Congratulations

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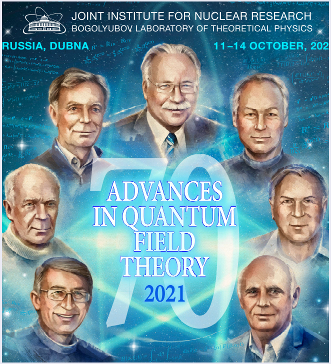

Estimates for transverse single-spin asymmetries in the hard processes at SPD NICA

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Outline

1. Hard processes at SPD NICA
2. Factorization for hard processes: collinear and TMD-factorization
3. Charmonium production
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   - Transverse Single Spin Asymmetries, $A_N(p_T, x_F)$
4. $D-$meson production
   - Cross sections and spectra
   - Transverse Single Spin Asymmetries $A_N(p_T, x_F)$
5. Prompt photon production
   - Cross sections and spectra
   - Transverse Single Spin Asymmetries
6. Conclusions

Hard processes at SPD NICA $\sqrt{s} = 27$ GeV

Charmonium production: J/ψ, $\psi(2S)$, χ_{cJ} and η_c (!), at $0 \le p_T \le 4$ GeV and $|y| < 3$

$D-$meson production at $0 \le p_T \le 4$ GeV and $|y| < 3$

Prompt photon production at $3 \le p_T \le 6$ GeV and $|y| < 3$

All these processes are originated dominantly from gluon-gluon fusion or gluon-quark scattering

$$g + g \to c + \bar{c}, \quad c \to D$$

$$g + g \to c + \bar{c} + g, \quad c\bar{c} \to J/\psi$$

$$q + g \to q + \gamma$$

SPD gluon program: study collinear and TMD gluon PDFs, gluon spin structure functions, ...

Factorization for hard processes: Collinear Parton Model and TMD-factorization

Collinear Parton Model

$$\sigma(pp \to hX) = \sum_{i,j=g,q,\bar{q}} \int dx_1 \int dx_2 f_i(x_1, \mu^2) f_j(x_2, \mu^2) \hat{\sigma}^{CPM}(ij \to hk, x_1 x_2 s)$$

$$q_1^\mu = x_1 P_1^\mu, \quad q_{1T} = 0, q_1^2 = 0$$

TMD-factorization approach (Collins-Stermann-Soper model) or phenomenological Generalized Parton Model(GPM)

$$\sigma(pp \to hX) = \sum_{i,j=g,q,\bar{q}} \int dx_1 \int dx_2 F_i(x_1, \vec{q}_{1T}, \mu^2, \zeta_1) \times$$

$$\times F_j(x_2, \vec{q}_{2T}, \mu^2, \zeta_2) \hat{\sigma}^{TMD}(ij \to hk, x_1 x_2 s)$$

$$q_1^\mu = x_1 P_1^\mu + y_1 P_2^\mu + q_{1T}^\mu, \quad q_{1T}^\mu \neq 0, \quad q_1^2 = 0$$

Factorization for hard processes: Collinear Parton Model and TMD-factorization

SPD NICA kinematical conditions for $c-$quark production processes

$$p_T \leq 3-4 \text{ GeV}, \quad \mu \simeq m_h(m_D, m_\psi, ..)$$

Collinear Parton Model works well at $p_T \geq \mu$, it has divergence at $p_T \to 0$

The CSS model (TMD) is applicable when $p_T \ll \mu$.

For most future data $p_T \sim \mu$, where predictive power of CPM and CSS is under the question

- To use Generalized Parton Model, $F(x, \vec{q}_T, \mu) = f(x,\mu) \times G(\vec{q}_T)$
- To use CPM (in LO+NLO+..) with cut $p_T > p_{T,min} \approx 3-4$ GeV

Charmonium production

Nonrelativistic Quantum Chromodynamics (NRQCD)

- **NRQCD-factorization:** *Different L, S and* **color** *states of $Q\bar{Q}$-pair hadronize to X with different "probability"* – **long-distance matrix element (LDME):** $\left\langle \mathcal{O}^X \left[{}^{2S+1}L_J^{(\text{color})} \right] \right\rangle$.
- LDME-s of states different from CSM-state are suppressed by powers of v^2 (~ 0.3 for J/ψ, ~ 0.1 for Υ) – *velocity-scaling rules for LDMEs*. E.g. for J/ψ and $\psi(2S)$: CSM$={}^3S_1^{(1)} = O(1)$ and ${}^3P_J^{(8)} = O(v^2)$ and ${}^3S_1^{(8)}$, ${}^1S_0^{(8)}$, contribute at $O(v^4)$.

