Angular distributions of D-meson in the $D\bar{D}$-pair production at high energy

[1]Alimov L., [1]Bektimirov K.,[1,2]Saleev V.

[1]Samara University

[2]Joint Institute for Nuclear Research

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САМАРСКИЙ УНИВЕРСИТЕТ

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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-particle **inclusive** distributions do not retain the angular information about pair-production dynamics.
- A nonzero transverse momentum of the $D\bar{D}$ pair introduces effects that can **obscure** its internal dynamics.
- In the collinear parton model, leading-order $2 \to 2$ kinematics produces a back-to-back pair. Describing angular decorrelations therefore requires **higher-order contributions**.
- An alternative way is high-energy factorization (HEF), a k_T-factorization approach that accounts for the transverse dynamics of initial-state partons and allows dynamical effects of relative motion in pair production to be probed already at **leading order**.

Conventional parton model

The (conventional) collinear parton model (CPM) is based on the factorization theorem. [Collins 2011]

$$d\sigma(pp \to FS) = \sum_{a,b} \int dx_1 \int dx_2 f_a(x_1, \mu^2) f_b(x_2, \mu^2) d\hat{\sigma}(ab \to FS) + \mathcal{O}\left(\frac{\Lambda_{QCD}}{\mu}\right)$$

$$q^{\mu}_{1,2} = x_{1,2} P^{\mu}_{1,2}, \quad q^2_{1,2} = 0 \tag{1}$$

Here, a and b denote the incoming partons, g, q, or $\bar{q}$, and FS denotes the final state.

- The incoming partons are treated as collinear with the proton beams.
- LO $2 \to 2$ kinematics gives $\vec{p}_T = \vec{p}_{1T} + \vec{p}_{2T} = 0$, so it cannot describe azimuthal decorrelations.
- Since $2 \to 2$ processes are insufficient to describe decorrelations, processes with more patricle in final states $2 \to n$, $n > 2$ must also be included.

NLO*: We include the real-gluon-emission contribution, to study angular decorrelations. We suppress the divergences at low-p_T region using the following regulator:

$$\frac{\vec{p}_T^{\,2}}{\vec{p}_T^{\,2} + p_{T0}^2}$$

High-energy factorization

HEF approach — Parton Reggeization approach (PRA). PRA is a implementation 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 expressed as a convolution in accordance with the k_T-factorization hypothesis:

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

$$\times d\hat{\sigma}^{PRA}(ab \to FS)$$

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

Here, a and b denote the incoming **Reggeized** gluons (R), quarks (Q), or antiquarks ($\bar{Q}$).

$\Phi_{a,b}(x, q_T^2, \mu^2)$ are unintegrated parton distribution functions (uPDFs) constructed using the modified Kimber–Martin–Ryskin–Watt (mKMRW) prescription, with exact normalization:

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

Advantages of the PRA

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 Collins–Soper–Sterman (CSS) approach at $p_T \ll \mu$. So the PRA provides a framework for studying both small and large pair transverse momenta, unlike the conventional approach, which uses various matching schemes to combine high-p_T CPM and TMD low-p_T results.

Advantages of mMRKW uPDFs over KMRW uPDFs:

- Provides a unified approach to quarks and gluons description.
- Due to the elimination of certain discrepancies, the condition $x \ll 1$ becomes less strict.
- The uPDFs satisfy the exact normalization condition shown on the previous slide.

The PRA has demonstrated its effectiveness in describing single D-meson production
[Kniehl, Shipilova, Saleev 2008] [Karpishkov, Nefedov, Saleev, Shipilova 2015]
[Karpishkov, Nefedov, Saleev, Shipilova 2016] [Karpishkov, Saleev, Shipilova 2016]

Modified KMRW prescription

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:

