Small-x improved TMD factorization

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Contents of the talk

- Gluon TMDs in the small-x limit

  TMDs = transverse-momentum-dependent parton distributions

  non-linear QCD evolution obtained from the JIMWLK equation

- Probing the gluon TMDs at colliders

  improved TMD factorization framework

  unification of BFKL and TMD physics at small x

- Unpolarized and linearly-polarized gluon TMDs

  using (transverse) gluon polarization to look for saturation effects

Gluon TMDs at small x

Gluon TMDs and gauge links

- the naive operator definition is not gauge-invariant

$$\mathcal{F}_{g/A}(x_2, k_t) \overset{\text{naive}}{=} 2\int \frac{d\xi^+ d^2\boldsymbol{\xi}_t}{(2\pi)^3 p_A^-} e^{ix_2 p_A^- \xi^+ - ik_t\cdot\boldsymbol{\xi}_t} \left\langle A\right|\mathrm{Tr}\left[F^{i-}\left(\xi^+, \boldsymbol{\xi}_t\right) F^{i-}(0)\right]\left|A\right\rangle$$

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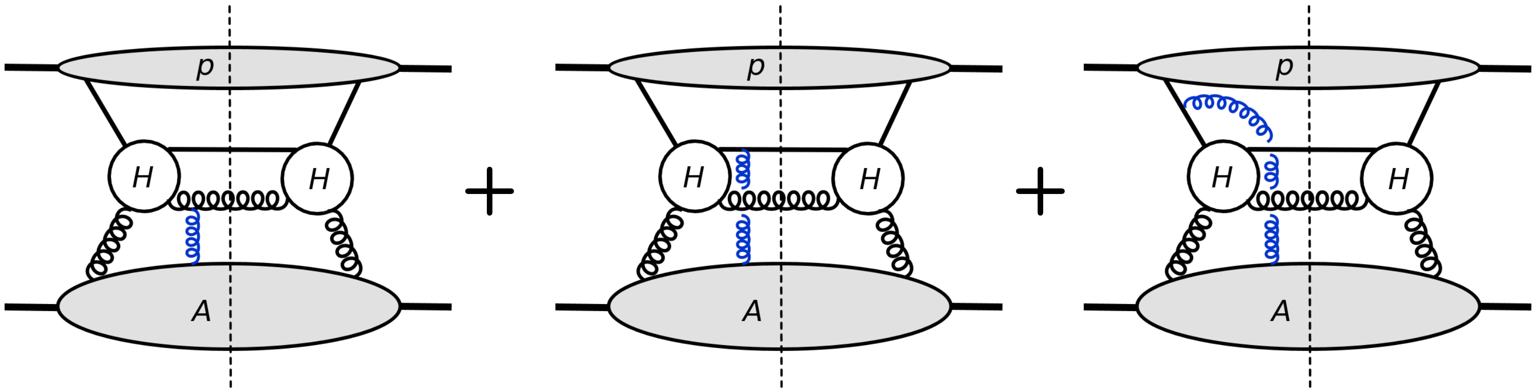
- a theoretically consistent definition requires to include more diagrams



$+$ similar diagrams with $2, 3, \ldots$ gluon exchanges

They all contribute at leading power and need to be resummed.

this is done by including gauge links in the operator definition

Process-dependent TMDs

- the proper operator definition(s)

some gauge link $\mathcal{P}\exp\left[-ig\int_{\alpha}^{\beta} d\eta^{\mu} A^{a}(\eta) T^{a}\right]$

$$\mathcal{F}_{g/A}(x_2, k_t) = 2\int \frac{d\xi^{+} d^{2}\boldsymbol{\xi}_t}{(2\pi)^3 p_A^{-}} e^{ix_2 p_A^{-}\xi^{+} - ik_t\cdot\boldsymbol{\xi}_t} \langle A|\mathrm{Tr}\left[F^{i-}\left(\xi^{+}, \boldsymbol{\xi}_t\right) U_{[\xi,0]} F^{i-}(0)\right]|A\rangle$$

- $U_{[\alpha,\beta]}$ renders gluon distribution gauge invariant

different processes require a different gauge-link structure,
implying in turn different gluon TMDs

Process-dependent TMDs

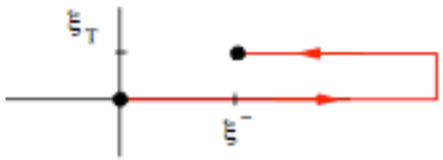
- the proper operator definition(s)

Dominguez, Xiao and Yuan (2011)

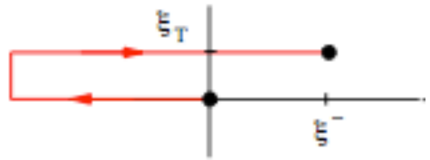
$$\mathcal{F}_{g/A}(x_2,k_t) = 2\int \frac{d\xi^+ d^2\boldsymbol{\xi}_t}{(2\pi)^3 p_A^-} e^{ix_2 p_A^- \xi^+ - ik_t\cdot\boldsymbol{\xi}_t} \left\langle A\right| \mathrm{Tr}\left[F^{i-}\left(\xi^+,\boldsymbol{\xi}_t\right) U_{[\xi,0]} F^{i-}(0)\right]\left|A\right\rangle$$

several paths are possible for the gauge links

examples :



$\mathcal{U}^{[+]}$



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Process-dependent TMDs

- the proper operator definition(s) Dominguez, Xiao and Yuan (2011)

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several paths are possible for the gauge links

examples :

- in the large k_t limit, the process dependence of the gauge links disappears (like for the integrated gluon distribution), and a single gluon distribution is sufficient

in particular, at small-x, all the TMDs share a universal perturbative tail called the unintegrated gluon distribution:

$$\mathcal{F}_{g/A}(x_2, k_t) = UGD(x_2, k_t) + \mathcal{O}(Q_s^2/k_t^2)$$

Kotko, Kutak, CM, Petreska, Sapeta, van Hameren (2015)

