Rozkłady partonowe przy wysokich energiach
(Parton Distributions at High Energy)

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Odbiory DBP
15 grudnia 2020 r.

w imieniu grupy teoretycznej QCD
(on behalf of the theoretical QCD group)

Narodowe Centrum Badań Jądrowych
National Centre for Nuclear Research
ŚWIERK
JRC collaboration partner

European Commission

National Science Centre Poland

Basic Information (I)

Theoretical QCD group at NCBJ

The studies of the Theoretical QCD group at NCBJ spans a wide a range of topics *that are of key importance for the current and future experimental studies.*

- *Moderate colliding energies:* (JLAB & future EIC)

Studies of exclusive processes such as Deeply Virtual Compton scattering (DVCS), Time like Compton scattering (TCS), Heavy vector meson production (HVMP) and associated Generalized Parton Distributions (GPDs), hadron tomography.

- *High colliding energies :* (RHIC & LHC & future EIC)

Studies of inclusive processes such as proton-proton (pp), proton-nucleus (pA), Deep Inelastic Scattering (DIS), effects of parton saturation on various observables at small-x, Color Glass Condensate (CGC).

Perfectly balanced topic-diversity and complementary expertise of its group members:

Exclusive processes & GPDs:

Prof. dr hab. Lech Szymanowski
dr hab. Jakub Wagner
dr Pawel Sznajder
Oskar Grocholski (from UW)
Victor Martinez Fernandez

Small-x physics & CGC:

dr hab. Tolga Altinoluk
dr Guillaume Beuf
dr Alina Czajka
Arantxa Tymowska

- **Prof. dr hab. L. Szymanowski** - expert on both exclusive and inclusive processes in QCD.
- **dr hab. J. Wagner & dr P. Sznajder -** experts on phenomenological studies of exclusive physics, who are among the founders of the PARTONS project, an open source framework to full fill the needs of the experimental and theoretical studies.
- **dr hab. T. Altinoluk and dr G. Beuf -** experts on the small-x physics, parton saturation and higher order perturbative calculations in QCD.

Basic Information (II)

Highlights in the QCD group during 2020:

(i) Reinforcements:

dr Guillaume Beuf (since Feb. 2020) **&** Victor Martinez Fernandez (since Oct. 2020 - PhD).

(ii) Grants & Scholarships:

In addition to the currently active grants (Harmonia, SONATA (NCN) - RISE (EU) - Polonium (NAWA)) that are run by the members of the QCD group in 2020:

✱ SONATA (NCN) & French Government Scholarship (for an extended working visit to CEA) by dr Paweł Sznajder

✱ Diamentowy grant (Ministry of Sci. and Higher Education) — by Oskar Grocholski

The project is being realized in our group together with dr hab. Jakub Wagner & dr Paweł Sznajder.

✱ The ULAM Programme (NAWA) — by Prof. dr hab. Lech Szymanowski and Prof. Igor Anikin (JINR, Dubna).

A prestigious scholarship for foreign scientists to visit research centers in Poland.

Prof. Anikin will join to the QCD group at NCBJ for 1 year starting from June 2020.

In addition, two of our group members dr G. Beuf (SONATA BIS) and dr A. Czajka (SONATA) applied to NCN grants during 2020 and waiting for the results.

(ii) Promotions:

Two of our group members T. Altinoluk and J. Wagner got their habilitations during 2020.

(iv) Talks and Seminars: As everyone else, our group was effected by COVID19 outburst and delivered less talks then usual:

J. Wagner - “Proton structure and universality of GPDs in the light of recent descriptions of DVCS data” (online seminar)
at Instytut Fizyki Jądrowej (IFJ), PAN, Kraków in May 2020

A. Czajka - “Full next-to-eikonal quark propagator in the CGC and its applications” (online workshop)
at Resummation, Evolution and Factorization Workshop (REF 2020) in December 2020

T. Altinoluk - “Particle correlations from the initial state” (online seminar)
at NCBJ in April 2020 & at JLAB in July 2020

Basic Information (III)

Highlights in the QCD group during 2020:

(v) Published and submitted papers in 2020:

(1) **“Probing the Gluon Sivers Function with an Unpolarized Target: GTMD distributions and the Odderons”**
R. Boussarie, Y. Hatta, L. Szymanowski, S. Wallon, **Phys. Rev. Lett. 124 (2020) no.17, 172501**

(2) “Diffractive deeply virtual Compton scattering”
B. Pire, L. Szymanowski, S. Wallon, **Phys. Rev. D101 (2020) no.7, 074005**

