Hard processes at NICA with TMD factorizations

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https://ssau.ru/science/ni/nip/nil/sltf

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SPD-NICA, JINR, Dubna

Hard processes at SPD NICA

Measurements of the lepton pair (Drell-Yan), J/ψ and direct photon production in collisions of non-polarized, longitudinally and transversally polarized proton and deuteron beams are suggested to be performed at the collider NICA of the JINR using the specialized Spin Physics Detector (SPD).

Hard processes at SPD NICA

At kinematical conditions of NICA collider

$$\sqrt{S} = 24 \text{ GeV}, 1 < p_T < 6 \text{ GeV}, Q, M_\psi \gtrsim 3 \text{ GeV}$$

effects related with **intrinsic non-perturbative transverse motion of partons** inside hadrons are important and some form of Transverse-Momentum-Dependent (TMD) factorization should be used for theoretical predictions.

It is more preferable, rather than conventional LO and NLO fixed order calculations in the Collinear Parton Model (CPM), which are diverged at any fixed order of perturbation theory at $p_T \to 0$.

The second task, **TMD factorization should regularized such divergences.**

Phenomenology of intrinsic motion

Naive model of intrinsic parton motion

The cross-section for the process $hN \to \mu^+\mu^- X$ in the QCD first order with allowance for the primordial transverse momentum of partons of the interacting hadron can be represented as[20,21]

$$\frac{d\sigma}{dM\,dyd^2p_T} = \frac{d\sigma^{\mathrm{DY}}}{dM\,dy}\phi_q^{hN}(\bar{p}_T) + \int d^2k_T \frac{d\sigma^{\mathrm{QCD}}}{dM\,dyd^2k_T}[\phi_q^{hN}(\bar{p}_T - \bar{k}_T) - \phi_q^{hN}(\bar{p}_T)]\,, \quad (4)$$

where the cross-sections $d\sigma^{\mathrm{DY}}/dydM$ and $d\sigma^{\mathrm{QCD}}/dydM\,d^2p_T$ are calculated using the distribution functions of given partons in the nucleon and hadron.

Figure 1: From [Saleev V.A., Zotov N.P. Mod. Phys. Lett. A, 7(7), 545 (1992)].

$$\Phi^{pN}(\mathbf{k}_T) = \frac{1}{\pi\langle\mathbf{k}_T^2\rangle}\exp\left(-\mathbf{k}_T^2/\langle\mathbf{k}_T^2\rangle\right), \text{ with}\langle\mathbf{k}_T^2\rangle = 0.9\mathrm{Ge}V^2. \quad (1)$$

Phenomenology of intrinsic motion

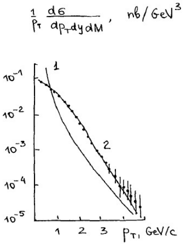


Fig. 3. Transverse momentum distributions of muon pairs at $y = 0$, $M = 5$ GeV and $s = 282$ GeV^2. Curve 1 represents the calculation by the first order QCD formula, curve 2 is the calculation by Eq. (4) with the inclusion of the primordial transverse momentum of partons. The experimental data are from Ref. 18.

Figure 2: Figure from [Saleev V.A., Zotov N.P. Mod. Phys. Lett. A, 7(7), 545 (1992)].

Phenomenology of intrinsic motion

Next step is "intuition" TMD Parton Model

$$\sigma^{DY} \sim L_{\mu\nu} W^{\mu\nu} \tag{2}$$

$$\begin{aligned} W^{\mu\nu} &= \sum_q |H_q(Q)|^{\mu\nu} \int d^2\mathbf{k}_{1T} \int d^2\mathbf{k}_{2T} F_{q/P_1}(x_1, \mathbf{k}_{1T}) F_{\bar{q}/P_2}(x_2, \mathbf{k}_{2T}) \times \\ &\times \delta^2(\mathbf{k}_{1T} + \mathbf{k}_{2T} - \mathbf{q}_T) \end{aligned} \tag{3}$$

$$Q^2 = x_1 x_2 S$$

Collins-Soper-Sterman TMD Parton Model

In 1985, Collins-Soper-Sterman (CSS) have suggested TMD Parton Model with evolution.