Process-dependent TMDs

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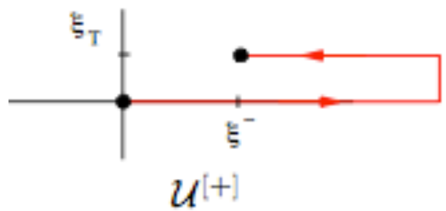

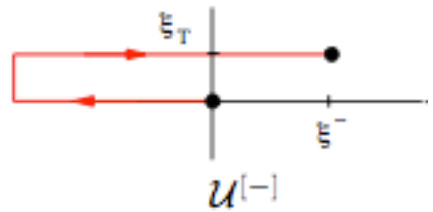

- one can compute the gluon TMDs at small x, using the Color Glass Condensate effective description of the dense parton content of the wave function, in terms of the large gluon field A^- :

$$\frac{\langle A|\ .\ |A\rangle}{\langle A|A\rangle}\rightarrow\langle\ .\ \rangle_x=\int DA^-|\phi_x[A^-]|^2\ .$$

Gluon TMDs at small-x

Dominguez, CM, Xiao and Yuan (2011)

- most-known examples of gluon TMDs :

the (fundamental) dipole gluon TMD

$$\mathcal{F}_{DP}(x_2,k_t)=2\int\frac{d\xi^+d^2\boldsymbol{\xi}}{(2\pi)^3p_A^-}e^{ix_2p_A^-\xi^+-ik_t\cdot\boldsymbol{\xi}}\left\langle A\middle|\mathrm{Tr}\left[F^{i-}(\xi)\,\mathcal{U}^{[-]\dagger}F^{i-}(0)\,\mathcal{U}^{[+]}\right]\middle|A\right\rangle$$

the Weizsäcker-Williams gluon TMD

$$\mathcal{F}_{WW}(x_2,k_t)=2\int\frac{d\xi^+d^2\boldsymbol{\xi}}{(2\pi)^3p_A^-}e^{ix_2p_A^-\xi^+-ik_t\cdot\boldsymbol{\xi}}\left\langle A\middle|\mathrm{Tr}\left[F^{i-}(\xi)\,\mathcal{U}^{[+]\dagger}F^{i-}(0)\,\mathcal{U}^{[+]}\right]\middle|A\right\rangle$$

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- at small x they can be written as:

$$U_{\mathbf{x}}=\mathcal{P}\exp\left[ig\int_{-\infty}^{\infty}dx^+A_a^-(x^+,\mathbf{x})t^a\right]$$

$$\mathcal{F}_{DP}(x_2,k_t)=\frac{4}{g^2}\int\frac{d^2\mathbf{x}d^2\mathbf{y}}{(2\pi)^3}\ e^{-ik_t\cdot(\mathbf{x}-\mathbf{y})}\left\langle\mathrm{Tr}\left[(\partial_iU_{\mathbf{y}})(\partial_iU_{\mathbf{x}}^\dagger)\right]\right\rangle_{x_2}$$

$$\mathcal{F}_{WW}(x_2,k_t)=-\frac{4}{g^2}\int\frac{d^2\mathbf{x}d^2\mathbf{y}}{(2\pi)^3}\ e^{-ik_t\cdot(\mathbf{x}-\mathbf{y})}\left\langle\mathrm{Tr}\left[(\partial_iU_{\mathbf{x}})U_{\mathbf{y}}^\dagger(\partial_iU_{\mathbf{y}})U_{\mathbf{x}}^\dagger\right]\right\rangle_{x_2}$$

these Wilson line correlators also emerge directly in CGC calculations

x evolution of the gluon TMDs

the evolution of Wilson line correlators with decreasing x can be computed from the so-called JIMWLK equation

$$\frac{d}{d\ln(1/x_2)}\left\langle O\right\rangle_{x_2}=\left\langle H_{JIMWLK}\;O\right\rangle_{x_2}$$

Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner

a functional RG equation that resums the leading logarithms in $y=\ln(1/x_2)$

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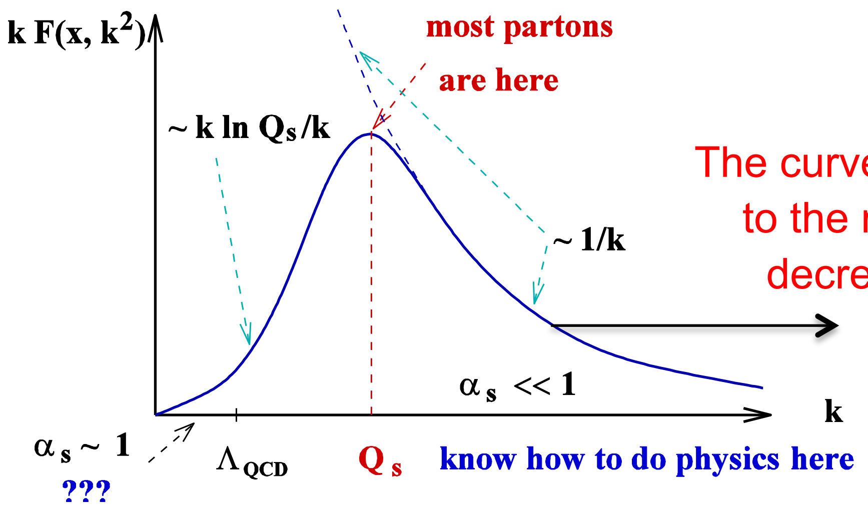
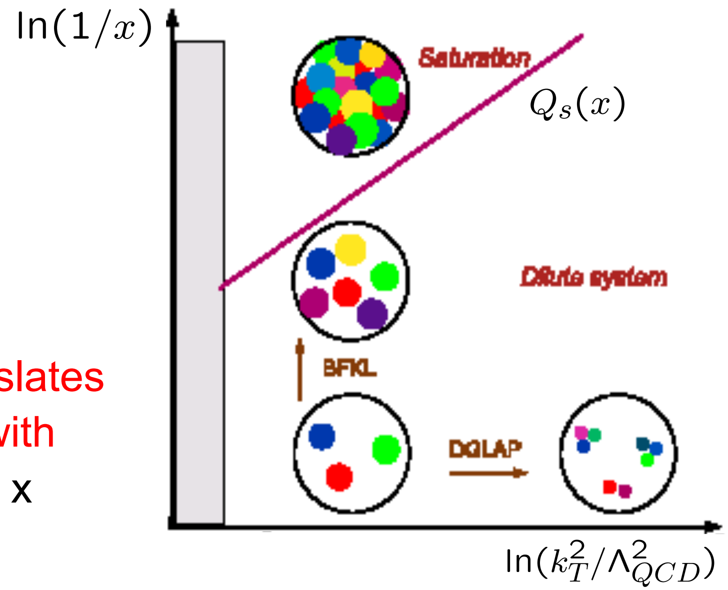
a functional RG equation that resums the leading logarithms in $y = \ln(1/x_2)$