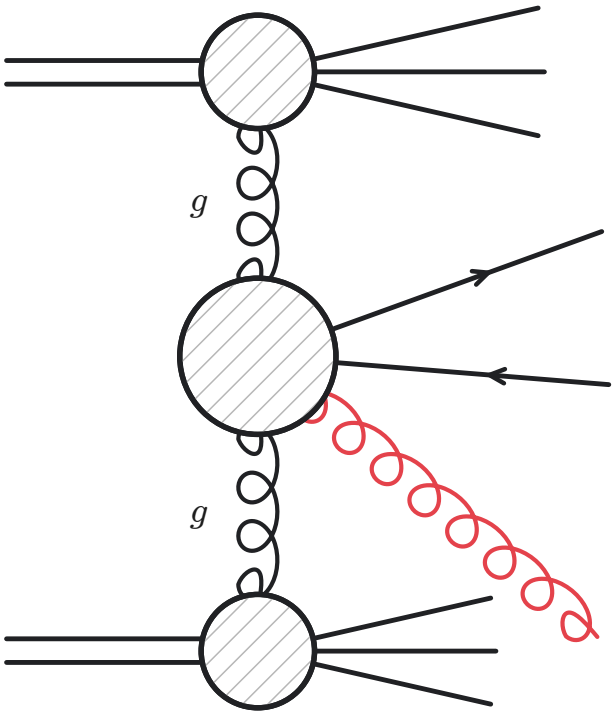
$$T_a(t,\mu^2,x) = \exp\left[-\int_t^{\mu^2}\frac{dt'}{t'}\frac{\alpha_S(t')}{2\pi}\left(\tau_a(t',\mu^2)+\Delta\tau_a(t',\mu^2,x)\right)\right]$$

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

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

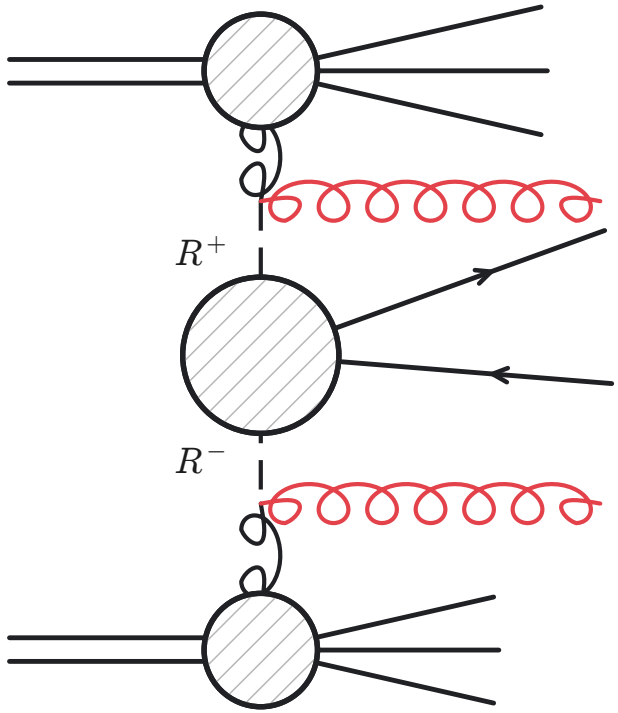
Origin of non-collinear dynamics

CPM NLO*



Real-emission correction

PRA LO



Parton hard-emission with resummation of soft-emission through the Sudakov form factor

Fragmentation mechanism

Hadronization is described using fragmentation functions (FFs):

$$d\hat{\sigma}(ab \to DX) = P_{c\to D} \times \int_{z^{min}}^{1} dz F_{c\to D}(z) d\hat{\sigma}(ab \to c\bar{c}X)$$

with $z^{min} = m_D/(E_c + |\vec{p}|_c)$.

$$z = \frac{E_D + |\vec{p}|_D}{E_c + |\vec{p}|_c}$$

The variable z relates the quark and hadron momenta. We use the fragmentation probabilities $P_{c\to D^0} = 0.542$ and $P_{c\to D^+} = 0.225$ [Gladilin 1999].

For pair production, we apply independent fragmentation to the charm quark and antiquark:

$$d\hat{\sigma}(ab \to D\bar{D}X) = P^2_{c\to D} \cdot F_{c\to D}(z_1) \otimes F_{\bar{c}\to \bar{D}}(z_2) \otimes d\hat{\sigma}(ab \to c\bar{c}X)$$

We use the Peterson parametrization for the fragmentation function:

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

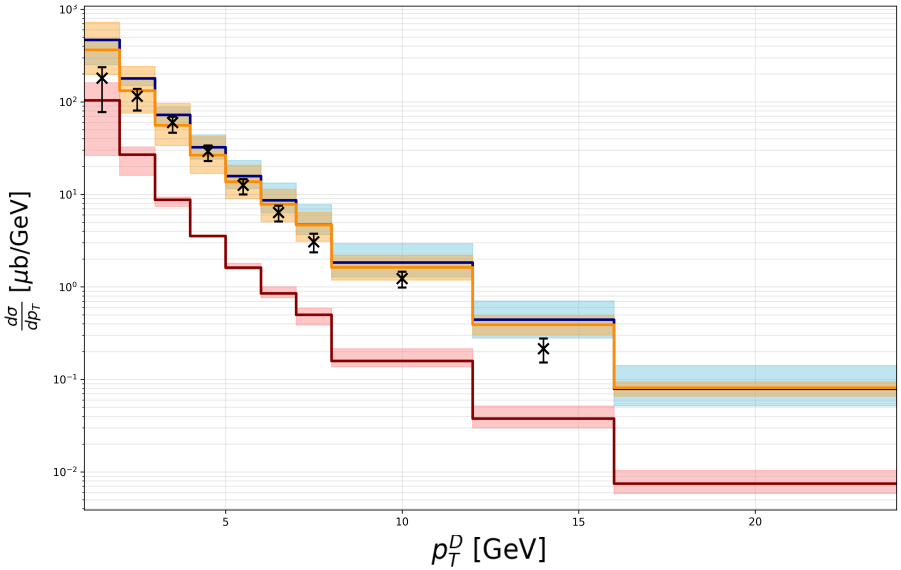
Here, N ensures $\int_0^1 F_{c\to D}(z)\, dz = 1$, and $\epsilon = 0.06$.

Numerical setup

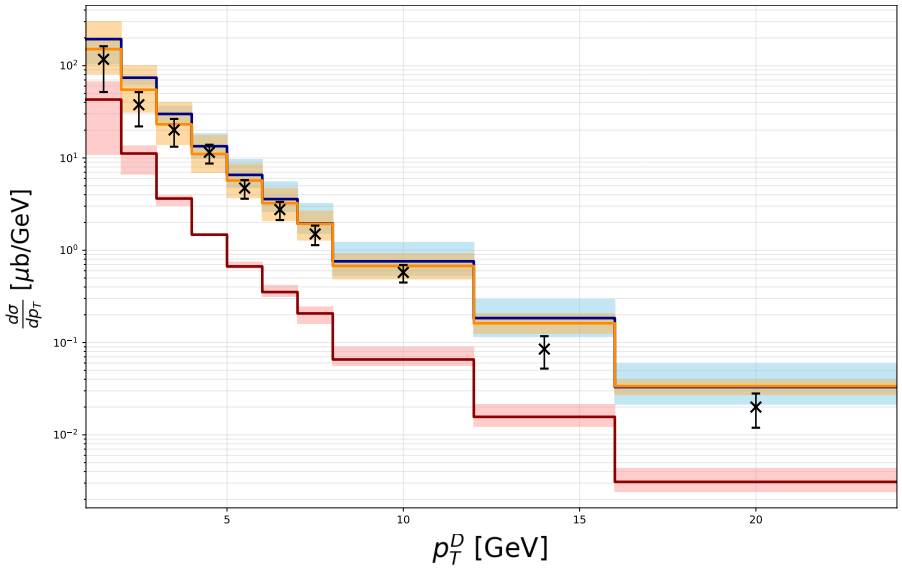
- We use **KaTie**, a parton-level Monte Carlo generator for computation in CPM and k_T-factorization approaches.[A. van Hameren 2018]
- The tree-level squared matrix elements $\overline{|M|^2}$ computed with **AvhLib** have been verified to agree with those obtained using the Feynman rules of **Lipatov's EFT**. AvhLib uses the spinor-helicity formalism and recursive BSFW relations for tree amplitudes.
- For the **PRA** calculations, we use exactly normalized mKMRW uPDFs constructed from the **MSTW2008LO** collinear PDF set.