$$\begin{aligned} W^{\mu\nu} &= \sum_q |H_q(Q,\mu)|^{\mu\nu} \int d^2\mathbf{k}_{1T} \int d^2\mathbf{k}_{2T} \times \\ &\times F_{q/P_1}(x_1,\mathbf{k}_{1T},\mu,\zeta_1) F_{\bar{q}/P_2}(x_2,\mathbf{k}_{2T},\mu,\zeta_2) \delta^2(\mathbf{k}_{1T}+\mathbf{k}_{2T}-\mathbf{q}_T) + \\ &+ Y^{\mu\nu}(Q,\mathbf{q}_T) + O((\Lambda/Q)^a) \end{aligned} \tag{4}$$

where $F_{q/P}(x,\mathbf{k}_T,\mu,\zeta)$ is universal TMD PDFs with evolution.

$$F_{q/P}(x,\mathbf{k}_T,\mu,\zeta) \Rightarrow \tilde{F}_{q/P}(x,\mathbf{b},\mu,\zeta)$$

$\mathbf{b}$ is conjugate to $\mathbf{k}_T$
μ is renormalization scale related to corresponding collinear PDF
ζ is the energy scale, serving as cutoff to regularize the light-cone singularity in the operator definition of the TMD PDF.

Collins-Soper-Sterman TMD Parton Model

$$\frac{\partial \ln \tilde{F}(x,b,\mu,\zeta)}{\partial\sqrt{\zeta}} = \tilde{K}(b,\mu) \tag{5}$$

$$\frac{d\tilde{K}}{d\ln\mu} = -\gamma_K\left(\alpha_S(\mu)\right) \tag{6}$$

$$\frac{d\ln\tilde{F}(x,b,\mu,\zeta)}{d\ln\mu} = \gamma_F\left(\alpha_S\left(\mu\right), \frac{\zeta^2}{\mu^2}\right) \tag{7}$$

$\tilde{K}$ is the CS evolution kernel,
γ_K and γ_F are the anomalous dimensions.

Collins-Soper-Sterman TMD Parton Model

$$
\begin{aligned}
W^{\mu\nu} &= \sum_q |H_q(Q,\mu)|^{\mu\nu} \int \frac{d^2\mathbf{b}}{(2\pi)^2} e^{i\mathbf{b}\cdot\mathbf{q}_T} \times \tilde{F}_{q/P_1}(x_1,\mathbf{b},\mu,\zeta_1)\tilde{F}_{\bar{q}/P_2}(x_2,\mathbf{b},\mu,\zeta_2) + \\
&+ Y^{\mu\nu}(Q,\mathbf{q}_T) + \text{ suppressed corrections} \qquad (8)
\end{aligned}
$$

TMD PDFs Library

F. Hautmann, H. Jung, M. Kramer, P. J. Mulders, E. R. Nocera, T. C. Rogers, A. Signori, **TMDlib and TMDplotter: library and plotting tools for transverse-momentum-dependent parton distributions** // *Eur.Phys.J. C74 (2014) 3220 arXiv:1408.3015 [hep-ph]*

However, this library of PDFs is oriented on application for high-energy and it's use for NICA energy needs special investigation.

Together with TMD PDFs for CSS formalism, TMDLib contains **unintegrated PDFs**, which are used in the k_T-factorization approach.

Collins-Soper-Sterman TMD Parton Model

Up to now, CSS formalism is in progress.

J. Collins, T. Rogers, **Connecting Different TMD Factorization Formalisms in QCD**, // *Phys.Rev. D96 (2017) no.5, 054011.*

J. Collins, L. Gamberg, A. Prokudin, T. C. Rogers, N. Sato and B. Wang, **Combining TMD factorization and collinear factorization**, *arXiv:1702.00387 [hep-ph].*

CSS approach mostly suitable for the situation when $Q \gg p_T \gg \Lambda$ but:

- it's application at low energies is spoiled by significant power corrections, $(p_T/Q)^n$.
- merging with $Y-$term is process dependent and model dependent procedure

Application of CSS formalism for hard processes at NICA

- in DY pair production $1 < q_T << Q \sim 3 - 5$ GeV —- intermediate region !
- in J/ψ production, $Q = M_\psi$ and $p_T = 1 - 5$ GeV — intermediate region !
- CSS formalism application to be under the question for direct γ production, where large scale Q is absent. Leading term is $\sim \alpha_s$ in TMD PM.