(3) “Electroproduction of a large invariant mass photon pair”
A. Pedrak, B. Pire, L. Szymanowski, J. Wagner, **Phys. Rev. D101 (2020) no.11, 114027**

(4) “Diffractive two-meson electroproduction with a nucleon and deuteron target”
W. Cosyn, B. Pire, L. Szymanowski, **Phys. Rev. D101 (2020) no.5, 054003**

(5) “Data-driven study of timelike Compton scattering”
O. Grocholski, H. Moutarde, B. Pire, P. Sznajder, J. Wagner, **Eur. Phys. J. C80 (2020) no.2, 171**

(6) “Photoproduction of three jets in the CGC: gluon TMDs and dilute limit”
T. Altinoluk, R. Boussarie, C. Marquet, P. Taels, **JHEP 2007 (2020) 143**

(7) “Particle correlations from the initial state” (invited review)
T. Altinoluk, N. Armesto, **Eur. Phys. J. A56 (2020) no.8, 215**

(8) “Color Glass Condensate at next-to-leading order meets HERA data”
G. Beuf, H. Hanninen, T. Lappi, H. Mantysaari, **Phys. Rev. D102 (2020) 074028**

(9) “Heavy Quarks Embedded in Glasma”,
M. E. Carrington, A. Czajka, S. Mrowczynski, **Nucl. Phys. A.1001 (2020) 121914**

✱ P. Sznajder together with COMPASS Collaboration: 3 papers published and 2 submitted.

✱ 3 published proceedings papers (T. Altinoluk (2) and L. Szymanowski (1))

✱ 2 submitted papers:

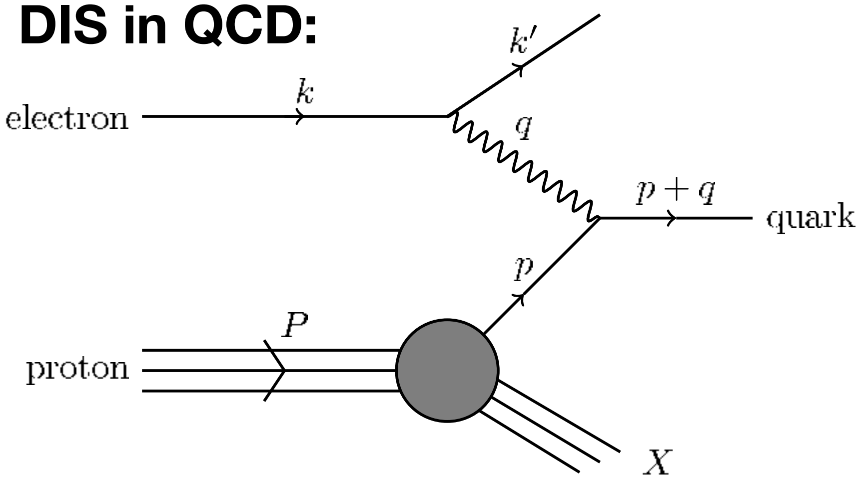
(i) “Angular correlations in pA collisions from CGC: multiplicity and mean transverse momentum dependence of v_2”
T. Altinoluk, N. Armesto, A. Kovner, M. Lublinsky, V. V. Skokov, arXiv: 2012.01810

(ii) “Quarks at next-to-eikonal accuracy in the CGC I: Forward quark-nucleus scattering”
T. Altinoluk, G. Beuf, A. Czajka, A. Tymowska, arXiv: 2012.03886

(Transverse Momentum Dependent) Parton Distributions at High Energy

High energy scattering in QCD

DIS in QCD:



Three Lorentz invariant quantities:

(i) $q^2 = -Q^2$ (virtuality of the incoming photon)

(ii) $x = \dfrac{Q^2}{2P\cdot Q}$ (longitudinal momentum fraction carried by the parton)

(iii) $s \simeq 2P\cdot Q$ (energy of the colliding $\gamma - p$ system)

Increasing the energy ($s = Q^2/x$) of the system

- *Bjorken limit:* fixed x, $Q^2 \to \infty$ (system becomes dilute)
- *Regge-Gribov limit:* fixed Q^2, $x \to 0$ (system becomes dense)

In the infinite momentum frame:

- transverse size of the photon $\sim 1/Q$ (very small probe)
- can scatter off a quark with size of $\sim 1/Q$