Charmonium production

Color Evaporation Model (CEM)

- In **Improved-Color-Evaporation Model:** *all $Q\bar{Q}$ states with $M_X < M_{Q\bar{Q}} < 2M_{(\text{open flav. Q}-\text{meson})}$ hadronize to quarkonium X with the same probability – F_X*
- Optionally [Ma, Vogt, 2016] ICEM takes into account kinematic (soft-gluon recoil) corrections from the difference of masses $M_{Q\bar{Q}}$ and M_X using simple relation $p_T(X) = p_T(Q\bar{Q}) \times M_X/M_{Q\bar{Q}}$.
- ICEM can be viewed as NRQCD-factorization without velocity-scaling rules for probabilities F_X.

Both models are well-defined to all orders in α_s, but NRQCD-factorization is viewed as more "rigorous" approach by the community.

Charmonium production

Predictions for prompt J/ψ transverse momentum spectra

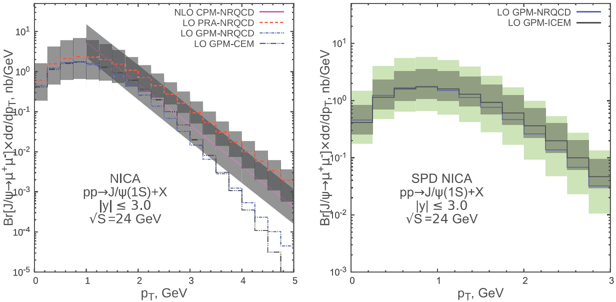


Figure 8 : Prompt J/ψ transverse momentum distribution at $\sqrt{s} = 24$ GeV, $|y| \leq 3$. Left panel: GPM results with $\langle q_T^2 \rangle = 1$ GeV^2 are shown by dash-dotted (NRQCD) and dash-double-dotted (ICEM) histograms. Solid and dashed histograms with uncertainty bands are PRA [A.V. Karpishkov, M.A. Nefedov and V.A. Saleev, J. Phys. Conf. Ser. **1435**, 012015 (2020)] and NLO CPM [M. Butenschön and B.A. Kniehl, private communication] predictions respectively. Right panel: GPM predictions in NRQCD (solid histogram with light green uncertainty band) and ICEM (dashed histogram with dark-green uncertainty band) approaches with their uncertainty bands shown.

Charmonium production

Predictions for prompt J/ψ transverse momentum spectra

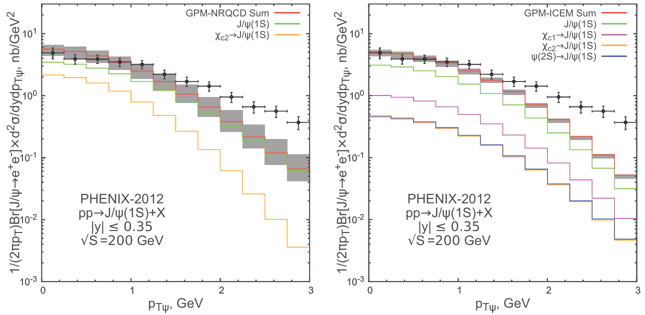


Figure 4 : Differential cross-section of prompt J/ψ production as function of transverse momentum at $\sqrt{s} = 200$ GeV, $|y| \leq 0.35$. The theoretical results are obtained in GPM with $\langle q_T^2 \rangle = 1$ GeV^2. Left panel: NRQCD-factorization prediction with only color-singlet channels included. Right panel: ICEM-prediction. In the left panel, non-zero contributions from decays $\chi_{c0} \to J/\psi$ and $\psi(2S) \to J/\psi$ are not shown. Experimental data are from the Ref. [A. Adare *et al.* [PHENIX], Phys. Rev. D **85**, 092004 (2012)].