Single D-meson production

D^0 production



D^+ production

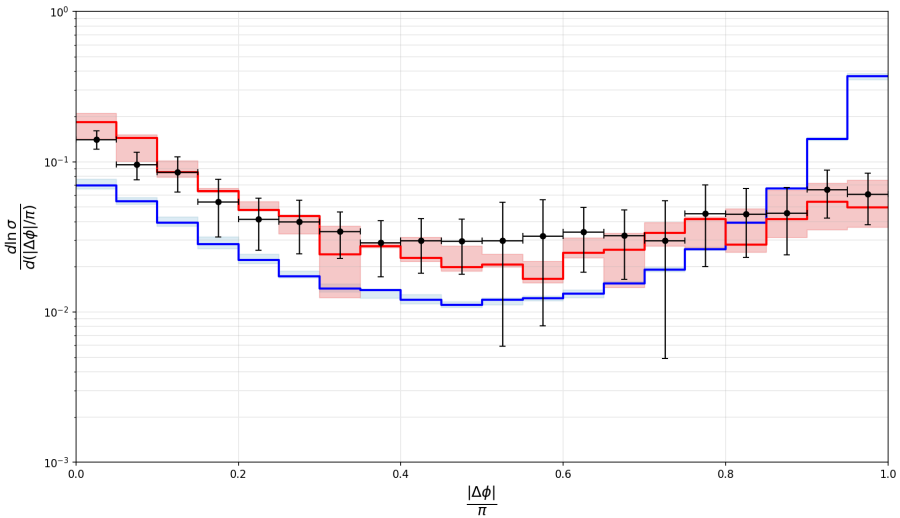


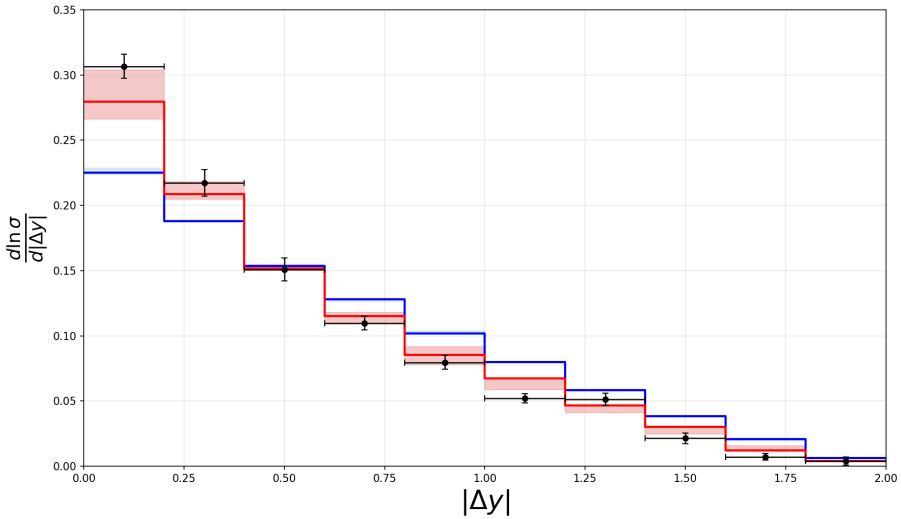
(Red) CPM LO, (Blue) CPM NLO*, (Yellow) PRA LO

Differential cross sections at $\sqrt{s} = 7$ TeV in the central rapidity region, $|y| < 0.5$.
Experimental data from [ALICE 2012].

PRA LO and CPM NLO* yield **same results at large** p_T.