$\Rightarrow$ **Q is the transverse resolution scale**

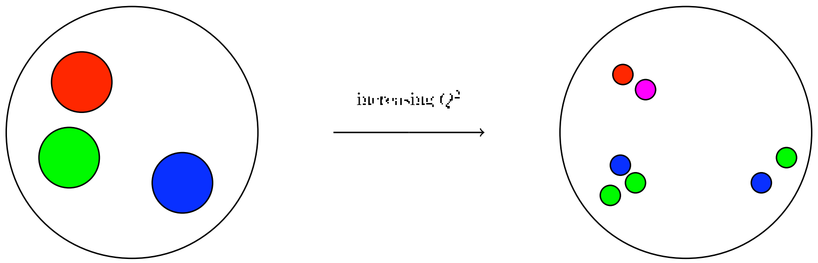
Bjorken limit: (fixed x, $Q^2 \to \infty$) proton $\simeq$ set of independent free partons (assumed to be dilute)

Perturbative Coeff. Func.

γp cross-section (collinear factorization) : $\sigma^{\gamma^* p \to X}(x_{bj}, Q^2) \propto \sum_i \int_{x_{bj}}^{1} \frac{dx}{x}\, f_i(x, Q^2)\; C_i\left(\frac{x_{bj}}{x}, \alpha_s(Q^2)\right)$

Parton **D**istribution **F**unction **(PDF)**

Increasing Q^2 at fixed x **:**



- more substructure is resolved by the probe
- target effectively contains more partons
- however, density of partons decrease

Evolution wrt Q^2 is given by the DGLAP equations $\Rightarrow$ $\dfrac{d}{d\log(Q^2)} f_i(x, Q^2)$

Regge-Gribov limit and gluon saturation

Regge-Gribov limit: fixed $Q^2, x \to 0$ (evolution wrt rapidity $Y = \ln(1/x)$)

- ✱ # of gluons increase due to splitting
- ✱ transverse scale doesn't change (fixed Q^2)
- ✱ mother and daughter partons have the same size

$\Downarrow$

density of partons increases and causes saturation

Saturation regime is defined by Q_s : saturation scale $\equiv \alpha_s \times$ (gluon density per unit area)

in the saturation regime, scattering prescription: Color Glass Condensate (CGC)

"effective degrees of freedom" wrt a cut-off λ^+

- fast partons: $k^+ > \lambda^+$: described by color sources $J^\mu(x)$
- slow partons: $k^+ < \lambda^+$: described by color fields $A^\mu(x)$

interaction between fast and slow partons : $\int d^4x \; J^\mu(x) \; A_\mu(x)$

Within the CGC framework: *expectation value of an observable* $\mathcal{O}$ $\Rightarrow$ $\langle \mathcal{O} \rangle \equiv \int [D\rho] \; W[\rho] \; \mathcal{O}[\rho]$

Rapidity, $Y = \ln(1/x)$, *evolution of the distribution function is governed by JIMWLK equation.*

←

distribution function for the color sources ρ^a

Eikonal interaction between the projectile and the target:

each parton picks up a Wilson line during the interaction with the target $\longmapsto$ $U_{\mathcal{R}}(x) = \mathcal{P}_+ \exp\left[ig \int_{-\infty}^{+\infty} dx^+ \, T^a_{\mathcal{R}} \, A^-_a(x^+, x)\right]$

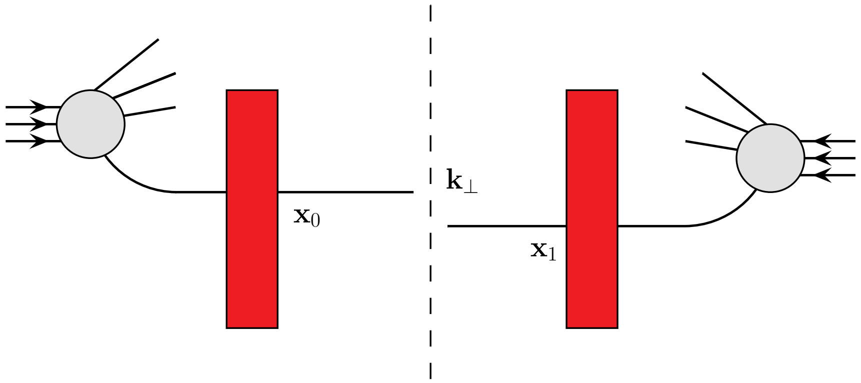
what appears in the observable is called *"dipole operator"* : $d_{\mathcal{R}}(x,y) = \dfrac{1}{D_{\mathcal{R}}} \, \mathrm{tr}\left[U_{\mathcal{R}}(x) \, U^\dagger_{\mathcal{R}}(y)\right]$