Task for theory: **We should find an approach which smoothly interpolate between low q_T and large q_T regions.**

Helicity structure functions for DY process

$$\frac{d\sigma}{dx_A dx_B d^2\mathbf{q}_T d\Omega} = \frac{\alpha^2}{4Q^2}\Big[F_{UU}^{(1)}\cdot(1+\cos^2\theta) + F_{UU}^{(2)}\cdot(1-\cos^2\theta) + \\ + F_{UU}^{(\cos\phi)}\cdot\sin(2\theta)\cos\phi + F_{UU}^{(\cos 2\phi)}\cdot\sin^2\theta\cos(2\phi)\Big], \quad (9)$$

were angles θ and ϕ define the direction of momentum of l^+ in the Collins-Soper frame, $F_{UU}^{(1,2,\dots)}(x_A, x_B, q_T)$ are the Helicity Structure Functions (HSFs) and $x_{A,B} = Qe^{\pm Y}/\sqrt{S}$.

$$W_{\mu\nu} = W_{\mu\nu}^{(\mathrm{TMD})} + Y_{\mu\nu} = \sum_{q,\bar{q}} \frac{e_q^2}{N_c} \mathrm{tr}\left[\gamma_\mu \Phi_q(q_1, P_1) \otimes_T \gamma_\nu \bar{\Phi}_{\bar{q}}(q_2, P_2)\right] + Y_{\mu\nu}, \quad (10)$$

where $f_1(\mathbf{q}_{T1}) \otimes_T f_2(\mathbf{q}_{T2}) = \int d^2\mathbf{q}_{T1} d^2\mathbf{q}_{T2} \delta(\mathbf{q}_T - \mathbf{q}_{T1} - \mathbf{q}_{T2}) f_1(\mathbf{q}_{T1}) f_2(\mathbf{q}_{T2})$ and four-momenta of quark(q_1) and anti-quark(q_2) are parametrized as $q_{1,2}^\mu = P_{1,2}^\mu x_{A,B} + q_{T1,2}^\mu$.

Gauge Invariance and Helicity structure functions for DY process

The full hadronic tensor should satisfy Ward identity of QED:

$$q^{\mu} W_{\mu\nu} = 0,$$

however, it is easy to verify, that for the first term in Eq. (10):

$$q^{\mu} W_{\mu\nu}^{(\mathrm{TMD})} = O(q_T/Q)$$

and the gauge invariance can not been restored by some $O(q_T/Q)$ power-corrections from $Y_{\mu\nu}$.

Gauge Invariance and Helicity structure functions for DY process

The problem of gauge-invariant definition of $W^{(\mathrm{TMD})}$-term has been considered in J. Collins textbook (Sec. 14.5.2). There it has been proposed to put momenta of initial-state quarks on-shell: $q_{1,2}^2 = 0$, while retaining their transverse momenta and “large” light-cone momentum components. We call this approach – Quasi-on-Shell Scheme (QOS).

$$(\tilde{q}_1^{(\mathrm{QOS})})^\mu = \frac{1}{2}\left(q_1^+ n_-^\mu + \frac{\mathbf{q}_{T1}^2}{q_1^+} n_+^\mu\right) + q_{T1}^\mu,$$
$$(\tilde{q}_2^{(\mathrm{QOS})})^\mu = \frac{1}{2}\left(\frac{\mathbf{q}_{T2}^2}{q_2^-} n_-^\mu + q_2^- n_+^\mu\right) + q_{T2}^\mu, \qquad (11)$$

where “large” light-cone components are determined from the condition $\tilde{q}_1 + \tilde{q}_2 = q$ to be $q_1^+ = (Q_T^2 + t_1 - t_2 + \sqrt{D})/(2q^-)$ and $q_2^- = (Q_T^2 - t_1 + t_2 + \sqrt{D})/(2q^+)$ where $D = (Q_T^2 - t_1 - t_2)^2 - 4t_1 t_2$.

Gauge Invariance and Helicity structure functions for DY process

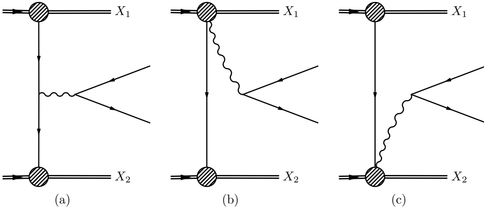


Figure 3: Feynman diagrams for the t-channel quark-antiquark annihilation subprocess (a), which leads to the usual parton-model picture, and direct interaction subprocesses (b,c) which are necessary to restore QED gauge invariance of diagram (a).

The gauge-invariance of the hadronic tensor holds because apart from the t-channel $q\bar{q}$ - annihilation (Parton Model) diagram, there exist other contributions to $p + p \to \gamma^\star + X$-amplitude, where photon is interacting directly with constituents of the colliding protons and beam-remnants.

