ab \to c\bar{c})$$

Subprocesses taken into account:

gluon fusion $RR \to c\bar{c}c\bar{c}$
quark-antiquark annihilation $Q\bar{Q} \to c\bar{c}c\bar{c}$

Strongly suppressed subprocesses:

charm excitation $RQ_c \to gcc\bar{c}$

DPS open charm production

The DPS cross section is expressed as a product of two SPS cross sections:

$$d\sigma^{DPS}(pp \to D^0 D^0) = \frac{d\sigma^{SPS}(pp \to D^0 X) \times d\sigma^{SPS}(pp \to D^0 X)}{S \cdot \sigma_{eff}}$$

where $S = 2$ is the symmetry factor, σ_{eff} is an effective parameter that controls the DPS mechanism contribution.

At similar energies, the effective DPS cross-sections have comparable values:

- Based on Pair-J/ψ, $J/\psi\Upsilon$, $\Upsilon\Upsilon$ fit $\sigma_{eff} = 11.0 \pm 0.2$ mb [Chernishev, Saleev 2022]
- In this research we estimate $\sigma_{eff} = 9.3^{+0.5}_{-0.4}$ mb based on the available $D^0 D^0$ mesurements [LHCb 2012].

Subprocesses taken into account:

$$\text{gluon fusion } RR \to c\bar{c} \otimes RR \to c\bar{c}$$
$$\text{quark-antiquark annihilation } Q\bar{Q} \to c\bar{c} \otimes Q\bar{Q} \to c\bar{c}$$
$$\text{mixed } RR \to c\bar{c} \otimes Q\bar{Q} \to c\bar{c}$$

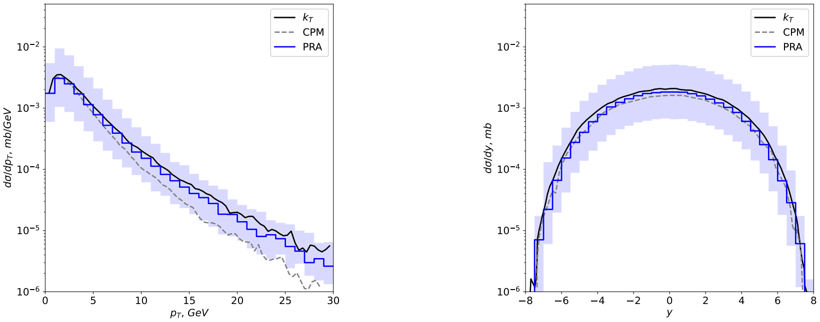
Strongly suppressed subprocesses:

$$\text{charm excitation } RQ_c \to gc \otimes \ldots$$

Numerical equipment

- Parton-level Monte-Carlo generator — KaTie
- It has been verified that the $\overline{|M|^2}$ calculated at AvhLib coincide with obtained using the Lipatov's EFT feinman rules at the tree-level.
- We use uPDFs with exact normalization based on mstw2008lo collinear PDF's set.

Quark comparison

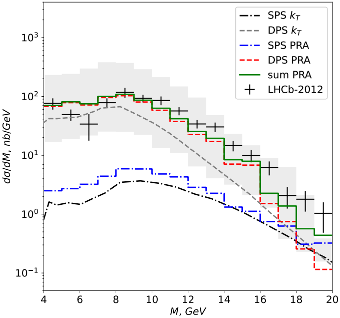


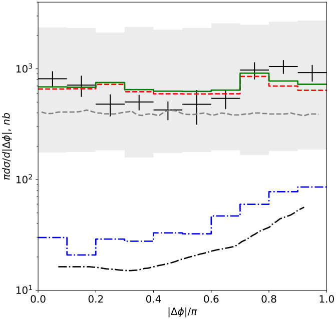
$$\sqrt{s} = 7 \text{ TeV}$$

CPM cross section $\simeq$ k_T-factorization cross section $\simeq$ PRA cross section

SPS using CPM (gray) and SPS using k_T (black) was taken from [van Hameren, Maciuła, Szczurek 2015].

LHCb $\sqrt{s} = 7$ TeV for σ_{eff} fitting





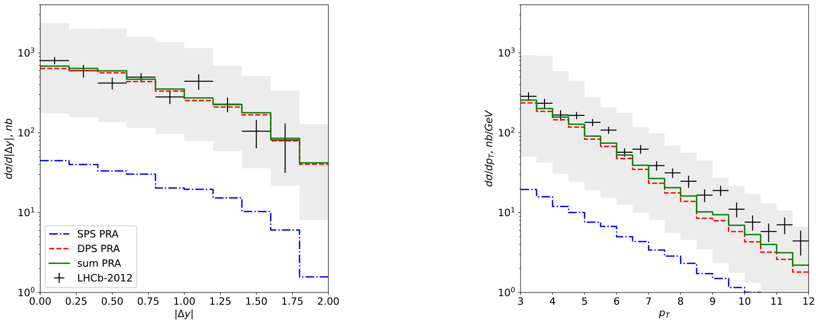
LHC $\sqrt{s} = 7$ TeV, $2 < y < 4$, $p_{TD} > 3$ GeV [LHCb 2012]

Calculations using k_T factorization ($\sigma_{eff} = 11$ mb) [van Hameren, Maciuła, Szczurek 2015]

Fit the experimental data and extract $\sigma_{eff} = 9.3^{+0.5}_{-0.4}$ mb

$$\sigma^{SPS} = 0.05\ \mu b,\ \sigma^{DPS} = 0.7\ \mu b,\ \sigma = 0.75^{+1.72}_{-0.51}\ \mu b$$

