Pair production of D-mesons at small and large transverse momenta

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SPD NICA

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Outline

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- Fragmentation, fusion and recombination approaches
- High-order corrections and HEF
- $D\bar{D}$-pair production at the LHC
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- Conclusions

Introduction

- D-meson production as a tool to study gluon PDF in a proton
- At the $p_T >> m_D$, the CPM is well used and Collinear PDFs can be extracted in principle.
- At the $p_T << m_D$, the TMD factorization can't be used correctly in case of single $D-$meson production instead of $D\bar{D}-$pair production.
- Phenomenological matching may be used for region $p_T \sim m_D$, $p_T = |\vec{p}_{TD} + \vec{p}_{T\bar{D}}|$.
- Hadronization approaches: Fragmentation $(p_T >> m_D)$, Fusion $(p_T \sim m_D)$ and Recombination $(p_T << m_D)$.
- To test our predictions, we will do comparison with data for $D\bar{D}$-pair production at the LHCb. There are no another data for $D\bar{D}$ or DD-pair production.
- Future measurement for $D\bar{D}$-pair production cross section at the SPD NICA my be unique and more informative compared with the single $D-$meson production.

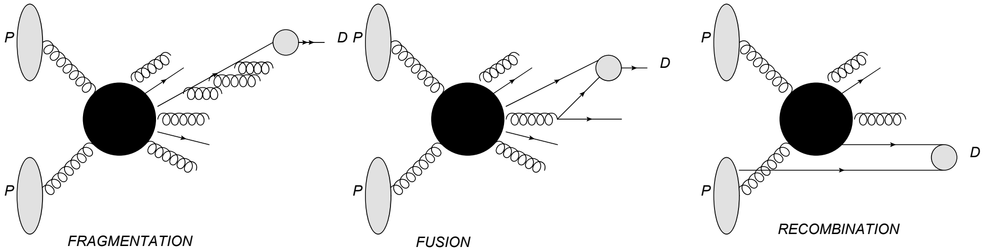
CPM, TMD and high-energy factorizations

- CPM: $\sigma(pp \to D\bar{D}) = \sum_{i,j} f_i(x_1,\mu) \otimes \hat{\sigma}(ij \to D\bar{D}) \otimes f_j(x_2,\mu)$, $p_{DT} >> m_D$, DGLAP evolution for $f(x,\mu)$

- TMD PM: $\sigma(pp \to D\bar{D}) = \sum_{i,j} \Phi_i(x_1, q_{T1}, \zeta_1, \mu) \otimes \hat{\sigma}(ij \to D\bar{D}) \otimes \Phi_i(x_2, q_{T2}, \zeta_2, \mu)$,
  $p_T = |\vec{p}_{TD} + \vec{p}_{T\bar{D}}|$, $p_T >> m_D$, CSS evolution for $\hat{\Phi}_i(x_1, b_T, \zeta_1, \mu)$

- HEF (parton Reggeization approach):
  $\sigma(pp \to D\bar{D}) = \sum_{i,j} F_i(x_1, q_{T1}, \mu) \otimes \hat{\sigma}(ij \to D\bar{D}) \otimes \Phi_i(x_2, q_{T2}, \mu)$, model dependent $\Phi_i(x, q_T, \mu)$, modified KMRW model [Nefedov, Saleev, 2020]. HEF smoothly interpolates predictions between small and large p_T and coinsides with CSS approach at $p_T << m_D$.

Fragmentation, fusion and recombination approaches



Fragmentation model, $p_T >> m_D$

$$\frac{d\sigma}{dp_{TD}} = \int \frac{dz}{z} D(z,\mu) \frac{d\sigma}{dp_{Tc}}, p_D^\mu = z p_c^\mu, \quad m_c = m_D = 0$$

- $$D(z) = D_0 z(1-z)^2/((1-z)^2+\epsilon z)^2 - \text{ Peterson}$$
- $$D(z) = D_0 \frac{(1-z)}{z} \exp(-b/z) - \text{ Lund}$$
- $$D(z) = D_0 z^a (1-z) - \text{ Kartvelishvili, Likhoded}$$
- $$D_{c\to D}(z,\mu) - \text{ with DGLAP evolution by Kniehl, Kramer, et al.}$$
- $$D_{g\to D}(z,\mu) - \text{ with DGLAP evolution by Kniehl, Kramer, et al.}$$

Fragmentation model, $p_T \sim m_D$

- When $m_c \neq m_D \neq 0$ there is uncertainty in a choice of z :