Gauge Invariance and Helicity structure functions for DY process

Such factorization is well-known in the small-x physics. It is proven in the Leading and Next-to-Leading Logarithmic Approximation w.r.t. resummation of $\log(1/x)$ in QCD, that in the Multi-Regge limit $Q^2, q_T^2 \ll S$ the universal vertex (Fadin-Sherman vertex, 1976) of production of virtual photon in an annihilation of Reggeized quark and antiquark factorizes-out from the amplitude:

$$\Gamma_\mu(q_1, q_2) = \gamma_\mu - \hat{q}_1 \frac{n_\mu^-}{q_2^-} - \hat{q}_2 \frac{n_\mu^+}{q_1^+}, \tag{12}$$

where $n_+^\mu = P_2^\mu/\sqrt{S}$. The vertex (12) satisfies the Ward identity

$$(q_1 + q_2)^\mu \Gamma_\mu(q_1, q_2) = 0.$$

Gauge Invariance and Helicity structure functions for DY process

We propose to modify the definition of $W^{(\mathrm{TMD})}$ in Eq. (10) as:

$$W_{\mu\nu}^{(\mathrm{TMD})} \Rightarrow W_{\mu\nu}^{(\mathrm{PRA})} = \sum_{q,\bar{q}} \frac{e_q^2}{N_c} \mathrm{tr}\left[\Gamma_\mu(q_1,q_2)\Phi_q(q_1,P_1) \otimes_T \Gamma_\nu(q_1,q_2)\bar{\Phi}_{\bar{q}}(q_2,P_2)\right]. \tag{13}$$

PRA is the *Parton Reggeization Approach.*

The detail description of PRA can be found in

- A. V. Karpishkov, M. A. Nefedov and V. A. Saleev, $B\bar{B}$ angular correlations at the LHC in parton Reggeization approach merged with higher-order matrix elements, Phys. Rev. D **96** (2017) no.9, 096019.
- M. Nefedov and V. Saleev, On the one-loop calculations with Reggeized quarks, Mod. Phys. Lett. A **32** (2017) no.40, 1750207
- M. Nefedov and V. Saleev, From LO to NLO in the parton Reggeization approach, EPJ Web Conf. **191** (2018) 04007.

Helicity structure functions for DY process

Due to a large boost between hadron rest frame and hadronic center-of-mass frame, only terms proportional to $n_-^\mu = P_1^\mu/\sqrt{S}$ contribute to the correlation function of quark fields $\Phi_q(q_1, P_1)$ at leading power, and it's Dirac structure can be parameterized as follows:

$$\Phi_q(q_1, P_1) = \frac{1}{2}\left[\hat{n}_- f_1^q(x_1, q_{T1}) + i\sigma^{i-}\gamma_5 \frac{\epsilon_T^{ij} q_{T1}^j}{\Lambda} h_1^{\perp q}(x_1, q_{T1})\right], \tag{14}$$

where, $f_1^q(x_1, q_{T1})$ is a number-density TMD Parton Distribution Function(PDF), $h_1^{\perp q}(x_1, q_{T1})$ is a Boer-Mulders function, Λ is a scale of non-perturbative intrinsic transverse momentum of partons inside a hadron, which is typically taken to be $\Lambda \sim M_p$, and analogous decomposition holds for $\bar{\Phi}_{\bar{q}}$.

Helicity structure functions for DY process

$$F_{UU}^{(\cos 2\phi)} \sim W_{\mu\nu} \cdot \varepsilon^{\mu}_{+1} \varepsilon^{\nu}_{-1}, \tag{15}$$

It can be shown that

$$F_{UU}^{(\cos 2\phi)}(\mathbf{TMD}) \sim h_1^{\perp q}(x_1, q_{T1}) \otimes h_1^{\perp q}(x_2, q_{T2}) \tag{16}$$

and

$$F_{UU}^{(\cos 2\phi)}(\mathbf{PRA}) \sim \mathcal{C}_1 \cdot h_1^{\perp q}(x_1, q_{T1}) \otimes h_1^{\perp q}(x_2, q_{T2}) + \mathcal{C}_2 \cdot f_1^{q}(x_1, q_{T1}) \otimes f_1^{q}(x_2, q_{T2}) \tag{17}$$

Parton Reggeization Approach

The cross section of lepton pair production in proton-proton collisions, $p(P_1) + p(P_2) \to l^+(k_1) + l^-(k_2) + X$, can be presented in k_T-factorized form:

$$d\sigma = \int_0^1 \frac{dx_1}{x_1} \int \frac{d^2\mathbf{q}_{T1}}{\pi} \Phi_q(x_1, t_1, \mu^2) \int_0^1 \frac{dx_2}{x_2} \int \frac{d^2\mathbf{q}_{T2}}{\pi} \Phi_{\bar{q}}(x_2, t_2, \mu^2) \cdot d\hat{\sigma}_{\mathrm{PRA}}, \quad (18)$$

