



Stony Brook **University**



Accessing (G)TMDs through pair production of jets, quarkonia and open heavy flavors

virtual Quarkonia as Tools 2021
Farid Salazar

March 23rd



Outline*

- I. TMDs and observables at the EIC
- II. GTMDs and observables at the EIC
- III. The CGC EFT: Beyond (G)TMDs at small-x

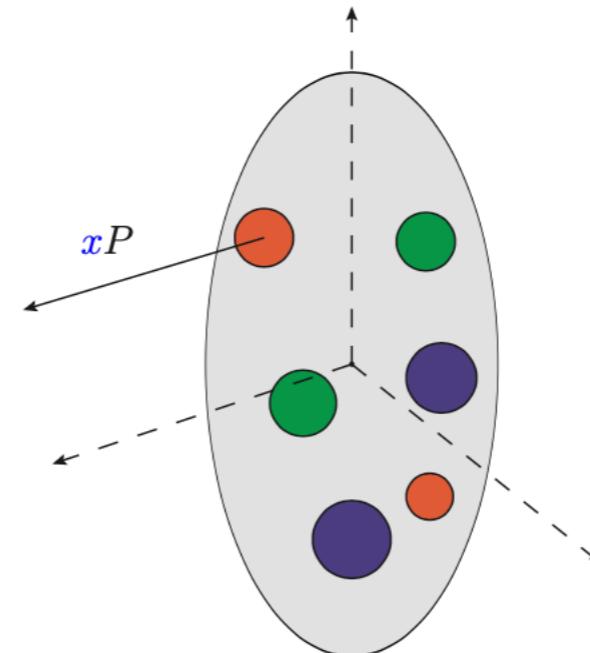
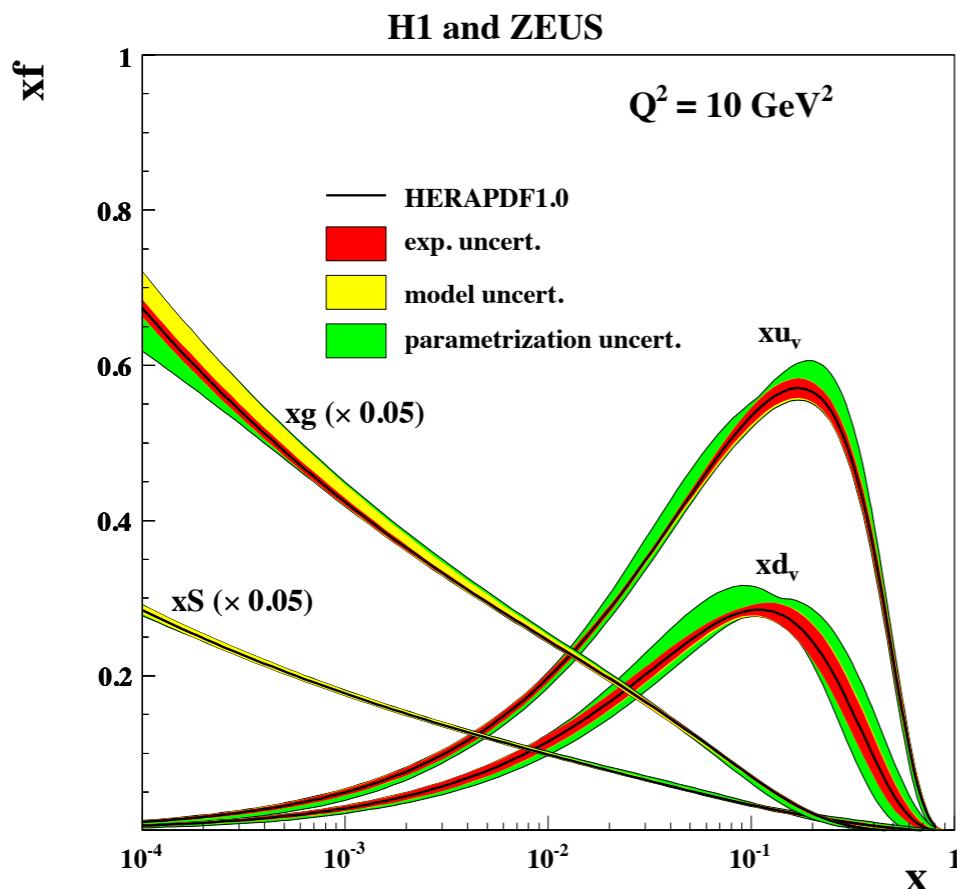
* I will focus on small- x , forward particle production at the EIC for unpolarized hadrons/nuclei