- qualitative solutions for the gluon TMDs:



The curve translates to the right with decreasing x



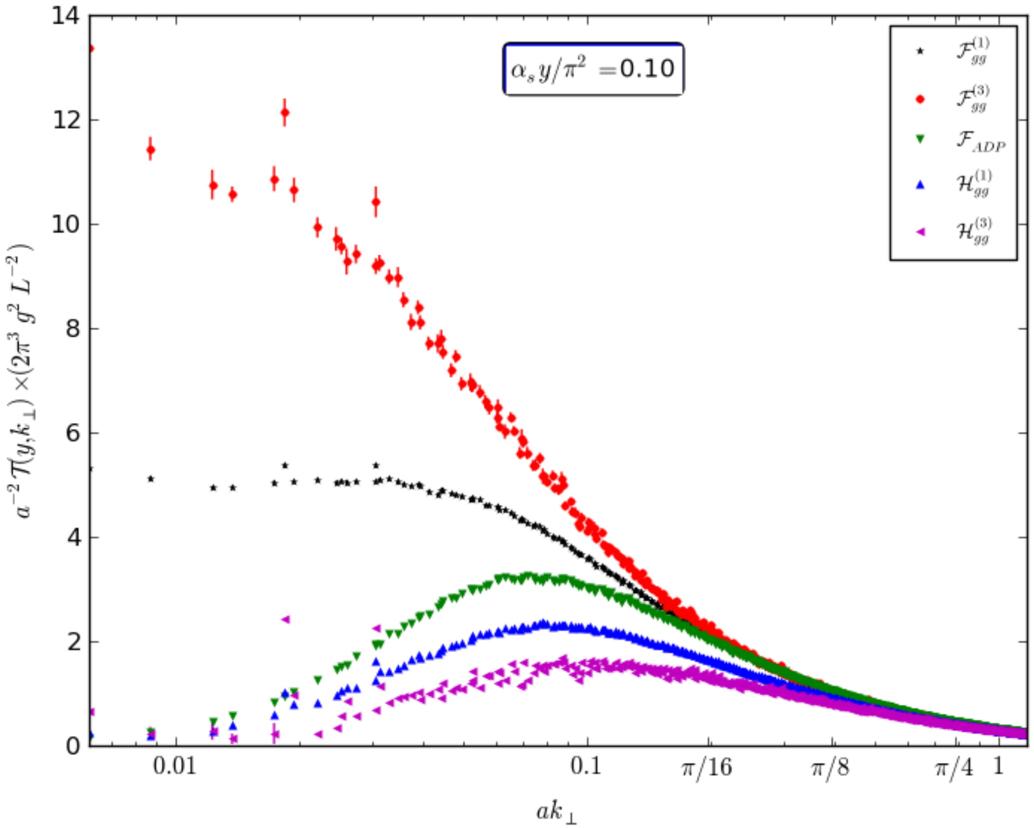
the distribution of partons as a function of x and k_T

JIMWLK numerical results

initial condition at y=0 : MV model
evolution: JIMWLK at leading log

CM, Petreska, Roiesnel (2016)

CM, Roiesnel, Taels (2017)