$D\bar{D}$ pair production



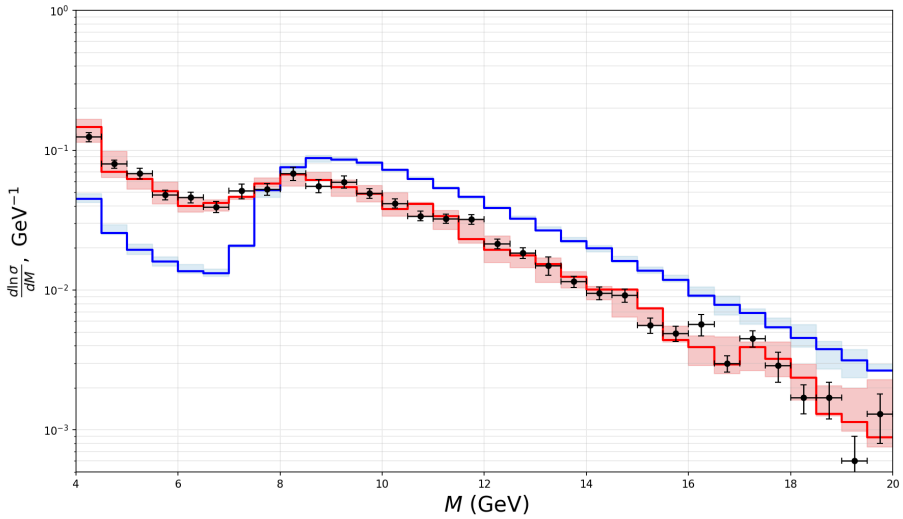


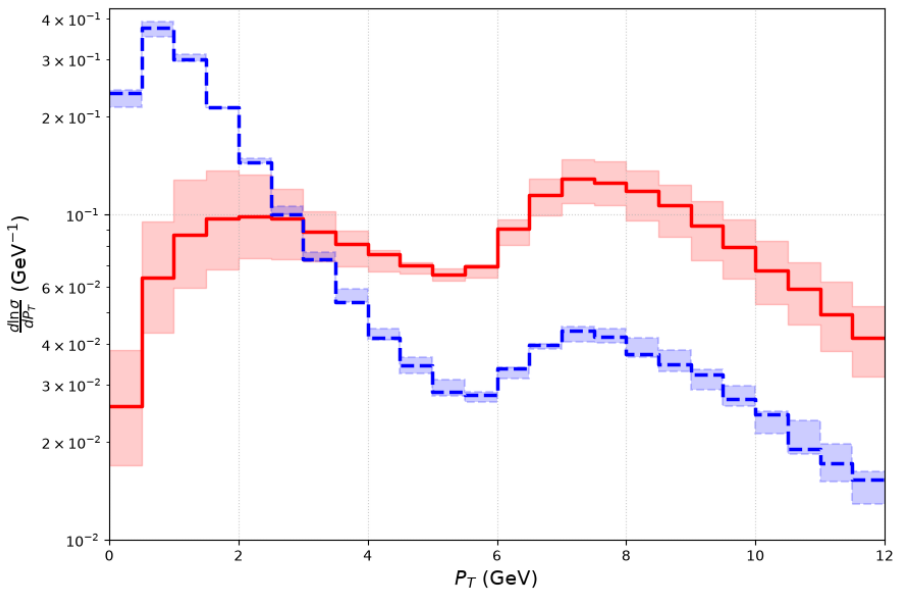
(Red) PRA LO, (Blue) CPM NLO*

Differential cross sections at $\sqrt{s} = 7$ TeV in the forward rapidity region, $2 < y < 4$.
Experimental data from [LHCb 2012].

The PRA LO and CPM NLO* predictions **differ significantly**.

LHCb production $D\bar{D}$ produciton





(Red) PRA LO, (Blue) CPM NLO*

Differential cross sections at $\sqrt{s} = 7$ TeV in the forward rapidity region, $2 < y < 4$.
Experimental data from [LHCb 2012].

Relative D-meson dynamics

To isolate the pair internal motion effects, we study angular distributions in the $D\bar{D}$ rest frame, using the **Collins–Soper (CS) frame**. [Collins, Soper 1977]

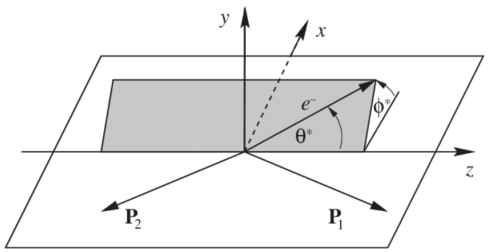
The transformation from the laboratory frame to the CS frame is written as:

$$\Lambda(Lab \to CS) = \Lambda^T \Lambda^L R$$

Here, R rotates the pair momentum into the xz plane, Λ^L is a longitudinal boost that sets $p^z = 0$, and Λ^T removes the remaining transverse momentum.

