Pair production is a key tool to study TMD PDFs

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VIII SPD collaboration meeting

November 8, 2024

Report on activity of Samara University group in 2024

- **People:** 3 principal researchers (Saleev V., Shipilova A., Karpishkov A.), PhD students (Alimov L., Shilyaev K.), students (Morosova S., Ospennikov N., Chernyshev A., Shapurin F., Pustobaeva A., Maloletnev G.)
- **New young researchers in the group:** Fedor Martynenko, Alexey Eskin
- **Tasks:** Theory (J/ψ, D, γ production in the TMD factorization, pair production at small p_T in the TMD factorization), MC modeling (S/B ratio study for hard probes with Pythia and KaTie, and timeslices simulation with Geant4)
- **Financial support in 2024:** total amount is 9360K rubles, two 128-core servers (3200K rubles)

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Report on activity of Samara University group in 2024

- **Relevant publications in 2024:**
  1. A. V. Karpishkov, V. A. Saleev and K. K. Shilyaev, Production of Polarized J/ψ Mesons within Nonrelativistic QCD and Generalized Parton Model, Phys. Atom. Nucl. **87** (2024) no.4, 494-497
  2. A. V. Anufriev and V. A. Saleev, High-Energy Production of η_c Mesons in Proton–Proton Collisions, Phys. Part. Nucl. **55** (2024) no.4, 836-840
  3. V. Saleev, Challenges and Problems in Charmonium Production at the SPD NICA, Physics of Particles and Nuclei, 2024, Vol. 55, No. 6, pp. 14601466.
  4. N. Y. Ospennikov and A. V. Shipilova, The Study of Backgrounds in Direct Photon Production at SPD NICA Energies, Phys. Part. Nucl. Lett. **21** (2024) no.4, 687-690
  5. S. D. Morozova and A. V. Shipilova, The Simulation of Interactions in the Straw-Based SPD Track Detector and Primary Vertex Reconstruction, Phys. Part. Nucl. Lett. **21** (2024) no.4, 727-730

- **Forthcoming publications in 2024-2025:**
  1. Small-p_T J/ψ production in the soft gluon resummation approach at NICA
  2. DLSA in the charmonium production at NICA
  3. $D\bar{D}$ pair production at NICA
  4. Relativistic correction in the charmonium production at NICA

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Outline

- CPM and TMD PM
- Hard probes at the SPD NICA
- Pair production at the small transverse momenta, $p_T << M$
- $\mu^+ + \mu^-$ production
- $\gamma + \gamma$ production
- $D + \bar{D}$ production
- $J/\psi + J/\psi$ production
- $\gamma + J/\psi$ production
- Conclusions

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CPM and TMD PM

- **Collinear Parton Model (CPM)**: $p_T >> q_{1,2T} \sim 1$ GeV, $\mu = \mu_F \sim p_T$

  $2 \to 2, 2 \to 3, ...$ parton subprocesses

$$d\sigma^{CPM}(pp \to kX) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu) f_j(x_2, \mu) d\hat{\sigma}(ij \to kl),$$

DGLAP evolution equations for collinear PDFs $f_i(x, \mu)$

$$\frac{d\sigma^{CPM}(pp \to kX)}{dp_T} \sim \frac{d\hat{\sigma}(ij \to kl)}{dp_T}$$

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CPM and TMD PM

- **TMD Parton Model (TMD):** $p_T \sim q_{1,2T} \sim 1$ GeV, $p_T << \mu$ and μ is a hard scale independent on p_T

$$d\sigma(pp \to kX) = \sum_{i,j} \int dx_1 dx_2 F_i(x_1, \mathbf{q}_{1T}) F_j(x_2, \mathbf{q}_{2T}) d\hat{\sigma}(ij \to k) + \mathcal{O}\left(\frac{p_T}{\mu}\right)^2,$$