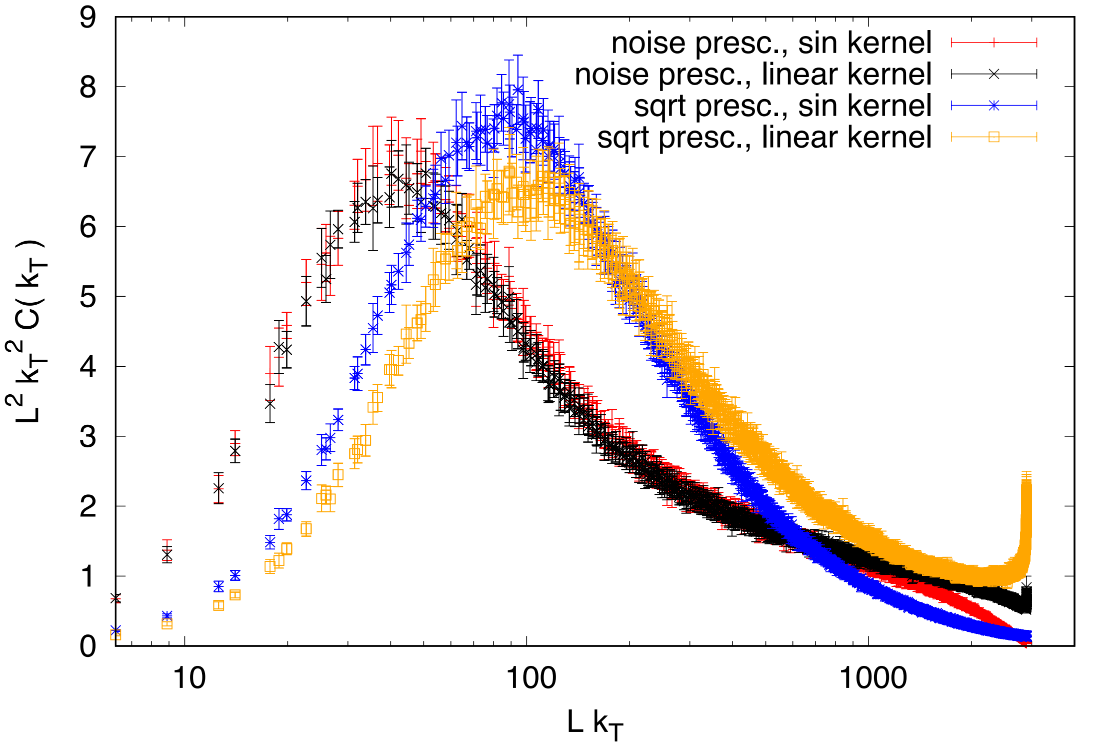


saturation effects impact the various gluon TMDs in very different ways

running-coupling JIMWLK

different prescriptions exist to introduce the running of the coupling in the JIMWLK equation

Rummukainen, Weigert (2004)
Lappi, Mäntysaari (2013)
Korcyl (2020)
Cali, Cichy, Korcyl, Kotko, Kutak, CM (2021)

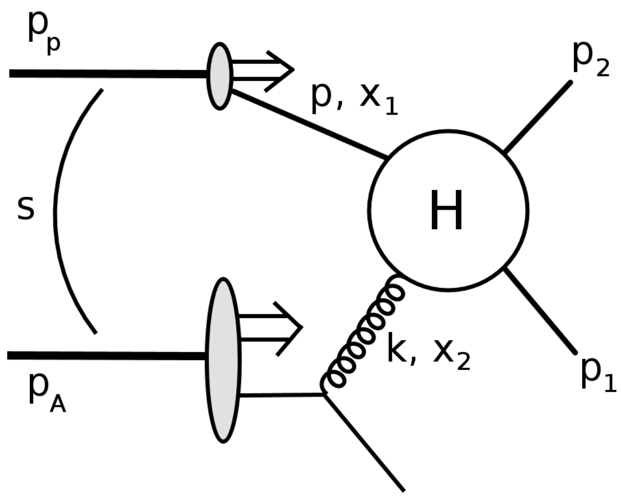


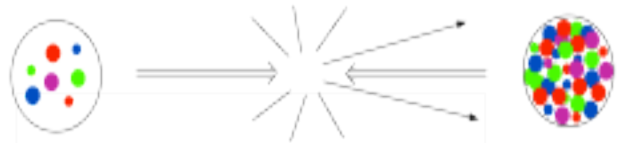
systematic effects impact the various prescriptions different ways

Probing the gluon TMDs at colliders

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:

$$x_1 = \frac{1}{\sqrt{s}}\left(|p_{1t}|e^{y_1} + |p_{2t}|e^{y_2}\right) \qquad \xrightarrow{y_1, y_2 \gg 0} \qquad x_1 \sim 1$$

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

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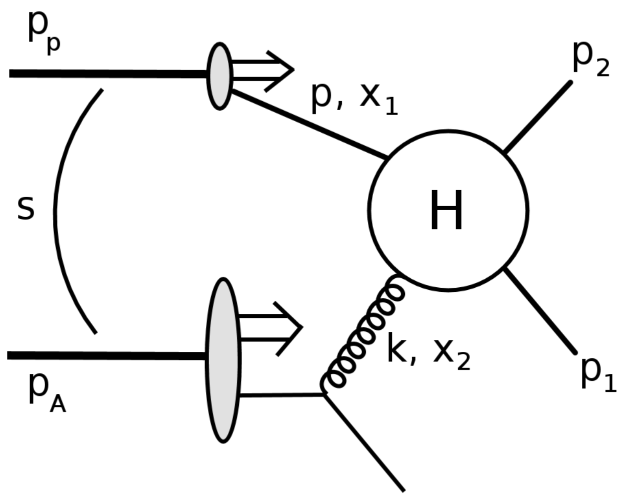

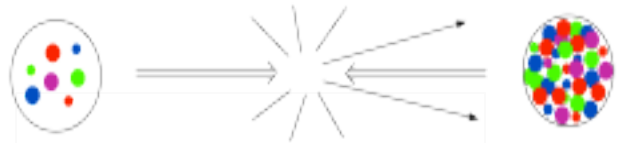

$\langle k_{1t} \rangle \sim \Lambda_{QCD}$ $\qquad$ $\langle k_{2t} \rangle \sim Q_s(x_2)$

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Incoming partons’ energy fractions:

$$\begin{aligned} x_1 &= \tfrac{1}{\sqrt{s}}\left(|p_{1t}|e^{y_1} + |p_{2t}|e^{y_2}\right) \\ x_2 &= \tfrac{1}{\sqrt{s}}\left(|p_{1t}|e^{-y_1} + |p_{2t}|e^{-y_2}\right) \end{aligned} \quad \xrightarrow{y_1, y_2 \gg 0} \quad \begin{aligned} x_1 &\sim 1 \\ x_2 &\ll 1 \end{aligned}$$