Transverse Single Spin Asymmetry (TSSA) in Charmonium production

$p^{\uparrow} p \to \mathcal{C} X$ $\mathcal{C} = J/\psi, \chi_c, \psi(2S), \eta_c$

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{d\Delta\sigma}{2d\sigma}.$$

The numerator and denominator of A_N have the form:

$$d\sigma \propto \int dx_1 \int d^2 q_{1T} \int dx_2 \int d^2 q_{2T} F_g(x_1, q_{1T}, \mu_F) F_g(x_2, q_{2T}, \mu_F) d\hat{\sigma}(gg \to \mathcal{C}X),$$

$$d\Delta\sigma \propto \int dx_1 \int d^2 q_{1T} \int dx_2 \int d^2 q_{2T} [\hat{F}_g^{\uparrow}(x_1, \mathbf{q}_{1T}, \mu_F) - \hat{F}_g^{\downarrow}(x_1, \mathbf{q}_{1T}, \mu_F)] \times F_g(x_2, q_{2T}, \mu_F) d\hat{\sigma}(gg \to \mathcal{C}X), \quad (1)$$

where $\hat{F}_g^{\uparrow,\downarrow}(x, q_T, \mu_F)$ is the distribution of unpolarized gluon (or quark) in polarized proton.
The gluon Sivers function (GSF) can be introduced as

$$\Delta \hat{F}_g^{\uparrow}(x_1, \mathbf{q}_{1T}, \mu_F) \equiv \hat{F}_g^{(\uparrow)}(x_1, \mathbf{q}_{1T}, \mu_F) - \hat{F}_g^{(\downarrow)}(x_1, \mathbf{q}_{1T}, \mu_F) \quad (2)$$

Transverse Single Spin Asymmetry (TSSA) in Charmonium production

CGI-GPM approach [L. Gamberg and Z. B. Kang, Phys. Lett. B 696, 109 (2011)]

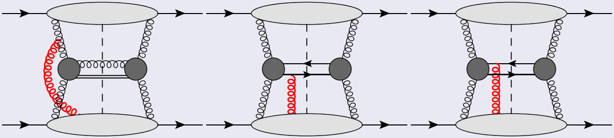


FIG. 2. Example diagrams for contributions to the numerator of TSSA in CGI-GPM. Left panel: ISI for production of ${}^3S_1^{(1)}$ state. Middle and right panels: FSI for $gg \to c\bar{c}$ process with both final-state quarks tagged.

Transverse Single Spin Asymmetry (TSSA) in Charmonium production

$A_N^{J/\psi}(x_F)$, prompt J/ψ

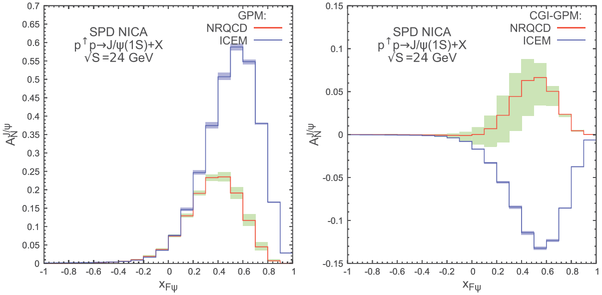


Figure 11 : Comparison of predictions for SSA $A_N^{J/\psi}$ as function of x_F at $\sqrt{s} = 24$ GeV in NRQCD (solid histogram) and ICEM (dashed histogram) approaches. Left panel: GPM-prediction. Right panel: CGI-GPM-prediction. The SIDIS1 parametrisation of GSFs is used.

Transverse Single Spin Asymmetry (TSSA) in charmonium production

$A_N^{J/\psi}(p_T)$, prompt J/ψ

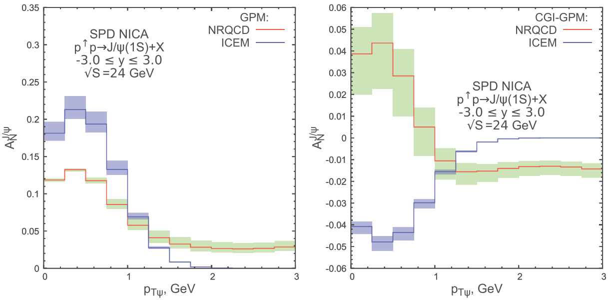


Figure 12 : Comparison of predictions for SSA $A_N^{J/\psi}$ as function of p_T at $\sqrt{s} = 24$ GeV in NRQCD (solid histogram) and ICEM (dashed histogram) approaches. Left panel: GPM-prediction. Right panel: CGI-GPM-prediction. The SIDIS1 parametrisation of GSFs is used.