Forward particle production

[Dumitru, Hayashigaki, Jalilian-Marian - hep-ph/0506308]

State-of-the-art calculation framework for forward production in pA collisions: **Hybrid factorization**

- ✱ Projectile proton (dilute) is treated in the spirit of collinear factorization (corrections provided by DGLAP)
- ✱ Target nucleus (dense) is treated within the CGC framework.



$$\frac{d\sigma^{pA\to q+X}}{dk^+d^2k} \propto \int dx_P\, f_q(x_P,\mu^2) \int e^{ik\cdot(x_0-x_1)}\big\langle d_F(x_0,x_1)\big\rangle_A$$

[Collins - hep-ph/0204004] / [Belitsky, Ji, Yuan - hep-ph/0208038]

The operator definition of a PDF: $\mathcal{F}(x_2) \propto \int dz^+\, e^{ix_2 p_A^- z^+}\big\langle \mathrm{tr}\big[F^{i-}(z^+)U(z^+,0)F^{i-}(0^+)U(0^+,z^+)\big\rangle_A$ (1 dimensional) only longitudinal

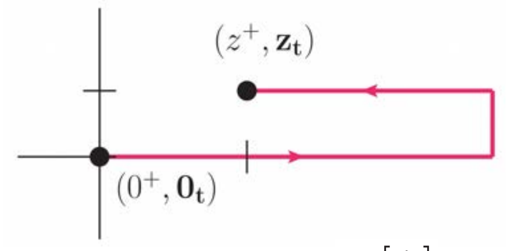
with $F^{i-} \sim \partial^i A^-$

Unpolarized Transverse Momentum Distribution functions (TMDs):

(3 dimensional) longitudinal+transverse

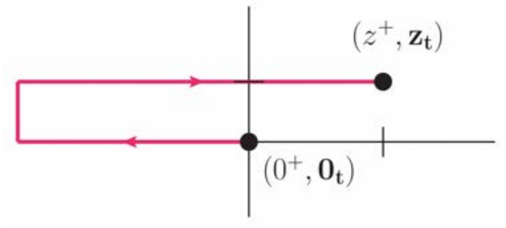
$$\mathcal{F}(x_2,k_t) \propto \int dz^+\, d^2z_\perp e^{ix_2 p_A^- z^+ - ik_t\cdot z_\perp}\big\langle \mathrm{tr}\big[F^{i-}(\underline{0})U^{[C]}(\underline{0},\underline{z})F^{i-}(\underline{z})U^{[C']}(\underline{z},\underline{0})\big\rangle_A$$

$U^{[C]}(\underline{0},\underline{z})$: Gauge links connecting the points $\underline{0} \equiv (0^+,0_t)$ and $\underline{z} \equiv (z^+,z_t)$



$U^{[+]}$

future pointing



$U^{[-]}$

past pointing

From Wilson lines to gauge links

What do we want? “*a connection between the dipole operators that appear in the CGC calculations and TMDs*”

Why do we want it?
- (+) TMDs carry 3d information about the nucleus structure / can be extracted from experiments.
- (-) TMD factorization is not universal changes from process to process / CGC is universal.
- (-) well established CGC techniques (rapidity evolution and modeling) can be used to study TMDs.

How can we do it?

[Dominguez, Marquet, Xiao, Yuan - arXiv: 1101.0715]

The Wilson line operator

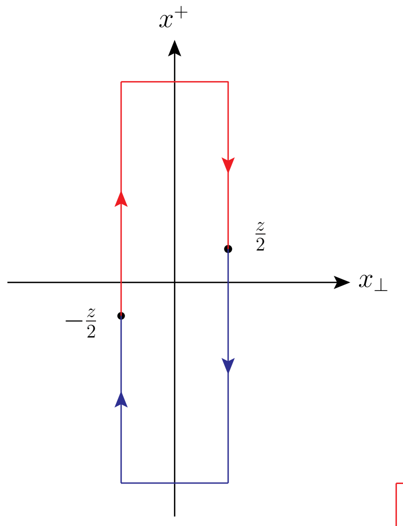
$$U(-\infty, +\infty; x) = \mathscr{P} \exp\left[i\, g \int_{-\infty}^{+\infty} dx^+ t^a A_a^-(x^+, x)\right]$$