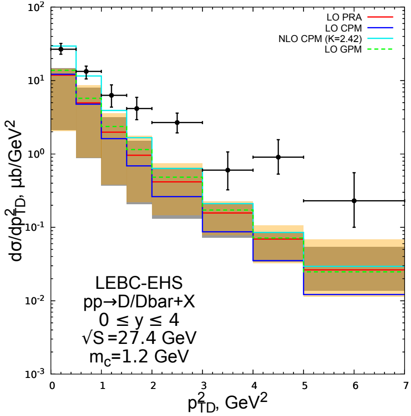
$$z = \frac{|\vec{p}_D|}{|\vec{p}_c|}, \qquad z = \frac{E_D + p_D}{E_c + p_c}, \ldots, \text{ and } \vec{p}_D \upuparrows \vec{p}_c$$

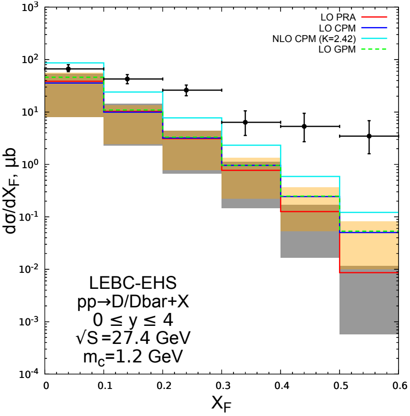
- From light-meson production in SIDIS, we know

$$D_{q\to h}(z,\mu,q_T) = D_{q\to h}(z,\mu)\exp(-q_T^2/<q_T^2>),$$

where q_T is transverse momentum of D-meson relatively to c-quark direction.

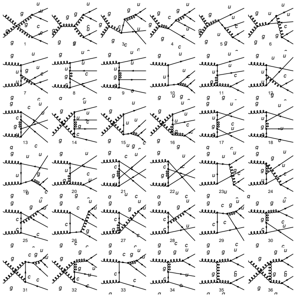
Fragmentation model (Peterson FF) and D-meson production at the $\sqrt{s} = 27.4$ GeV





Fusion model, based on NRQCD or light-cone QCD

- A.V. Berezhnoy, V.V. Kiselev and A.K.Likhoded, New insight into the photoproduction of D^* meson in QCD, [arXiv:hep-ph/9901333 [hep-ph]].
  $p_D^\mu = p_c^\mu + p_q^\mu, \quad m_D = m_c + m_q,$
  $U_q \bar{U}_c \to \langle \mathcal{O}^{1,8} \rangle \hat{\mathcal{P}}_{S=0,1}$
  $D^0 + \bar{D}^0 = (c\bar{u}) + (\bar{c}u)$
- G.P. Lepage, S.J. Brodsky, Exclusive processes in perturbative quantum chromodynamics, PRD 22(9), 2157 (1980) The formalism of "distribution amplitudes" $\Phi(x, Q)$ which control the valence quark distributions in the light-cone perturbative theory



Recombination model

- In LO pQCD, the elementary $c\bar{c}$ production cross section underestimates open charm production in hadronic collisions by large factors of 5. NLO estimates typically account for half of the deficit, with appreciable uncertainties inherent in underlying parameters such as the bare charm quark-mass, renormalization and factorization scales. This obviously leaves room for additional contributions of nonperturbative origin.
- At low transverse momentum and large x_F, $D-$meson production cannot be captured by standard fragmentation functions
- K.P. Das and R.C. Hwa, Quark-antiquark Recombination in the Fragmentation Region, Phys. Lett. B **68**, 459 (1977)
- V.G. Kartvelishvili, A.K. Likhoded and S.R. Slabospitsky, ON CHARMED PARTICLE HADRONIC PRODUCTION, Sov. J. Nucl. Phys. **33**, 434 (1981).
- R. Rapp and E.V. Shuryak, D meson production from recombination in hadronic collisions, Phys. Rev. D **67**, 074036 (2003)

High-order corrections and HEF

The high-energy factorization (HEF) formalism was first introduced as a resummation tool for high-order QCD corrections enhanced by logarithms of partonic center-of-mass energy $\ln(\hat{s}/\mu^2)$ in the CPM. Later, the parton Reggeization approach (PRA) was suggested to define the partonic cross sections with off-shell initial states in a gauge-invariant way using high-energy QCD effective field theory (EFT) formulated by L.N. Lipatov and to include the resummation of Sudakov logartithms $\ln(q_T^2/\mu^2)$ in the unintegrated PDFs. In the limit of $q_T/\mu << 1$, the PRA is consistent with conventional CSS formalism of the TMD factorizasion.