Transverse Single Spin Asymmetry (TSSA) in charmonium production

Main results for $A_N^{J/\psi}$

- NRQCD versus CEM
- Only $f-$type GSF contribute in $A_N^{J/\psi}$ in CGI-GPM
- η_c production may very good tool to study GSF in exact TMD-factorization

Details of calculations and collection of results have been published recently

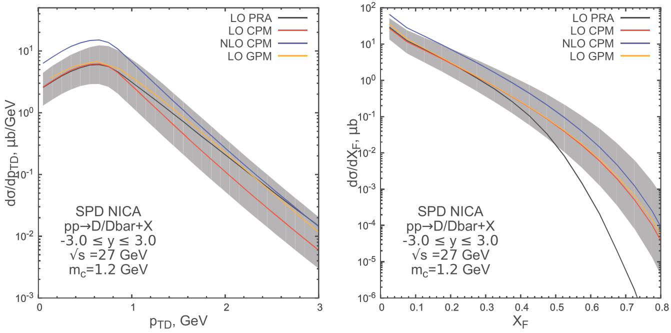
A. Karpishkov, M. Nefedov and V. Saleev,
Estimates for the single-spin asymmetries in the $p^{\uparrow}p \to J/\psi X$ process at PHENIX RHIC and SPD NICA
Phys. Rev. D **104** (2021) no.1, 016008 doi:10.1103/PhysRevD.104.016008

$D-$meson production at SPD NICA

Massive scheme ($m_c = 1.2 - 1.5$ GeV) with nonperturbative fragmentation function $D_{c\to D}(z)$ or $D_{c\to D}(z, \vec{q}_T, \mu^2)$

$$z = \frac{E_D + p_D}{E_c + p_c}$$

$D-$meson cross sections at SPD NICA



$D-$meson production at SPD NICA

$A_N^D(p_T)$

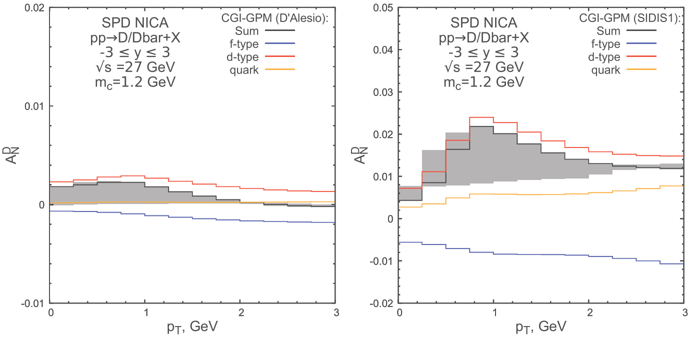


Figure 6 : Predictions for SSA on SPD NICA as function of p_T within the CGI-GPM and parametrizations of D'Alesio (*et. al.*) (left) and SIDIS1 (right). Phenomenological fragmentation function of Peterson with $\epsilon = 0.06$ and $N = f(c \to D^0) + f(c \to D^+) + f(c \to D_s^+) = 0.859$ is used.

$D-$meson production at SPD NICA

$A_N^D(x_F)$

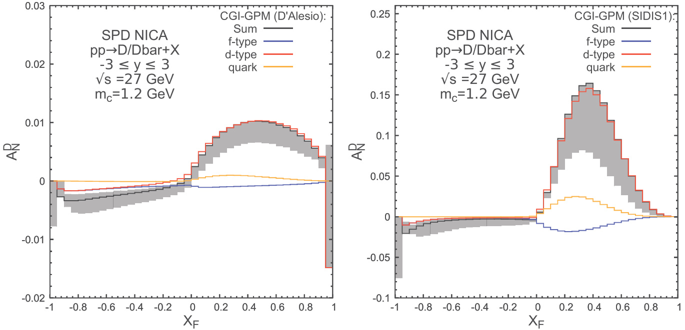


Figure 7 : Predictions for SSA on SPD NICA as function of x_F within the CGI-GPM and parametrizations of D'Alesio (*et. al.*) (left) and SIDIS1 (right). Phenomenological fragmentation function of Peterson with $\epsilon = 0.06$ and $N = f(c \to D^0) + f(c \to D^+) + f(c \to D_s^+) = 0.859$ is used.