The partonic cross-section $d\hat{\sigma}_{\mathrm{PRA}}$ is:

$$d\hat{\sigma}_{\mathrm{PRA}} = \frac{\overline{|\mathcal{A}_{PRA}|^2}}{2Sx_1x_2} \cdot (2\pi)^4 \delta^{(4)} \left(q_1 + q_2 - k_1 - k_2\right) d\Phi(k_1, k_2), \quad (19)$$

where $d\Phi(k_1, k_2)$ is the element of Lorentz-invariant phase space for final-state leptons, $2x_1x_2S$ is the appropriate flux-factor for initial state off-shell partons. $\mathcal{A}_{PRA}$ is **off-shell amplitude of Reggeized quark – Reggeized antiquark annihilation**. For arbitrary process $\mathcal{A}_{PRA}$ can be written using Feynman rules of Lipatov's effective theory of Reggeized gluons and quarks.

Parton Reggeization Approach

The LO unintegrated PDF (unPDF) $\Phi_{q,\bar{q}}(x_{1,2}, t_{1,2}, \mu^2)$ in Eq. 18 is related with ordinary PDFs of CPM as follows:

$$\Phi_q(x, t, \mu^2) = \frac{T_q(t, \mu^2)}{t} \times \frac{\alpha_s(t)}{2\pi} \int_x^{1-\Delta} dz \frac{x}{z} \left[P_{qq}(z) f_q\left(\frac{x}{z}, \mu^2\right) + P_{qg}(z) f_g\left(\frac{x}{z}, \mu^2\right) \right], \tag{20}$$

where $f_{q,g}(x, \mu^2)$ are relevant collinear PDFs, and the Kimber-Martin-Ryskin cut condition, $\Delta = \frac{\sqrt{t}}{\sqrt{\mu^2} + \sqrt{t}}$, follows from the rapidity ordering between the last emission and the hard subprocess.

M. A. Kimber, A. D. Martin and M. G. Ryskin, Unintegrated parton distributions, Phys. Rev. D **63** (2001) 114027

Parton Reggeization Approach

$$T_i(t,\mu^2,x) = \exp\left[-\int\limits_t^{\mu^2}\frac{dt'}{t'}\frac{\alpha_s(t')}{2\pi}\left(\tau_i(t',\mu^2)+\Delta\tau_i(t',x,\mu^2)\right)\right], \quad (21)$$

$$\tau_i(t',\mu^2) = \sum_j\int\limits_0^1 d\tilde z\ \Theta_{ji}(\tilde z,t',\mu^2)\cdot\tilde z P_{ji}(\tilde z), \quad (22)$$

$$\Delta\tau_i(t',x,\mu^2) = \sum_j\int\limits_0^1 d\tilde z\ \left(1-\Theta_{ij}(\tilde z,t',\mu^2)\right)\cdot\left[\tilde z P_{ji}(\tilde z)-\frac{\frac{x}{\tilde z}f_j\left(\frac{x}{\tilde z},t'\right)}{xf_i(x,t')}P_{ij}(\tilde z)\cdot\theta(\tilde z - x)\right] \quad (23)$$

where $\Theta_{ij}(\tilde z,t,\mu^2)=\theta(1-\Delta_{ij}(t,\mu^2)-\tilde z)$

$$T_i^{\rm KMR}(t,\mu^2) = \exp\left[-\int\limits_t^{\mu^2}\frac{dt'}{t'}\frac{\alpha_s(t')}{2\pi}\left(\tau_i(t',\mu^2)\right)\right] \quad (24)$$

Relation between PRA and CSS TMD

$$
\begin{aligned}
\frac{d\sigma}{dQ^2 dq_T^2 dy} \quad &\sim \quad \int d^2\mathbf{b}\; e^{i\mathbf{q}_T\mathbf{b}} \sum_{j,a} e_j^2 \left[\int\limits_{x_A}^{1} \frac{dz_A}{z_A} C_{ja}\left(\frac{x_A}{z_A}, \alpha_s\left(\frac{1}{\mathbf{b}^2}\right)\right) f_{a/A}\left(z_A, \frac{1}{\mathbf{b}^2}\right) \right] \\
&\times \quad \left[\int\limits_{x_A}^{1} \frac{dz_B}{z_B} C_{\bar{j}b}\left(\frac{x_A}{z_B}, \alpha_s\left(\frac{1}{\mathbf{b}^2}\right)\right) f_{b/B}\left(z_B, \frac{1}{\mathbf{b}^2}\right) \right] \\
&\times \quad \exp\left[- \int\limits_{1/\mathbf{b}^2}^{Q^2} \frac{dt'}{t'} \left(\log\left(\frac{Q^2}{t'}\right) A(\alpha_s(t')) + B(\alpha_s(t')) \right) \right] \qquad (25) \\
&+ \quad Y(q_T, Q, y),
\end{aligned}
$$

$$
\Phi_q^{(CSS)}(x,t,\mu^2) \sim T_q^{(CSS)}(t,\mu^2) \times \sum_{j=q,\bar{q},g} \int\limits_{x}^{1} \frac{dz}{z} C_{qj}\left(\frac{x}{z}, \alpha_s(t)\right) f_j(z,t),
$$

