NA2- Small-x Physics at the LHC and future DIS experiment

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reporting for

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Task 3- Gluon TMDs at small-x

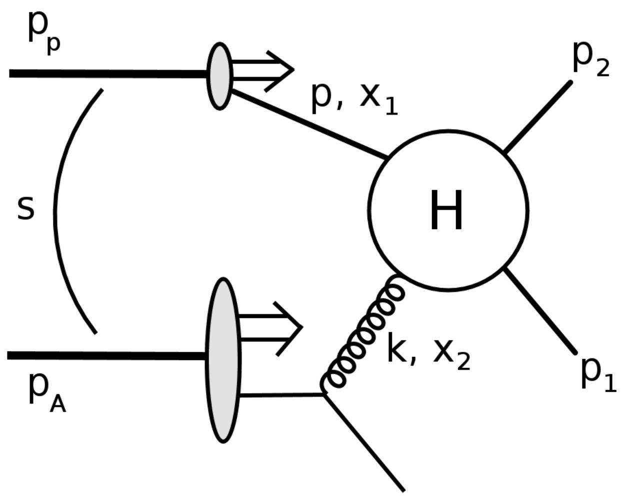
we are there

TASKS/Subtasks	Year 1				Year 2				Year 3				Year 4			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1. Nuclear PDFs																
1.1 Perform a reweighting analysis of nuclear PDFs with LHC data																
1.2 Produce a new nuclear PDF set																
2. NLO Calculations in CGC and BFKL																
2.1 Compare NLO calculations with DIS and forward pA data																
2.2 Establish the connection between the CGC formulation at NLO and resummations in BFKL																
3. Gluon TMDs at small-x																
3.1 Establish (or disprove) TMD factorization for processes with three final-state particles																
3.2 Establish (or disprove) TMD factorization at NLO, starting with the simplest processes, e.g. for photon+jet																
3.3 Implement the hard-scale evolution of TMDs, on top of the small-x evolution																
3.4 Develop the phenomenology for processes sensitive to the linear polarization of gluons																
4. Multi-particle Correlations & Thermalization																
4.1 Combine calculations of initial and final state multiparticle correlations																
4.2 Establish the initial state for kinetic theory or hydrodynamical calculations from the CGC																

in CPHT we have been working on Task 3

Dilute-dense 2-to-2 processes

- large-x projectile (proton) on small-x target (proton or nucleus)



$\langle k_{1t}\rangle \sim \Lambda_{QCD}$ $\qquad$ $\langle k_{2t}\rangle \sim Q_s(x_2)$

$$Q_s(x_2) \gg \Lambda_{QCD}$$

so-called “dilute-dense” kinematics

Incoming partons’ energy fractions:

$$x_1 = \frac{1}{\sqrt{s}}\left(|p_{1t}|e^{y_1} + |p_{2t}|e^{y_2}\right) \qquad\qquad x_1 \sim 1$$

$$x_2 = \frac{1}{\sqrt{s}}\left(|p_{1t}|e^{-y_1} + |p_{2t}|e^{-y_2}\right) \xrightarrow{y_1,y_2\gg 0} x_2 \ll 1$$

Gluon’s transverse momentum (p_{1t}, p_{2t} imbalance):

$$|k_t|^2 = |p_{1t} + p_{2t}|^2 = |p_{1t}|^2 + |p_{2t}|^2 + 2|p_{1t}||p_{2t}|\cos\Delta\phi$$

$|p_{1t}|, |p_{2t}| \gg Qs$ $\qquad$ however, $|k_t|$ can be small or large

Improved TMD factorization

- This formalism, made for two-scale processes, emerges from CGC calculations after neglecting $O(Q_S/P_t)$ terms (so-called genuine higher-twist corrections) where P_t is the hard scale

- It resums $(Q_S/k_t)^n$ and $(k_t/P_t)^n$ terms, where k_t is the semi-hard scale, and therefore encompasses other frameworks that account for either, but not both

- From the TMD perspective, the improvement is the matching to BFKL at high k_t, due to the additional resummation of the $(k_t/P_t)^n$ terms (so-called kinematical higher-twist corrections)

- From the BFKL/HEF/kt-factorization perspective, the improvement is the matching to TMD factorization at low k_t due to the additional resummation of the $(Q_S/k_t)^n$ terms (leading-twist saturation corrections)

The ITMD factorization formula

$$\frac{d\sigma^{pA\to \text{dijets}+X}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\sum_{a,c,d} x_1 f_{a/p}(x_1,\mu^2)\sum_{i=1}^{2} K^{(i)}_{ag^*\to cd}\Phi^{(i)}_{ag\to cd}\frac{1}{1+\delta_{cd}}$$

standard collinear pdf
for the large-x projectile

several gluon TMDs
for the small-x target

and their associated hard matrix elements

$$\Phi^{(i)}_{ag\to cd}(x_2,k_t^2)$$

- research directions explored so far:

- study the quality of that approximation compared to the full CGC calculation
- establish (I)TMD factorization for processes sensitive to linearly-polarized gluons
- establish (I)TMD factorization for 2-to-3 processes
- establish (I)TMD factorization for 2-to-2 processes at NLO

2-to-3 processes

- $\gamma A \to \text{trijets} + X$ to start with, since the photon simplifies things

TMD formula and HEF formula obtained in

Photoproduction of three jets in the CGC: gluon TMDs and dilute limit
T. Altinoluk, R. Boussarie, C. Marquet and P. Taels, JHEP 07 (2020) 143.