Derivative of the Wilson line

$$\partial^i U(x) = ig \int dx^+ U(-\infty, x^+; x) F^{i-}(x^+, x) U(x^+, +\infty; x)$$

$$\partial^i U^\dagger(x) = -ig \int dx^+ U^\dagger(+\infty, x^+; x) F^{i-}(x^+, x) U^\dagger(x^+, -\infty; x)$$

Dipole TMD →

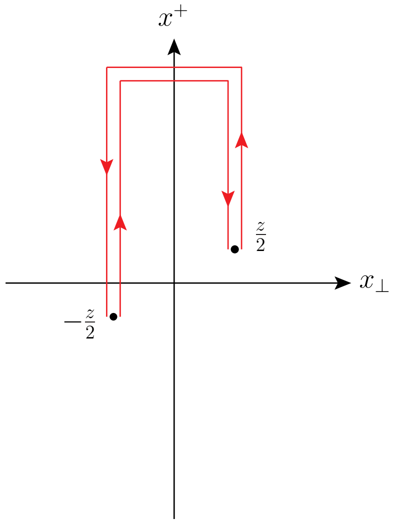


→

$$\mathscr{F}_{qg}^{(1)}(x_2, k_t) \propto \int dz^+ d^2z\, e^{ix_2 p_A^- - ik_t z} \left\langle \mathrm{tr}\left[F^{i-}\left(\frac{z}{2}\right) U^{[-]\dagger} F^{i-}\left(-\frac{z}{2}\right) U^{[+]}\right]\right\rangle$$

in the small-x limit: $\mathscr{F}_{qg}^{(1)}(x_2, k_t) \mapsto \int d^2z\, e^{-ik_t z} \left\langle \mathrm{tr}\left\{\left[\partial^i U^\dagger\left(\frac{z}{2}\right)\right]\left[\partial^i U\left(-\frac{z}{2}\right)\right]\right\}\right\rangle$

Weizsäcker-Williams TMD →



→

$$\mathscr{F}_{gg}^{(3)}(x_2, k_t) \propto \int dz^+ d^2z\, e^{ix_2 p_A^- - ik_t z} \left\langle \mathrm{tr}\left[F^{i-}\left(\frac{z}{2}\right) U^{[+]\dagger} F^{i-}\left(-\frac{z}{2}\right) U^{[+]}\right]\right\rangle$$

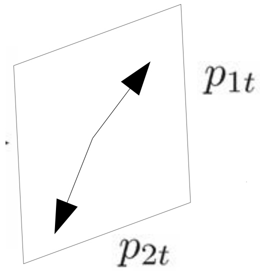
in the small-x limit:

$$\mathscr{F}_{qg}^{(1)}(x_2, k_t) \mapsto \int d^2z\, e^{-ik_t z} \left\langle \mathrm{tr}\left\{\left[\partial^i U\left(\frac{z}{2}\right)\right] U^\dagger\left(-\frac{z}{2}\right)\left[\partial^i U\left(-\frac{z}{2}\right)\right] U^\dagger\left(\frac{z}{2}\right)\right\}\right\rangle$$

How do we get derivatives of Wilson lines? - Correlation limit in the CGC

[Altinoluk, Boussarie, Kotko - arXiv: 1901.01175] / [Altinoluk, Boussarie - arXiv: 1902.07930]

Consider production of two hard jets: $|p_1| \sim |p_2| \gg Q_s$ & $|p_1 + p_2| \sim Q_s$



Two typical transverse scales:
$k_T = p_1 + p_2$: total momentum of the produced jets
$Q_T = p_1 - p_2$: momentum imbalance of the produced jets

$k_T \ll Q_T$: *jets fly almost back-to-back (correlation limit)* ⇒ small transverse size

perform a Taylor expansion of the Wilson lines
and
get access to TMDS

$$U\Big(b + \frac{r}{2}\Big)U^\dagger\Big(b - \frac{r}{2}\Big) - 1 = \frac{r^i}{2}\Big[(\partial^i U_b)U_b^\dagger - U_b\big(\partial^i U_b^\dagger\big)\Big] + O(r^2)$$

in the small-x limit of TMDs: *phase drops - only longitudinal dependence in gauge links*

in the correlation limit of the CGC: *expansion around small dipole size* → *derivatives of Wilson lines*

small-x limit of TMD factorization ≡ correlation limit of the CGC

Can we do better than this?

keep expanding in r & use integration by parts and extract 1-body contributions from n-body terms & remaining terms can be cast into 2-body contributions & resum the categorized terms