LHCb $\sqrt{s} = 7$ TeV



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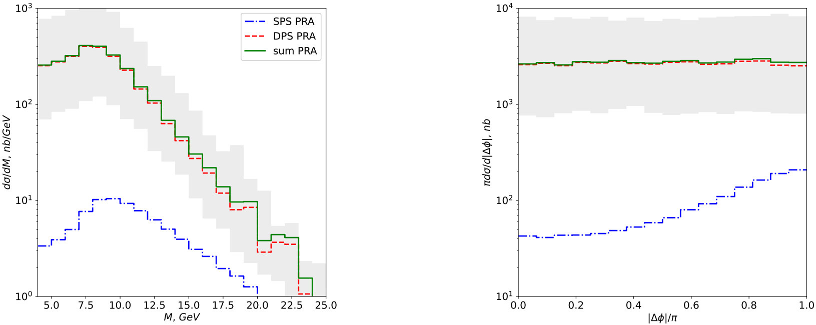
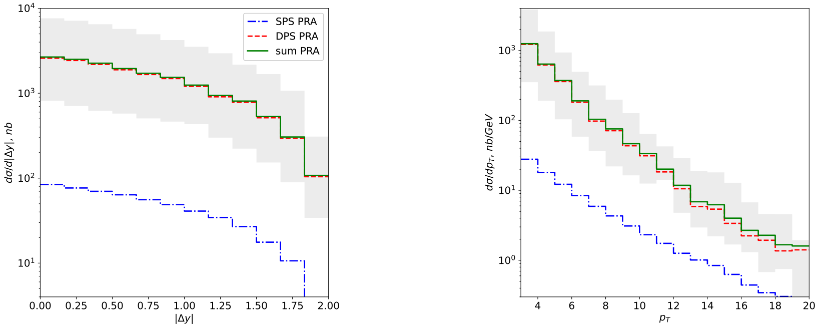
LHCb forward region prediction



LHC $\sqrt{s} = 13$ TeV, $2 < y < 4$, $p_{TD} > 3$ GeV

$\sigma^{SPS} = 0.09\ \mu b$, $\sigma^{DPS} = 2.6\ \mu b$, $\sigma = 2.7^{+5.1}_{-1.9}\ \mu b$

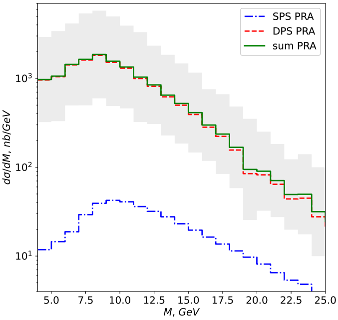
LHCb forward region prediction

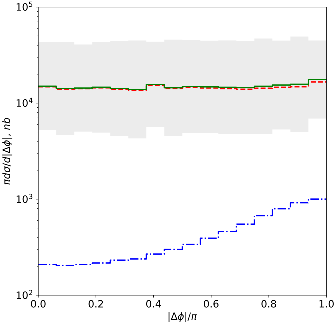


$$\text{LHC } \sqrt{s} = 13 \text{ TeV},\ 2 < y < 4,\ p_{TD} > 3 \text{ GeV}$$

$$\sigma^{SPS} = 0.09\ \mu b,\ \sigma^{DPS} = 2.6\ \mu b,\ \sigma = 2.7^{+5.1}_{-1.9}\ \mu b$$

LHC central region prediction

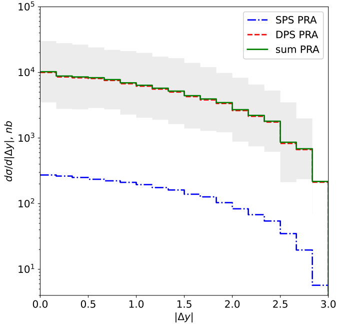


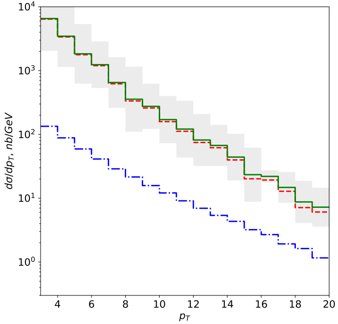


$$\text{LHC } \sqrt{s} = 13 \text{ TeV}, \ |y| < 2, \ p_{TD} > 3 \text{ GeV}$$

$$\sigma^{SPS} = 0.5 \ \mu b, \ \sigma^{DPS} = 15.5 \ \mu b, \ \sigma = 20.0^{+26.5}_{-9.7} \ \mu b$$

LHC central region prediction





LHC $\sqrt{s} = 13$ TeV, $|y| < 2$, $p_{TD} > 3$ GeV

$\sigma^{SPS} = 0.5\ \mu b$, $\sigma^{DPS} = 15.5\ \mu b$, $\sigma = 20.0^{+26.5}_{-9.7}\ \mu b$

Summary

- Our PRA-based calculations demonstrate good agreement with the experimental data on $D^0 D^0$ production at $\sqrt{s} = 7$ TeV.

- The results obtained in the PRA are consistent with previous calculations performed in [van Hameren, Maciuła, Szczurek 2015].

- Has also been demonstrated the applicability of the mMRK uPDFs [Nefedov, Saleev 2020]
- The value $\sigma_{eff} = 9.3^{+0.5}_{-0.4}$ mb was extracted from a fit to the experimental data on $D^0 D^0$ pair production at $\sqrt{s} = 7$ TeV.

- Predictions for the production cross sections at the current LHC energy of $\sqrt{s} = 13$ TeV have been obtained for both the central and forward kinematic regions.

Thank you for your attention!