$$F_i(x, q_T, \mu) = F_i^{KMR}(x, q_T, \mu) \otimes F_i^{NP}(q_T), \quad F_i^{NP}(q_T) = \frac{1}{\pi\sigma_i^2} \exp\left(-q_T^2/\sigma_i^2\right), \quad \sigma_i = 0.35 \text{ GeV}$$

$$F_i^{KMR}(x, q_T^2, \mu) = \sum_j \int_x^z \frac{dz}{z} \tilde{f}_j\left(\frac{x}{z}, \mu\right) C_{ij}^{KMR}(z, q_T, \mu)$$

$$C_{ij}^{KMR}(z, q_T, \mu) = \frac{\alpha_s(q_T^2)}{2\pi} \frac{T_i(x, q_T^2, \mu)}{q_T^2} z P_{ij}(z) \theta(\Delta(q_T, \mu) - z), \qquad \Delta(q_T, \mu) = \frac{\mu}{\mu + q_T}$$

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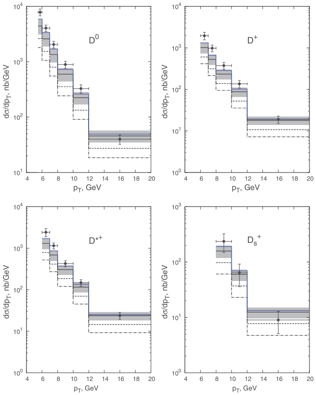
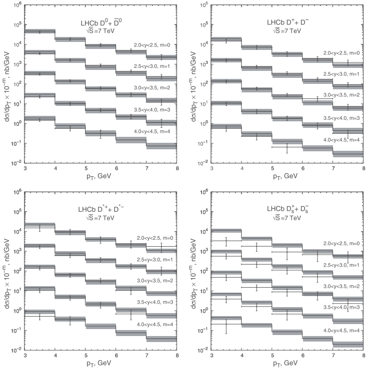
Single D-meson production at the Tevatron and LHC





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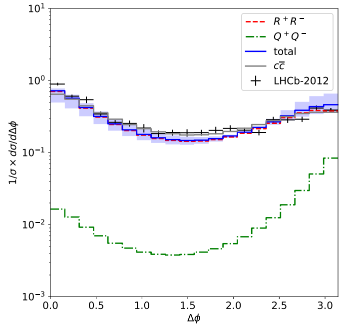
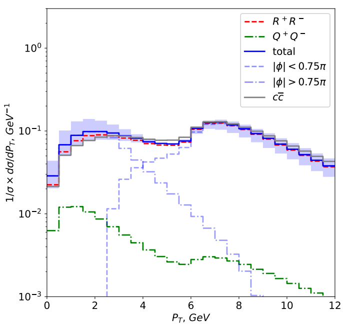
$D\bar{D}$-pair production at the LHC

The LHCb kinematics: $\sqrt{s} = 7$ TeV, $2.0 < y < 4.5$, $4 < p_{TD} < 12$ GeV.





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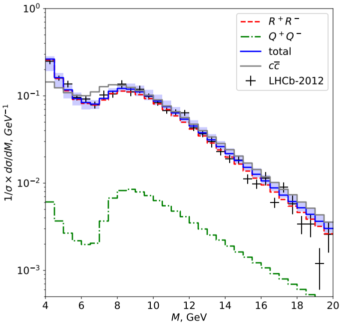
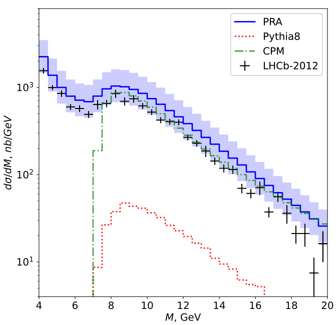
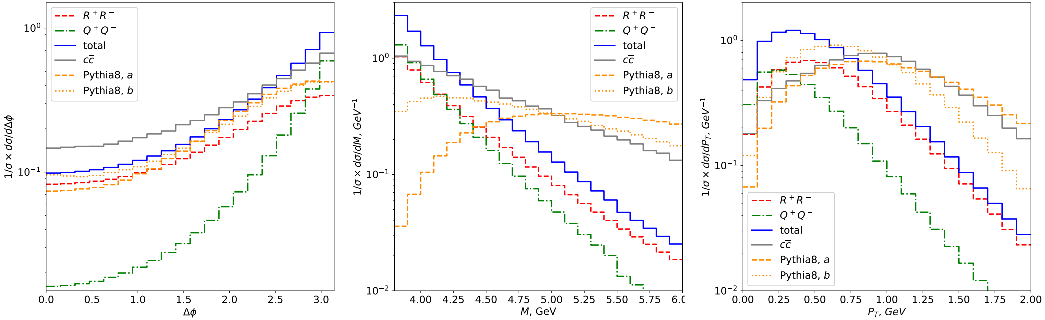