Any generic $1 \to 2$ CGC amplitude can be written as $\mathscr{A} = \mathscr{A}_1 + \mathscr{A}_2$

- resummation of $k \cdot r \sim k/Q \Rightarrow k$ can be $O(Q)$

$$\mathcal{A}_1 = (2\pi)\delta(p_1^+ + p_2^+ - p_0^+)\int_b e^{-ik\cdot b}(-i)\int_r e^{-iq\cdot r} r^\alpha \mathcal{H}(r)$$
$$\times\left[\left(\frac{e^{i\bar{z}k\cdot r}-1}{k\cdot r}\right)\left(\partial_\alpha U_b^{R_1}\right)T^{R_0}U_b^{R_2} + \left(\frac{e^{-izk\cdot r}-1}{k\cdot r}\right)U_b^{R_1}T^{R_0}\left(\partial_\alpha U_b^{R_2}\right)\right]$$

Resulting X-section interpolates between TMD ($k_t \ll Q_T$) and CGC ($k_t \sim Q_T$) regimes!!

This is the derivation of "small-x improved TMD framework (iTMD)" which was conjectured in

[Kotko, Kutak, Marquet, Petreska, Sapeta, van Hameran - arXiv: 1503.03421]

Linearly polarized gluon TMDs

Linearly polarized gluon TMDs from Wilson lines:

$$\left\langle P_A \middle| \partial^i U \partial^j U \middle| P_A \right\rangle \to \frac{1}{2}\Big[\underbrace{\delta^{ij}\mathcal{F}(x_2,k_t)}_{\text{unpolarized TMD}} - \left(\delta^{ij} - 2\frac{k_t^i k_t^j}{k_t^2}\right)\underbrace{\mathcal{H}(x_2,k_t)}_{\text{polarized TMD}}\Big]$$

Polarized TMDs can be probed in:

dijet production in pA collisions with massive quarks **[Marquet, Roisenel, Taels - arXiv:1710.05698]**

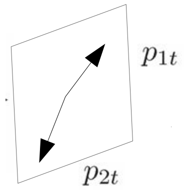
dijet+photon production in pA collisions with massless quarks **[Altinoluk, Boussarie, Marquet, Taels - arXiv:1810.11273]**

Photoproduction of trijets with massless quarks **[Altinoluk, Boussarie, Marquet, Taels - arXiv:2001.00765]**

one needs either mass or virtuality in dijet production or trijet production to probe linearly polarized TMDs!

correlation limit in the CGC:

dijet



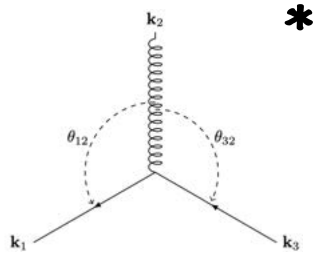
- ✱ back-to-back configuration

$k_T = p_1 + p_2$

$Q_T = p_1 - p_2$

$k_T \ll Q_T$

trijet



- ✱ star-like configuration

$k_T = p_1 + p_2 + p_3$

$Q_T = p_1 - \frac{\xi_1}{\xi_3} p_3 \quad P_T = p_3 + \frac{\xi_3}{\xi_1} p_1$

$k_T \ll Q_T \sim P_T$

$\xi_i = \frac{p_i^+}{p^+}$

How about resummation (iTMD formulation) with linearly polarized gluon TMDs?

The iTMD formulation up to now only accounts for unpolarized gluon TMDs! Applicable to dijet production with $m = Q^2 = 0$

[Altinoluk, Marquet, Taels - arXiv:2101.XXXXX]

We have performed the resummation in the correlation limit to get the iTMD formulation for:

(i) DIS massive dijet production

(ii) Heavy quark production in pA collisions

Next challenge: generalization to trijet production

Summary and outlook

- ✱ It is known that there is an equivalence between the CGC and TMD frameworks: (The correlation limit of the CGC = high energy limit of TMD)

- ✱ The equivalence can be extended beyond these limits by performing the resummation which corresponds to iTMD formulation.

- ✱ One can probe both unpolarized and linearly polarized gluon TMDs, by considering dijet production with $m \neq Q^2 \neq 0$ or trijet production.

- ✱ The iTMD formulation with linearly polarized TMDs is performed for dijets and the paper will be submitted soon!

- ✱ Future work: generalization of the iTMD formulation to trijet production with linearly polarized gluon TMDs.

Summary and outlook

Thank you very much for your attention!

MIŁYCH ŚWIĄT BEZ WIRUSA