Relation between PRA and CSS TMD

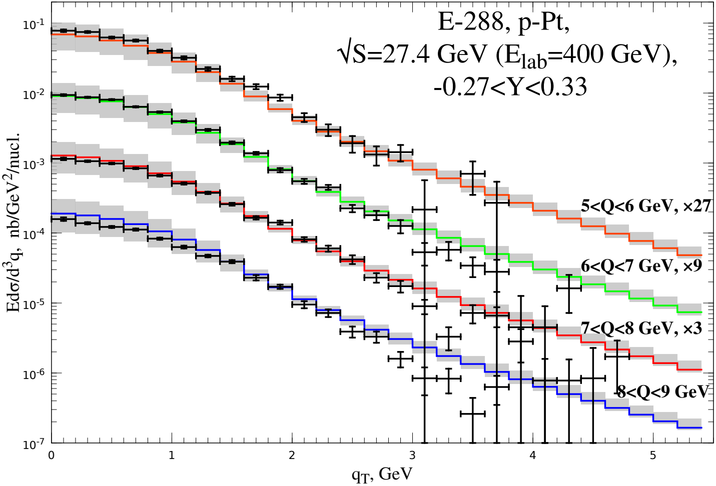
$$T_q^{(CSS)}(t,\mu^2) \sim \exp\left[-\frac{1}{2}\int\limits_t^{\mu^2}\frac{dt'}{t'}\left(\log\left(\frac{\mu^2}{t'}\right)A(\alpha_s(t'))+B(\alpha_s(t'))\right)\right], \qquad (26)$$

$$A = C_F\frac{\alpha_s}{\pi}+O(\alpha_s^2),\;\; B = 2C_F\left[-\frac{3}{4}+\log\frac{C_1}{2C_2}+\gamma_E\right]\frac{\alpha_s}{\pi}+O(\alpha_s^2),$$

$$t \ll \mu^2:\;\; \Delta^{(KMR)}(t,\mu^2) \simeq \sqrt{\frac{t}{\mu^2}}. \qquad (27)$$

$$T_q^{(KMR)} \simeq \exp\left[\frac{\alpha_s(t)}{4\pi}C_F\int\limits_t^{\mu^2}\frac{dt'}{t'}\left(4\log\sqrt{\frac{t'}{\mu^2}}+3\right)\right] = T_q^{(CSS)} \;\; !!! \qquad (28)$$

Description of E-288 q_T-spectra



Constant NLO K-factor ~ 1.8 from $\alpha_s \pi^2$-corrections is included.

Description of NuSea data ($\sqrt{S} = 39$ GeV) on angular coefficients

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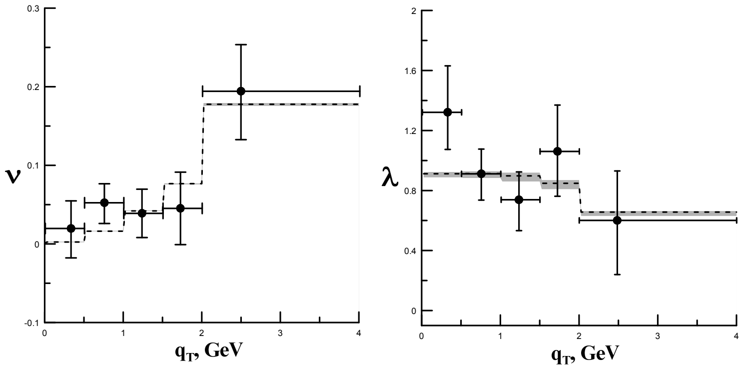
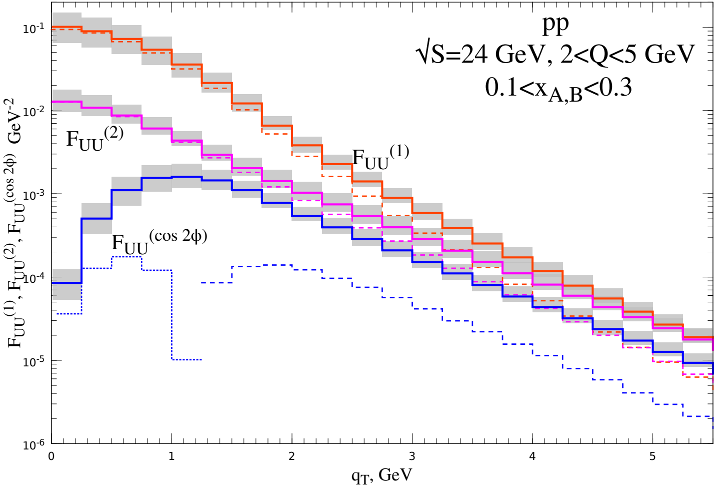