$D\bar{D}$-pair production at the NICA

The SPD NICA kinematics: $\sqrt{s} = 27$ GeV, $|y| < 3$, $0 < p_{TD} < 3$ GeV.
PYTHIA8a - standart settigs, PYTHIA8b - spd open-charm settings



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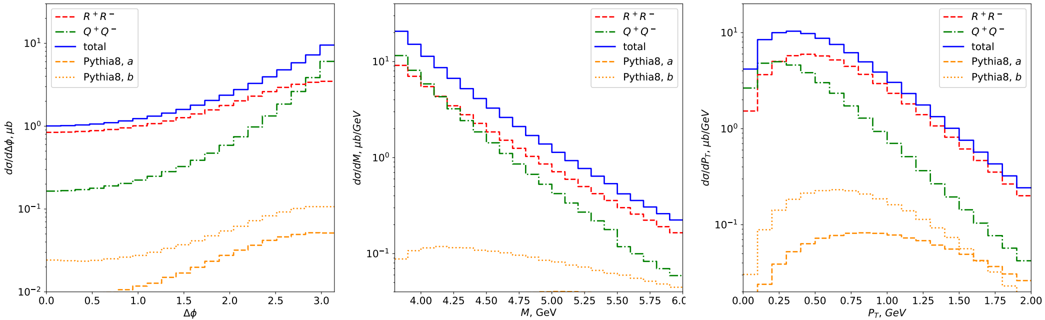
$D\bar{D}$-pair production at the NICA

The SPD NICA kinematics: $\sqrt{s} = 27$ GeV, $|y| < 3$, $0 < p_{TD} < 3$ GeV.



Summary

1. In $pp-$collisions at the $\sqrt{s} = 27$ GeV and $p_{TD} \leq m_D$ different hadronization mechanisms may be occur: fragmentation, fusion and recombination. All relevant models are non-perturbative.

2. Cross section of $D\bar{D}-$pair production is in a few times smaller single $D-$meson production cross section at the $\sqrt{s} = 27$ GeV, $\sigma(pp \to D\bar{D}X) \sim 5 - 10$, μb. LEBC-EHS[1987] data:
$\sigma(pp \to DX) \sim 2 \cdot \sigma(pp \to D\bar{D}) \sim 30$, μb.

3. $D\bar{D}-$pair production is a tool to extract TMD PDFs instead of single $D-$meson production which is used to extract collinear PDFs.

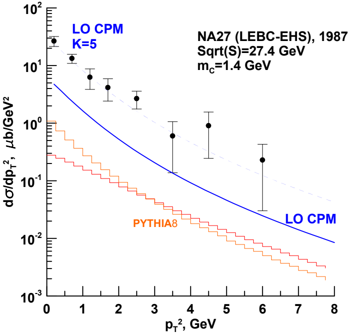
4. At the $\sqrt{s} = 27$ GeV , at the small $p_T < 1$ GeV or large $x_F > 0.5$, quark-antiquark annihilation contribution to $D-$meson production becomes dominant and must be taken into account together with gluon-gluon fusion.

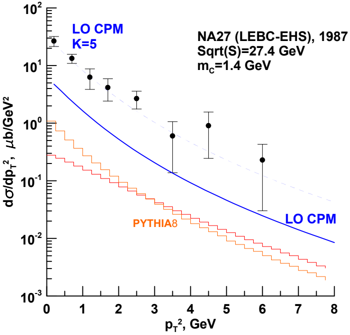
5. We find sufficient differenecs between theoretical calculations (LO CPM, PRA) and predictions obtained using MC PYTHIA8 for $D-$meson and $D\bar{D}$-pair production.

THANK YOU FOR YOUR ATTENTION!

D-meson production at the NICA

The SPD NICA kinematics: $\sqrt{s} = 27$ GeV, $|y| < 3$, $0 < p_{TD} < 3$ GeV.





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