Prompt photon production

Prompt = Direct + Fragmentation but Isolated photon production

It is well known that at high energies and large photon p_T so called Isolation Criteria (ISO) can be used:

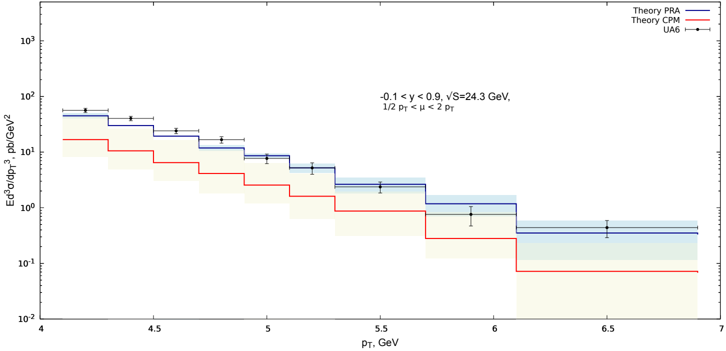
$$r = \sqrt{\Delta\phi^2 + \Delta y^2} > R$$

At first, ISO strongly suppress fragmentation contribution for large-p_T photon production

At second, ISO with Frixione receipt ("Frixione cone condition") help to estimate fragmentation contribution without knowledge on $D_{q\to\gamma}(z,\mu)$ and to exclude double counting. It makes HO calculations more simple

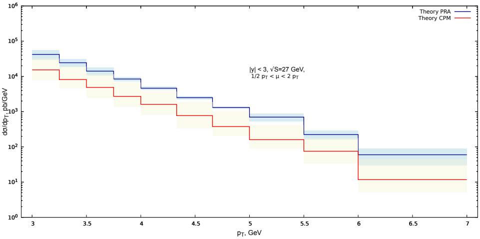
Prompt photon production

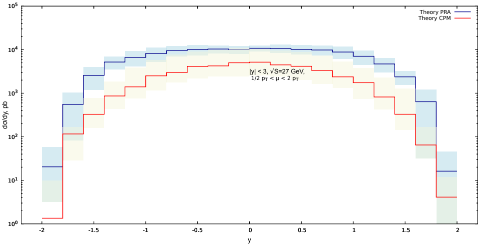
Transverse momentum spectrum in LO CPM and in TMD (it is coincide with NLO*). Data from CERN-UA6 Collaboration (1998).



Prompt photon production

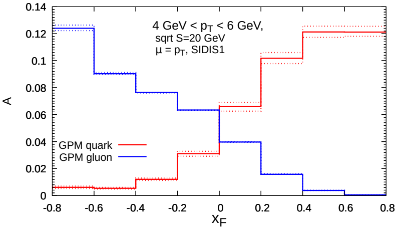
Prediction for SPD NICA, LO CPM and PRA (NLO*)

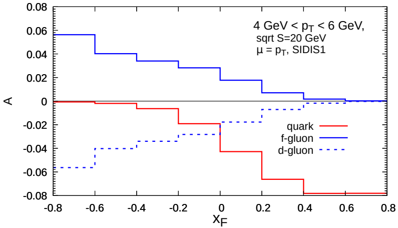




Prompt photon production, TSSA

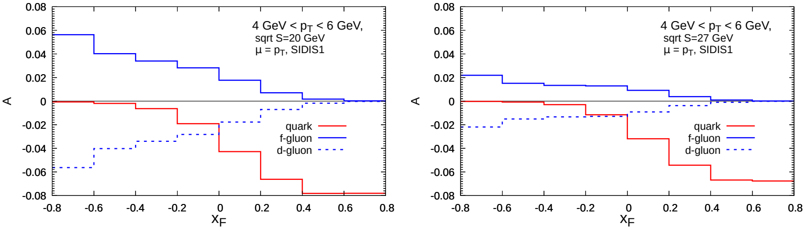
$A_N^\gamma(x_F)$, GPM versus CGI-GPM



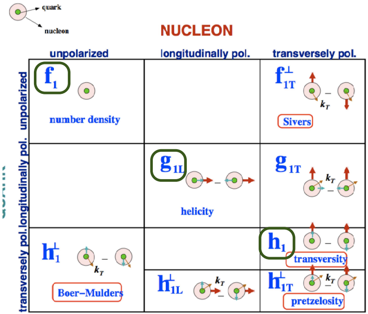


Prompt photon production, TSSA

$A_N^\gamma(x_F)$, CGI-GPM, at $\sqrt{s} = 20$ and $\sqrt{s} = 27$ GeV



Conclusions

1. We have estimated TSSA and gluon Sivers Function at SPD NICA conditions
   - In charmonium production
   - In D-meson production
   - In large-p_T photon production
2. 

3. At the NICA energies we deal with intermediate region (perturbative/nonperturbative) and the task for theory is to take into account precisely perturbative effects for exact study nonperturbative structure of proton

Thank you for your attention!