The polar and azimuthal **angles** are defined by the direction of one selected meson in the CS frame:

$$\vec{n}_D = (\sin\theta_{CS}\cos\phi_{CS}, \sin\theta_{CS}\sin\phi_{CS}, \cos\theta_{CS})$$

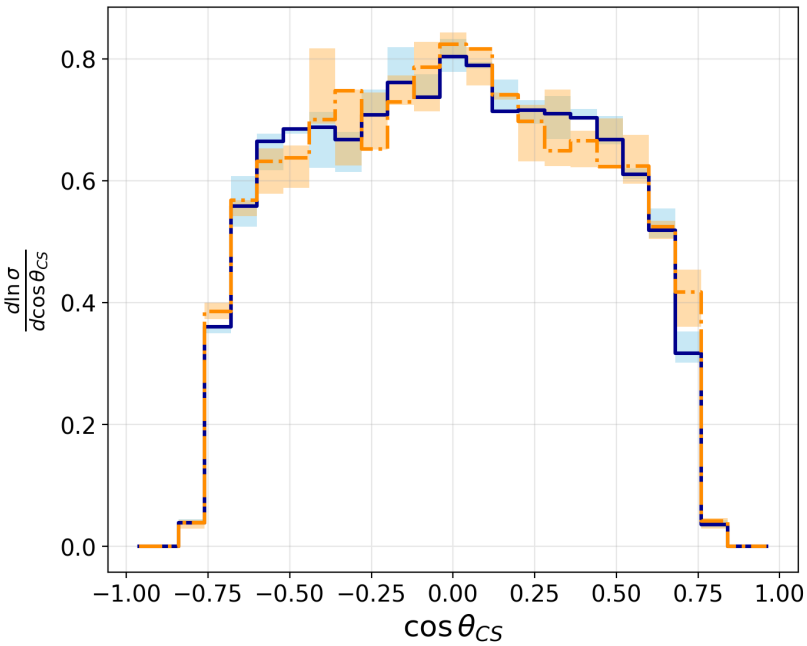


We investigate two regions $r = p_T/M$:

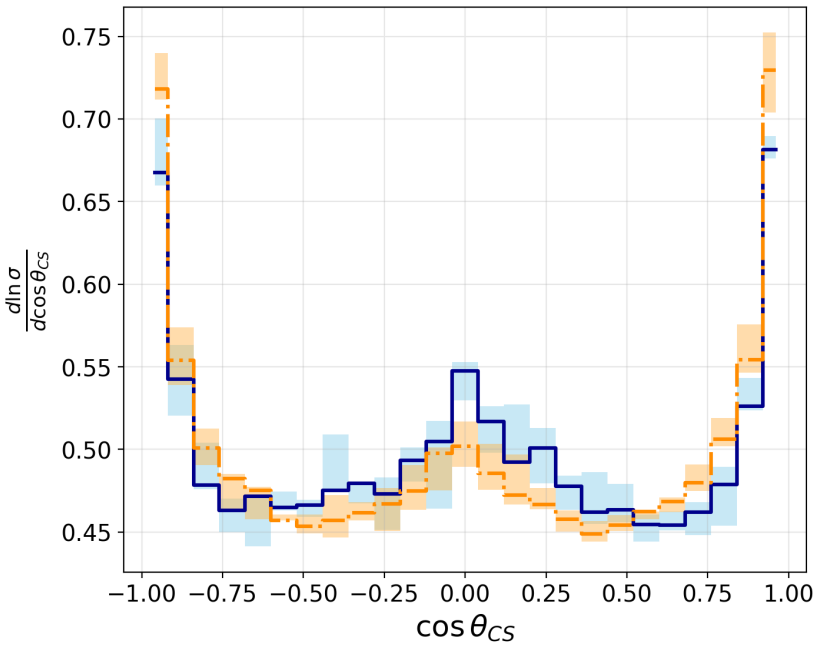
associated with TMD $p_T \ll \mu$ kinematics	associated with pure CPM $p_T \gg \mu$ kinematics
$r < 0.05$	$r > 0.5$