This figures from: M. A. Nefedov, N. N. Nikolaev and V. A. Saleev, Drell-Yan lepton pair production at high energies in the Parton Reggeization Approach, Phys. Rev. D **87** (2013) no.1, 014022.

Predictions for HSFs at JINR-NICA ($\sqrt{S} = 24$ GeV)



Solid lines – PRA predictions, dashed lines – QOS-predictions. At small q_T, the $F_{UU}^{\cos 2\phi}$ HSF in QOS is negative.

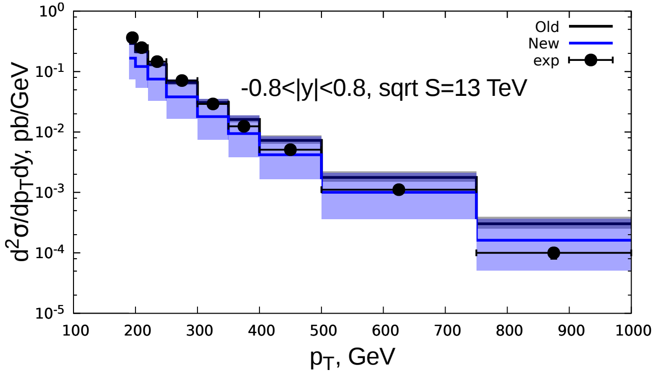
Conclusions for DY process

- Gauge-invariance of hadronic tensor is important for Helicity Structure Functions in Drell-Yan process
- Structure-function $F_{UU}^{\cos 2\phi}$ gets contribution not only from Boer-Mulders TMD PDF but also from number-density TMD PDF. Well-established factorization formula is required to separate them.
- PRA predictions with simple KMR unPDF reproduce existing data rather well, however polarization information is still limited. New experiments are needed, NICA-SPD, RHIC, COMPASS, ...

Direct photon production at NICA with the PRA

In the **PRA**, the Fadin-Sherman vertex describes production of real photon in subprocess

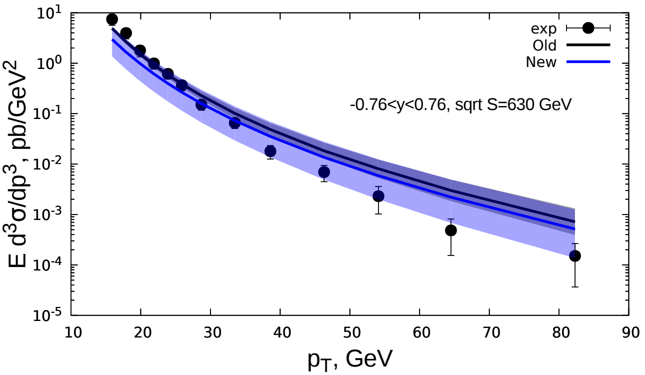
$$Q + \bar{Q} \to \gamma \tag{29}$$



The data from CMS Collaboration.

Direct photon production at NICA with the PRA

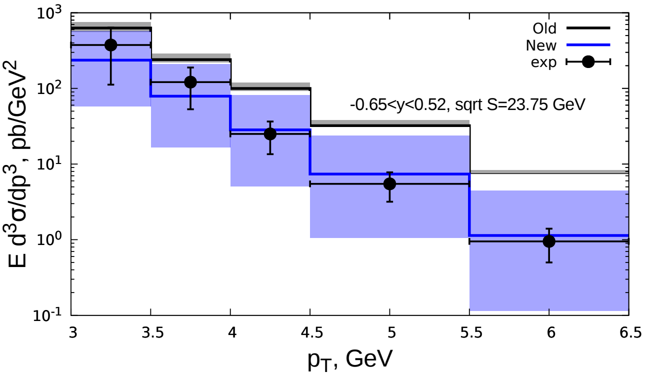
$$Q + \bar{Q} \to \gamma$$



The data from UA2 Collaboration.