$2 \to 1$ processes at the parton level

$$\tilde{F}(x, \mathbf{b}_T) = \int d^2 q_T e^{i\mathbf{b}_T \mathbf{q}_T} F(x, \mathbf{q}_T), \qquad \text{two-scale Collins-Soper evolution}$$

$$\tilde{F}(x, \mathbf{b}_T) = \tilde{F}(x, \mathbf{b}_T, \mu, \zeta)$$

$$\frac{d\sigma(pp \to kX)}{dp_T} = \sum_{i,j} \sigma_{ij} \int d^2 b_T e^{i\mathbf{b}_T \mathbf{p}_T} \tilde{F}_i(x_1, \mathbf{b}_T) \tilde{F}_j(x_2, \mathbf{b}_T)$$

$$\sigma = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + ...$$

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Hard probes at the SPD NICA

- **Inclusive γ production**: $pp \to \gamma X$ and $p_{T\gamma} >> 1$ GeV
  At the parton level LO subprocesses are

$$q + g \to q + \gamma, \qquad q + \bar{q} \to g + \gamma, \qquad \text{and } \mu \sim p_{T\gamma}$$

- **The process of single γ production is not a subject of TMD PM**

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Hard probes at the SPD NICA

- **Inclusive $D-$meson production:** $pp \to DX$
  1. At the large $p_{TD} >> m_D$, the only Collinear Factorization and CPM can be applicable
  2. At the small $p_{TD} << m_D (2m_D)$ we may suggest that TMD PM can be used, but ...

     At the parton level LO subprocesses are $2 \to 2$

     $$g + g \to c + \bar{c}, \qquad q + \bar{q} \to c + \bar{c}$$

     $$\frac{d\sigma}{dp_{TD}} \sim \int d^2 p_{T\bar{D}} \overline{|M(gg \to c\bar{c})|^2}, \qquad p_{TD} \approx p_{T\bar{D}}$$

     To control TMD PM conditions, we must known that $p_{T\bar{D}} \sim p_{TD} << m_D$, and, in fact, we study D-meson pair production, $pp \to D\bar{D}X$.
  3. There is FSI $c\bar{c}$-pair with spectator partons and interference between FSI and ISI, which destroy TMD factorization. Formally, we can use TMD factorization formula but the gluon TMD PDF became process dependent.

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Hard probes at the SPD NICA

- **Inclusive $J/\psi-$meson production:** $pp \to J/\psi X$

1. At the large $p_{T\psi} >> m_\psi$, the only Collinear Factorization and CPM is used, and $\mu \sim p_T$
2. At the small $p_{T\psi} << m_\psi \sim \mu$ we can use TMD PM can be used, but the answer depends on hadronization model

- In the Color Singlet Model (CSM) the LO subropcess is $2 \to 2$, $g + g \to J/\psi + g$
- In the NRQCD and ICEM, the LO subprocess is $2 \to 1$, $g + g \to J/\psi$ with color-octet intermediate state $[^1S_0^{(8)}, ^3P_{0,2}^{(8)}]$. In this case **the soft FSI and ISI+FSI** destroy factorization formula and TMD PDFs became process dependent.

- *Theoretically sound* processes for gluon TMD PDF study at the NICA energy in the charmonium production are the following (CSM works !):

$$pp \to \eta_c X \quad (g + g \to \eta_c)$$

,

$$pp \to \chi_c X \quad (g + g \to \chi_c).$$

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Pair production at the small transverse momenta, $p_T << M$