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

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

relevant regime here : $|p_{1t}|, \ |p_{2t}| \sim \mathbf{P} \gg Q_s$

Small-x improved TMD factorization

Kotko, Kutak, CM, Petreska, Sapeta, van Hameren (2015 - 2016)
Altinoluk, Boussarie, Kotko (2019)

$$d\sigma \propto f(x_1) \sum_c H_{(c)}(\mathbf{P}, k_t) \times \mathrm{TMD}_{(\mathrm{c})}(x_2, k_t)$$

standard collinear pdf
for the large-x projectile

off-shell
hard factors

several gluon TMDs
for the small-x target

ITMD factorization (schematically)

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ITMD ~ $f(x_1) \sum_c \left[H_{(c)}(\mathbf{P}, 0) + \mathcal{O}\left(\frac{k_t^2}{\mathbf{P}^2}\right)_{(\mathrm{c})} \right] \times \left[\mathrm{UGD}(x_2, k_t) + \mathcal{O}\left(\frac{Q_s^2(x_2)}{k_t^2}\right)_{(\mathrm{c})} \right]$

leading-twist hard factors

kimenatic higher twists

universal perturbative tail

leading-twist saturation corrections

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$$\text{TMD} \sim \quad f(x_1) \sum_c \left[H_{(c)}(\mathbf{P}, 0) + \cancel{\mathcal{O}\left(\frac{k_t^2}{\mathbf{P}^2}\right)_{(\mathrm{c})}} \right] \times \left[\mathrm{UGD}(x_2, k_t) + \mathcal{O}\left(\frac{Q_s^2(x_2)}{k_t^2}\right)_{(\mathrm{c})} \right]$$

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improvement wrt TMD factorization is all-order resummation of kinematic twists, which allows proper matching to BFKL physics at large kt

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standard collinear pdf
for the large-x projectile

off-shell
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several gluon TMDs
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HEF ~ $$f(x_1)\sum_c\left[H_{(c)}(\mathbf{P},0)+\mathcal{O}\left(\frac{k_t^2}{\mathbf{P}^2}\right)_{(\mathrm{c})}\right]\times\left[\mathrm{UGD}(x_2,k_t)+\cancel{\mathcal{O}\left(\frac{Q_s^2(x_2)}{k_t^2}\right)_{(\mathrm{c})}}\right]$$

leading-twist
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leading-twist
saturation corrections

improvement wrt HEF factorization is all-order resummation of leading twist saturation corrections, which unveils the process-depenpent TMDs and allows matching to TMD physics at low k_t

Genuine higher-twist corrections

ITMD factorization emerges from CGC calculations in the $\mathbf{P} \gg Q_s$ limit

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

TMD regime

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

BFKL regime

+ $(k_t/P_t)^n$

+ $(Q_S/k_t)^n$

ITMD

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

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ITMD

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Altinoluk, Boussarie (2019)

+ $(Q_S/P_t)^n$

CGC

- CGC and ITMD can be compared numerically

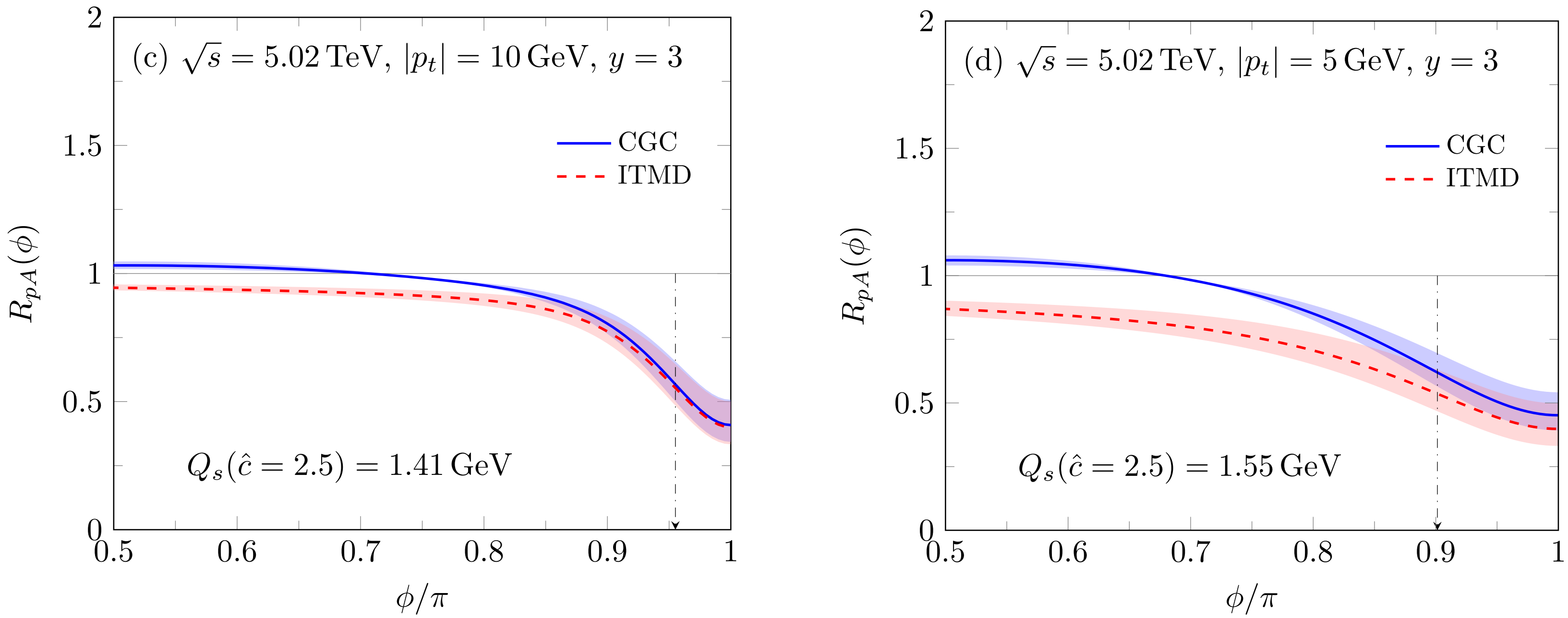
Fujii, CM, Watanabe (2020) Boussarie, Mäntysaari Salazar, Schenke (2021)