Direct photon production at NICA with the PRA

$$Q + \bar{Q} \to \gamma$$



The data from NA24 Collaboration.

Conclusions for direct γ production

- In PRA, initial partons are off-mass shell and leading subprocess is $Q + \bar{Q} \to \gamma$.
- PRA predictions with modified KMR unPDF reproduce existing data rather well for NICA energies.
- It is impossible to study gluon TMD PDF directly in γ production.

J/ψ prompt production at NICA with the PRA

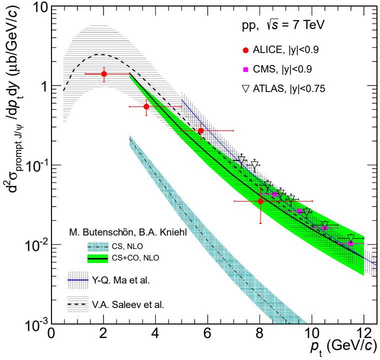


Fig. 4: $\frac{d\sigma_{\mathrm{prompt}\,J/\psi}}{dp_t dy}$ as a function of p_t compared to results from ATLAS [16] and CMS [18] at mid-rapidity and to theoretical calculations [19–21]. The error bars represent the quadratic sum of the statistical and systematic uncertainties.

J/ψ prompt production at NICA with the PRA

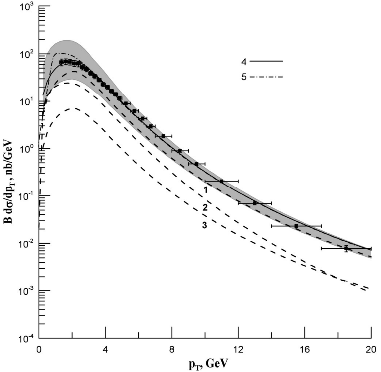
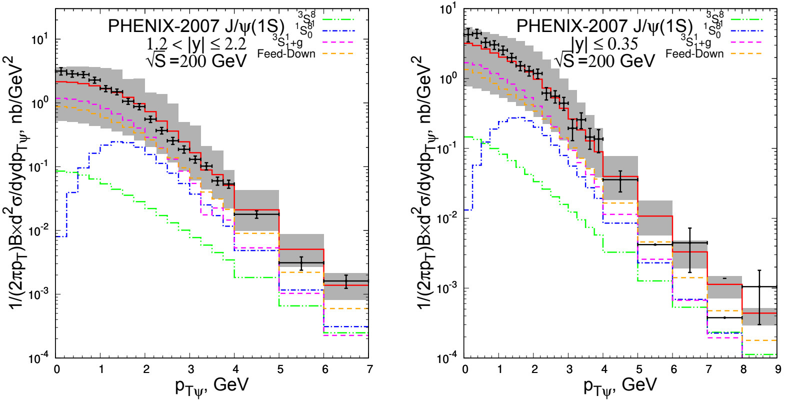


FIG. 4. Prompt J/ψ transverse-momentum spectrum from CDF Collaboration [28], $\sqrt{S} = 1.96$ TeV, $|y| < 0.6$, (1) is the direct production, (2) from χ_{cJ} decays, (3) from ψ' decays, (4) sum of all contributions (KMR unPDF), (5) sum of all contributions (Blümlein unPDF).

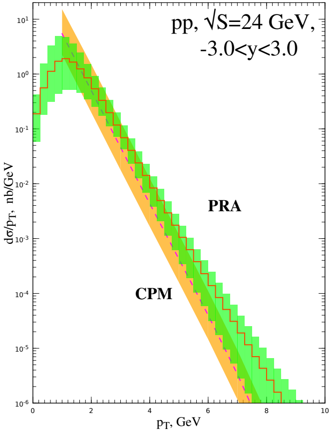
The data from CDF Collaboration, $sqrt\,S = 1.96$ TeV

J/ψ prompt production at NICA with the PRA



The data from PHENIX Collaboration.

J/ψ prompt production at NICA with the PRA



Prediction for NICA Collider. PRA versus NLO CPM calculation by B.A. Kniehl, and M. Butenschoen (Hamburg Uni.)

Conclusions J/ψ production at NICA

- PRA + NRQCD approach can be used for NICA energy.
- Relative roles of different production channels (color singlet and color octet, direct and feed-down) at NICA energy are not the same as at high energy.
- Polarization effects in J/ψ production can be studied in PRA. Our calculations are in progress.