- The TMD formula involves linearly-polarized gluons:

that makes obtaining the ITMD matrix elements more difficult

$$(2\pi)^9 \frac{\mathrm{d}\sigma^{\gamma A\to q\bar{q}g+X}}{\mathrm{d}^3\vec{k}_1\mathrm{d}^3\vec{k}_2\mathrm{d}^3\vec{k}_3}\Bigg|_{\text{corr. limit}} = 2\pi\delta\Big(p^+ - \sum_{i=1}^{3} k_i^+\Big)\,[\mathrm{H}]_{ij}^{\text{total}} \times\left[\frac{1}{2}\delta^{ij}\mathcal{F}_{gg}^{(3)}(x_A,\mathbf{q}_T) + \frac{1}{2}\left(2\frac{\mathbf{q}_T^i\mathbf{q}_T^j}{\mathbf{q}_T^2} - \delta^{ij}\right)\mathcal{H}_{gg}^{(3)}(x_A,\mathbf{q}_T)\right]$$

unpolarized gluon TMD

linearly-polarized gluon TMD

On the CGC/ITMD comparison

- for massless 2-to-2 processes, the relationship between the various frameworks is understood

$|p_{1t}|, |p_{2t}| \gg |k_t|, Q_s$

TMD regime

$|p_{1t}|, |p_{2t}|, |k_t| \gg Q_s$

BFKL regime

$+ (k_t/P_t)^n$

$+ (Q_S/k_t)^n$

ITMD

$|p_{1t}|, |p_{2t}| \gg Qs$

$+ (Q_S/P_t)^n$

CGC

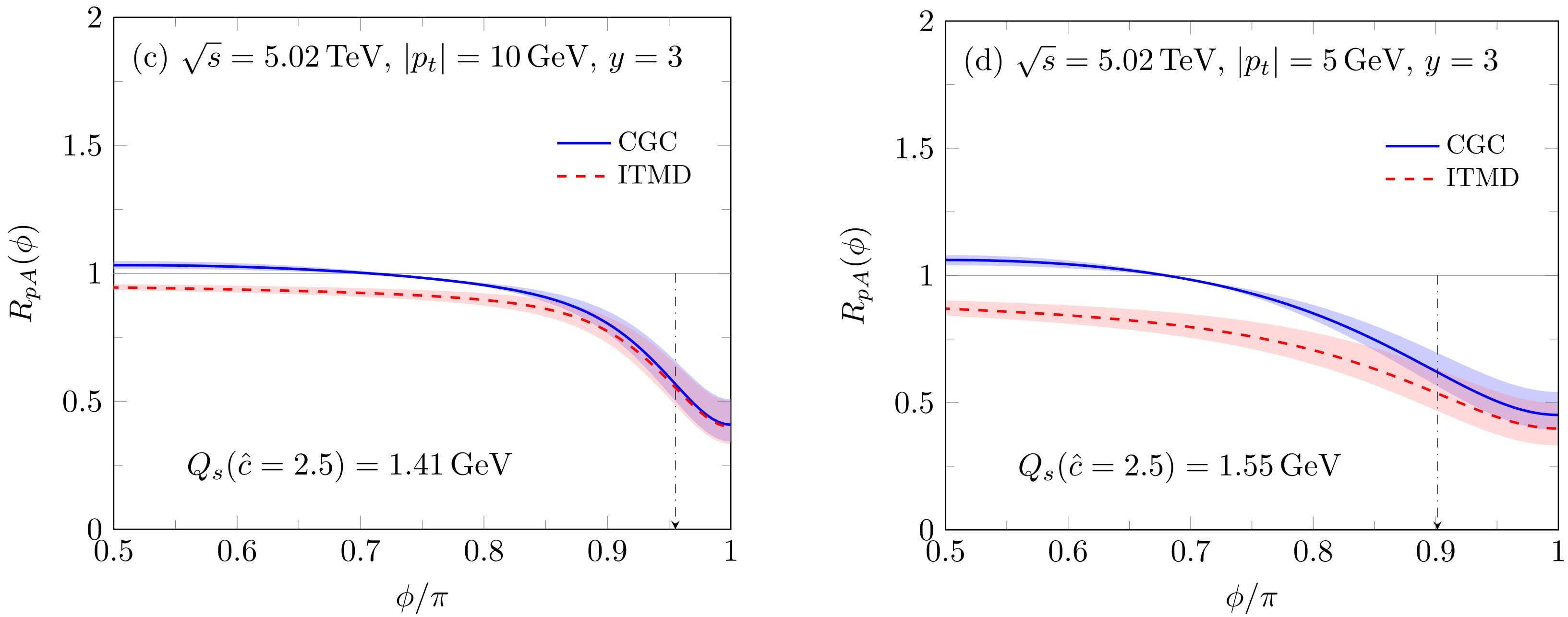
- we can compare them numerically

Genuine higher-twist corrections

for instance, one can look at the genuine-twist corrections, which start to matter when the jet transverse momenta get closer to Qs

Comparison of improved TMD and CGC frameworks in forward quark dijet production

H. Fujii, C. Marquet and K. Watanabe, 2006.16279[hep-ph]



for the $gA \rightarrow q\bar{q} + X$ final state