Genuine higher-twist corrections

the genuine-twist corrections start to matter when the jet transverse momenta get closer to Qs

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

Fujii, CM, Watanabe (2020)



Unpolarized & linearly-polarized gluon TMDs

Spin physics and TMDs

TMDs are crucial to describe hard processes in polarized collisions

(e.g. Drell-Yan and semi-inclusive DIS)

8 leading-twist TMDs

Sivers function

correlation between transverse spin of the nucleon and transverse momentum of the quark

Boer-Mulders function

correlation between transverse spin and transverse momentum of the quark in unpolarized nucleon

nucleon polarization

quark polarization

	U	L	T
U	f_1 number density q		$f_{1T}^{\perp}$ Sivers
L		g_1 helicity Δq	g_{1T}
T	$h_1^{\perp}$ Boer Mulders	$h_{1L}^{\perp}$	h_1 transversity $h_{1T}^{\perp}$

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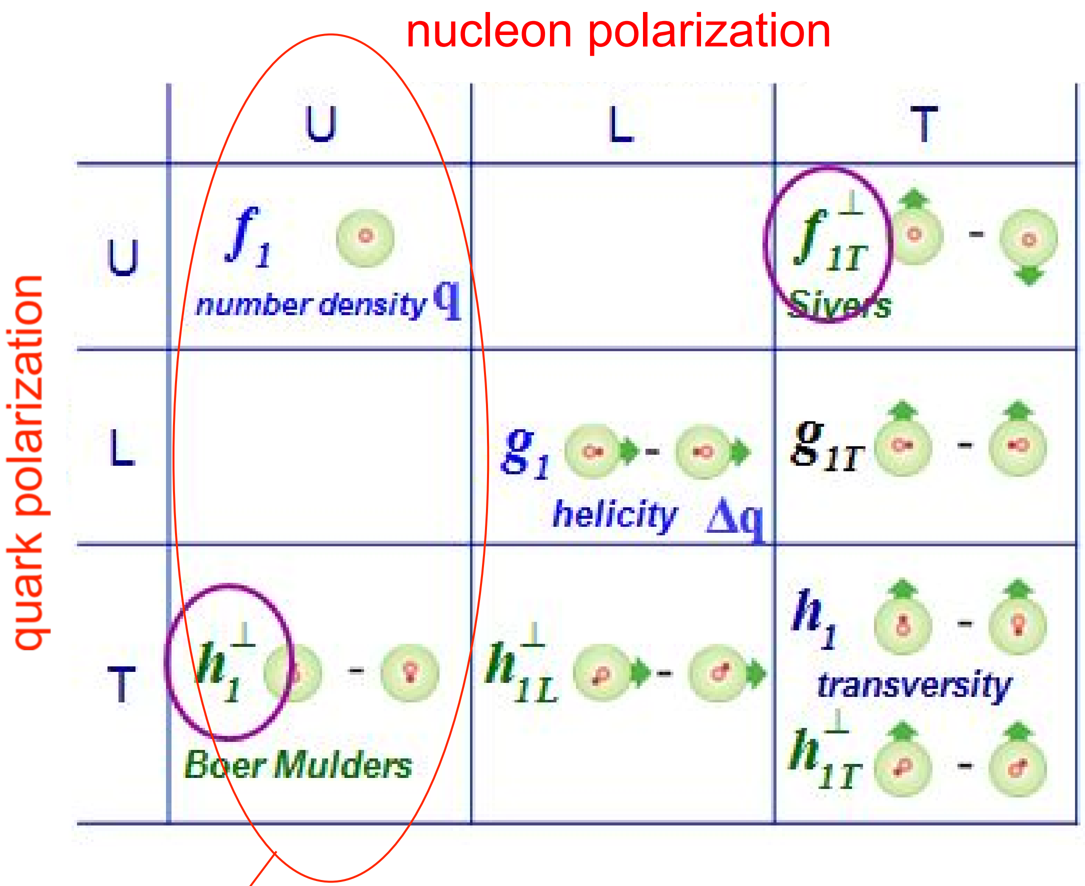

Sivers function

correlation between transverse spin of the nucleon and transverse momentum of the quark

Boer-Mulders function

correlation between transverse spin and transverse momentum of the quark in unpolarized nucleon

I discuss those for gluons

Generic definitions of gluon TMDs

I consider only hadronic/nuclear states that are *unpolarized*

$$2\int \frac{d\xi^+ d^2\boldsymbol{\xi}_t}{(2\pi)^3 p_A^-} e^{ixp_A^-\xi^+ - ik_t\cdot\boldsymbol{\xi}_t} \left\langle A\right|\mathrm{Tr}\left[F^{i-}\left(\xi^+,\boldsymbol{\xi}_t\right)F^{j-}(0)\right]\left|A\right\rangle$$

$$= \frac{\delta_{ij}}{2}\mathcal{F}(x,k_t) + \left(\frac{k_i k_j}{k_t^2} - \frac{\delta_{ij}}{2}\right)\mathcal{H}(x,k_t)$$

unpolarized gluon TMD

linearly-polarized gluon TMD

Generic definitions of gluon TMDs

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$$= \frac{\delta_{ij}}{2}\underbrace{\mathcal{F}(x,k_t)}_{\text{unpolarized gluon TMD}} + \left(\frac{k_i k_j}{k_t^2} - \frac{\delta_{ij}}{2}\right)\underbrace{\mathcal{H}(x,k_t)}_{\text{linearly-polarized gluon TMD}}$$