Polar distributions

$r < 0.05$



$r > 0.5$



(Yellow) PRA LO, (Blue) CPM NLO*

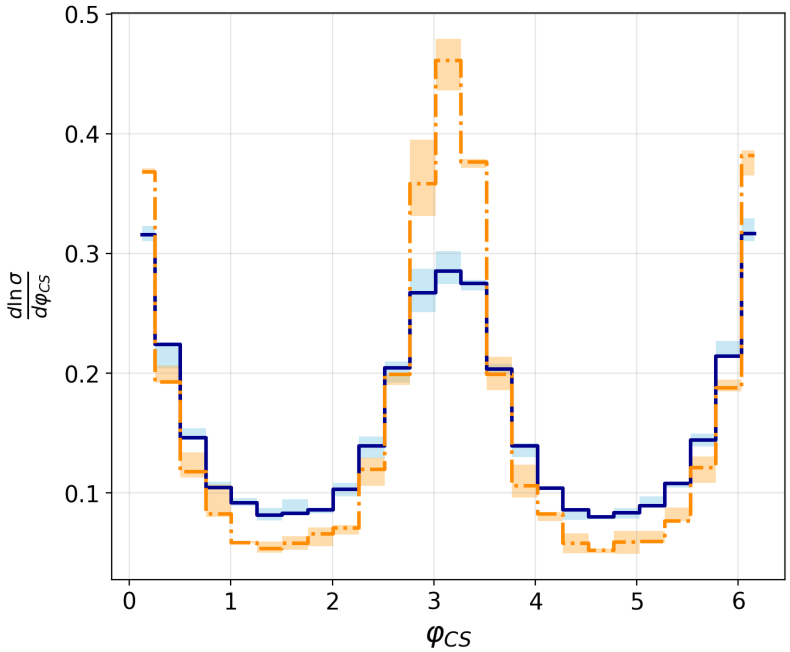
The polar distribution follows $d\sigma/d\cos\theta_{CS} \propto 1 - a\cos^2\theta_{CS}$ at TMD associated range.

PRA LO and CPM NLO* give **similar distributions**.

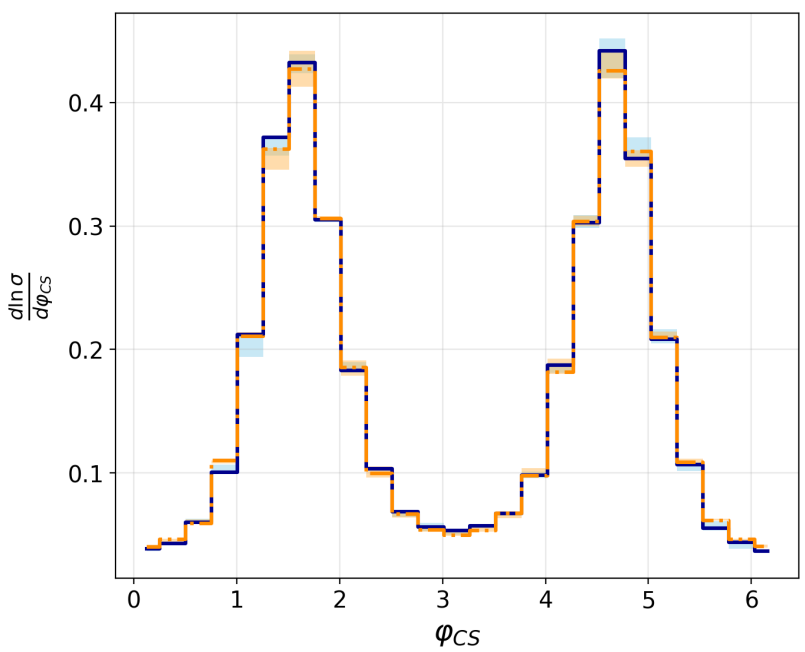
The angular distributions behavior strongly **depends** on r in both approaches.

Azimuthal distributions

$r < 0.05$



$r > 0.5$



(Yellow) PRA LO, (Blue) CPM NLO*

The PRA LO and CPM NLO* azimuthal distributions **differ substantially** at small r.

The angular distributions behavior strongly **depends** on r in both approaches.

Conclusions

- We calculate D-meson angular distributions in the $D\bar{D}$ rest frame using two approaches: leading-order PRA and the collinear parton model with a real-emission contribution CPM NLO*.
- PRA LO and CPM NLO* give similar predictions for single-inclusive D-meson production but differ for observables in $D\bar{D}$ pair production.
- The polar angle distributions are similar at small and large r, whereas the azimuthal distributions differ at small r and agrees at large r.

THANK YOU FOR YOUR ATTENTION!