The short motivation list of theoretical publications on pair production

- C. Balazs, E. L. Berger, S. Mrenna and C. P. Yuan, Photon pair production with soft gluon resummation in hadronic interactions, Phys. Rev. D **57** (1998), 6934-6947
- C. Pisano, D. Boer, S. J. Brodsky, M. G. A. Buffing and P. J. Mulders, Linear polarization of gluons and photons in unpolarized collider experiments, JHEP **10** (2013), 024
- T. Altinoluk, C. Marquet and P. Taels, Low-x improved TMD approach to the lepto- and hadroproduction of a heavy-quark pair, JHEP **06** (2021), 085
- R. F. del Castillo, M. G. Echevarria, Y. Makris and I. Scimemi, Transverse momentum dependent distributions in dijet and heavy hadron pair production at EIC, JHEP **03** (2022), 047 doi:10.1007/JHEP03(2022)047
- D. Boer, L. Maxia and C. Pisano, Azimuthal asymmetries in lepton and heavy-quark pair production in UPCs, [arXiv:2410.23924 [hep-ph]].
- A. C. Serri, J. Bor, D. Boer and J. P. Lansberg, $J/\psi-$pair production at NLL in TMD factorisation at the LHC, PoS **EPS-HEP2023** (2024), 272 doi:10.22323/1.449.0272

Pair production at the small transverse momenta, $p_T << M$

- **DY pair production**, $pp \to l\bar{l}X$, with $p_T = |\mathbf{p}_{Tl} + \mathbf{p}_{T\bar{l}}| << M = \sqrt{(p_l + p_{\bar{l}})^2}$. The TMD factorization is OK.
- **Direct photon pair production**, $pp \to \gamma\gamma X$, with $p_T << M = \sqrt{(p_{\gamma 1} + p_{\gamma 2})^2}$. The TMD factorization is OK.
- $D-$**meson pair production**, $pp \to D\bar{D}X$, with $p_T << M = \sqrt{(p_D + p_{\bar{D}})^2}$. There is final state interaction, the TMD factorization is not OK.
- $J/\psi + J/\psi$ **pair production**. The TMD factorization is OK, if CSM is OK as hadronization model.
- $J/\psi + \gamma$ **pair production**. The TMD factorization is OK, if CSM is OK as hadronization model.

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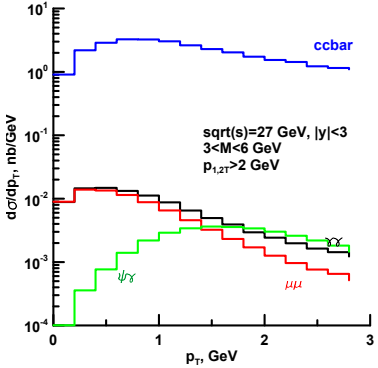
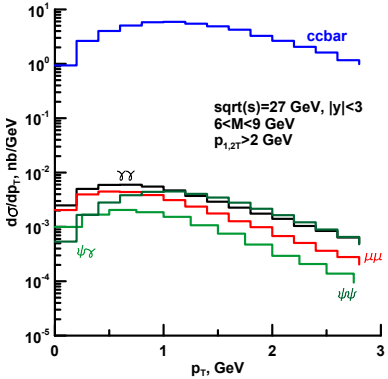
Pair production at the small transverse momenta, $p_T << M$, *KaTie*



Pair production at the small transverse momenta, $p_T << M$, *KaTie*



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Conclusions

- Single particle production processes to study gluon TMD PDFs
  1. $pp \to \eta_c X$, $pp \to \chi_c X$ (**CSM !**)
  2. $pp \to J/\psi X$ (**COM !**)
- Pair particle production processes to study TMD PDFs
  1. $pp \to l\bar{l}X$ and $pp \to \gamma\gamma X$, (**quark TMD PDFs**)
  2. $pp \to D\bar{D}X$ (**FSI+ISI !**)
  3. $pp \to J/\psi J/\psi X$ (**CSM ! **)
  4. $pp \to J/\psi\gamma X$ (**CSM ! **)
- $\sigma(pp \to D\bar{D}X) \approx 10$ nb, $\sigma(pp \to l\bar{l}X) \approx \sigma(pp \to \gamma\gamma X) \approx 10$ pb, $\sigma(pp \to J/\psi J/\psi X) \approx 1$ pb, here $p_{1,2T} > 2$ GeV
- The opportunity of pair production of D-mesons and charmonia at NICA should be study carefully, as from the theory side as in the MC modeling.

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THANK YOU FOR YOUR ATTENTION!