- TMDs appear in cross-sections by pairs:

several pairs may be involved depending on the process

$$\mathrm{d}\sigma \propto f(x_1)\sum_c H^{ij}_{(c)}(\mathbf{P},k_t)\Big[\frac{1}{2}\delta^{ij}\mathcal{F}_{(\mathrm{c})}(x_2,k_t) + \Big(\frac{k^i k^j}{k_t^2} - \frac{1}{2}\delta^{ij}\Big)\mathcal{H}_{(\mathrm{c})}(x_2,k_t)\Big]$$

Generic definitions of gluon TMDs

I consider only hadronic/nuclear states that are *unpolarized*

$$2\int \frac{d\xi^+ d^2\boldsymbol{\xi}_t}{(2\pi)^3 p_A^-} e^{ixp_A^-\xi^+ - ik_t\cdot\boldsymbol{\xi}_t} \langle A|\mathrm{Tr}\left[F^{i-}\left(\xi^+,\boldsymbol{\xi}_t\right) F^{j-}(0)\right]\Big| A\rangle$$

$$= \frac{\delta_{ij}}{2}\mathcal{F}(x,k_t) + \left(\frac{k_i k_j}{k_t^2} - \frac{\delta_{ij}}{2}\right)\mathcal{H}(x,k_t)$$

unpolarized gluon TMD

linearly-polarized gluon TMD

- TMDs comes by pair, expect dipole type TMDs for which $\mathcal{F} = \mathcal{H}$
- at small x, $\mathcal{F} = \mathcal{H}$ = UGD in the BFKL regime, for all TMD types :

$$\mathcal{F}(x_2,k_t) - \mathcal{H}(x_2,k_t) = \mathcal{O}(Q_s^2/k_t^2)$$

Processes sensitive to $\mathcal{H}$

- ITMD factorization may be rewritten

$$d\sigma \propto f(x_1) \sum_c \left[H^{ns}_{(c)}(\mathbf{P}, k_t) \mathcal{F}_{(\mathrm{c})}(x_2, k_t) + H^h_{(c)}(\mathbf{P}, k_t) \underbrace{\Big(\mathcal{H}_{(\mathrm{c})}(x_2, k_t) - \mathcal{F}_{(\mathrm{c})}(x_2, k_t) \Big)}_{= 0 \text{ in BFKL regime}} \right]$$

projections onto
"non-sense" polarization

$$H^{ns}_{(c)} = H^{ij}_{(c)} k^i k^j / k_t^2$$

projections onto linear polarization

$$H^h_{(c)} = H^{ij}_{(c)} (k^i k^j / k_t^2 - \delta^{ij}/2)$$

Processes sensitive to $\mathcal{H}$

- ITMD factorization may be rewritten

$$d\sigma \propto f(x_1) \sum_c \Big[\underbrace{H^{ns}_{(c)}}_{\text{projections onto “non-sense” polarization}}(\mathbf{P}, k_t)\mathcal{F}_{(\mathrm{c})}(x_2, k_t) + \underbrace{H^{h}_{(c)}}_{\text{projections onto linear polarization}}(\mathbf{P}, k_t)\underbrace{\Big(\mathcal{H}_{(\mathrm{c})}(x_2, k_t) - \mathcal{F}_{(\mathrm{c})}(x_2, k_t)\Big)}_{= 0 \text{ in BFKL regime}} \Big]$$

= 0 in BFKL regime

projections onto
“non-sense” polarization

$$H^{ns}_{(c)} = H^{ij}_{(c)} k^i k^j / k_t^2$$

projections onto linear polarization

$$H^{h}_{(c)} = H^{ij}_{(c)} (k^i k^j / k_t^2 - \delta^{ij}/2)$$

- processes for which the $H^{h}_{(c)}$ hard factors are non-zero:

  - dijets in deep inelastic scattering (e+p or e+A)
  - heavy-quark pair production (in photo-production or p+A collisions)
  - trijets or more

Altinoluk, Boussarie, CM, Taels (2019 - 2020)
Altinoluk, CM, Taels (2021)

linearly-polarized gluons come with a $\cos(2\phi)$ modulation
(at small k_t / **P**) where ϕ is the angle between k_t and **P**

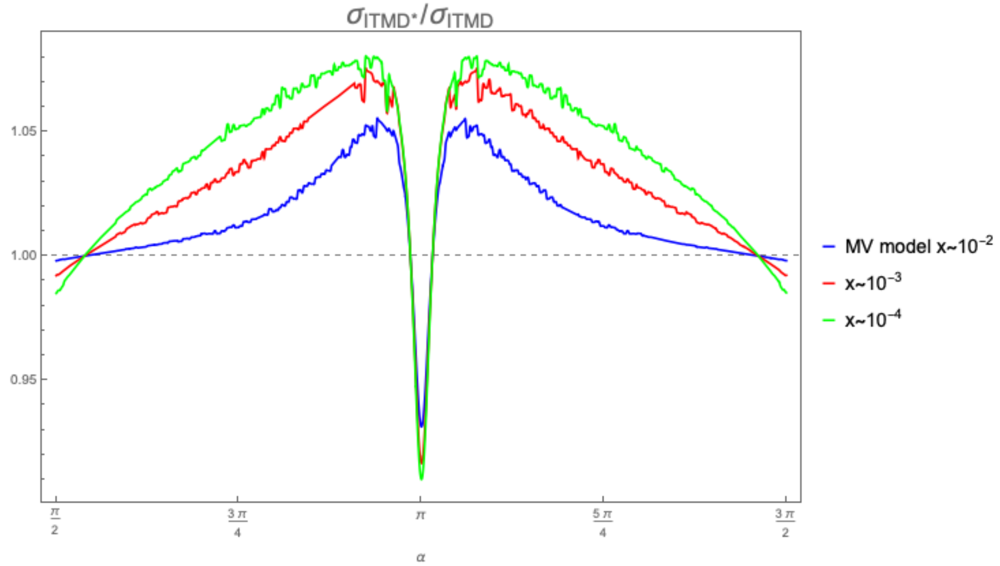
Dijets in deep inelatic scattering

- looking at $\Delta\Phi$ distributions:

Altinoluk, CM, Taels (2021)

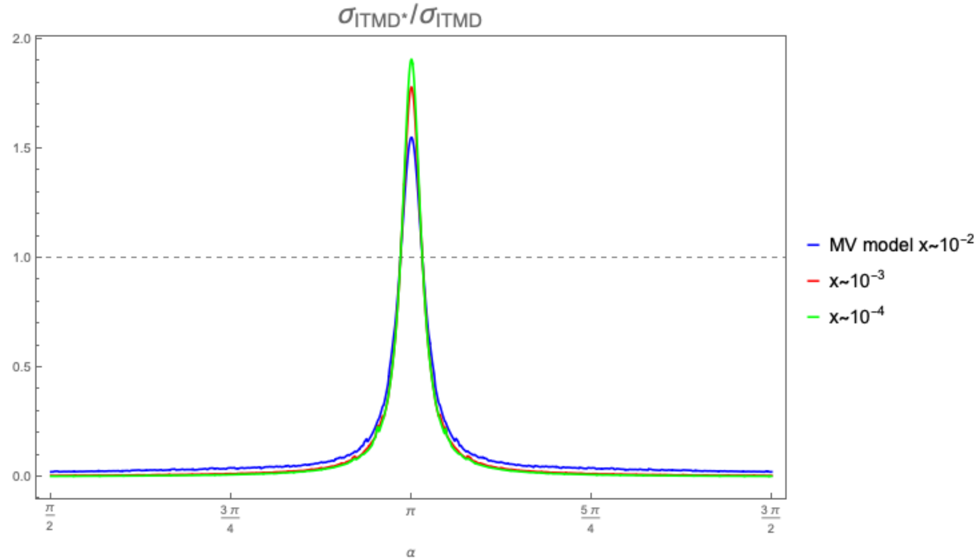
$$\frac{\text{BFKL}}{\text{BFKL + saturation}}$$

for transverse photon



$$\frac{\text{BFKL}}{\text{BFKL + saturation}}$$

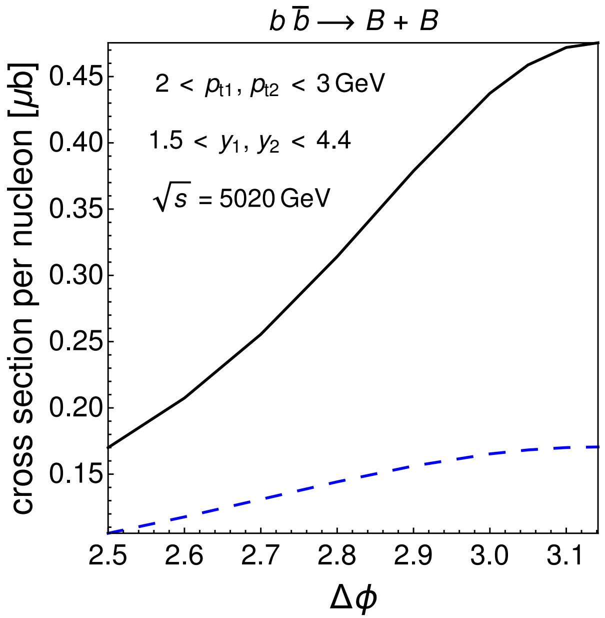
for longitudinal photon

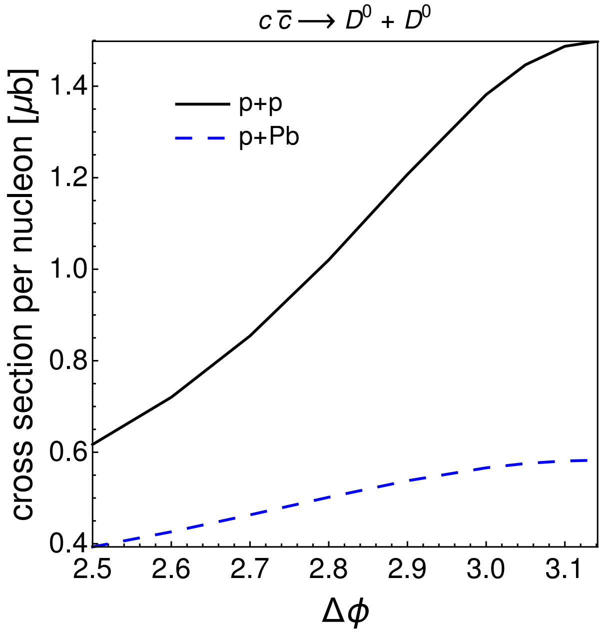


Forward $Q\bar{Q}$ pair in p+A collisions

- preliminary study performed for HL-LHC yellow report

CM, Giacalone (2018)





ITMD hard factors to be implemented

important away from $\Delta\Phi = \pi$, when $k_t \sim \mathbf{P}$

soft-gluon resummation to be added as well

important near $\Delta\Phi = \pi$, when $\log(\mathbf{P}/k_t)$ becomes large

Conclusions I

- ITMD factorization 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)

Conclusions II

- different processes involve different gluon TMDs, with different operator definitions
- each operator definition provides an unpolarized gluon TMD and a linearly-polarized one
- the various gluon TMDs coincide at large transverse momentum, in the linear regime
- however, they differ significantly from one another at low transverse momentum, in the non-linear saturation regime
- one could use small-x gluons which are not fully linearly polarized to look for saturation effects