Parton distribution functions (PDFs)

One dimensional description of partons

Gluon PDF

$$\mathcal{F}(x) = 2 \int \frac{d\xi^+}{(2\pi)P^-} e^{ixP^-\xi^+} \langle P | F^{i-}(0^+) [0^+, \xi^+] F^{i-}(\xi^+) [\xi^+, 0^+] | P \rangle$$



Credit: Renaud Boussarie

Collinear factorization applicable for:

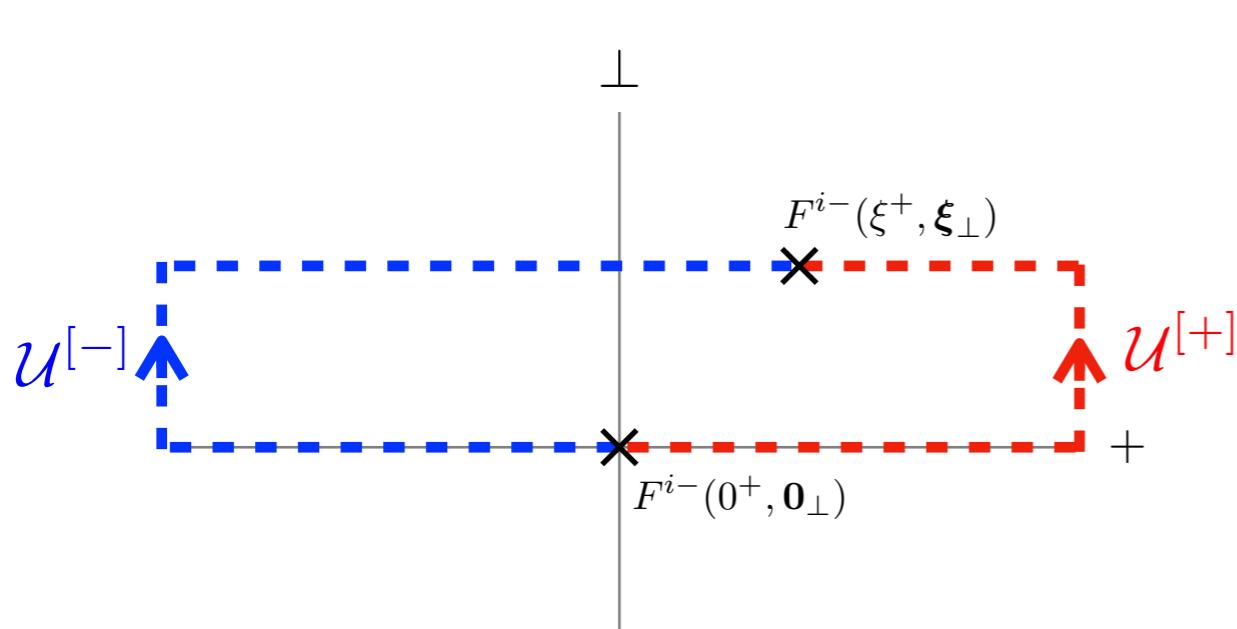
- Fully inclusive DIS
- SIDIS (integrated k_\perp , and large k_\perp)
- etc

Transverse momentum dependent PDFs (TMDs)

Unraveling the 3D momentum structure of partons

Gluon TMD

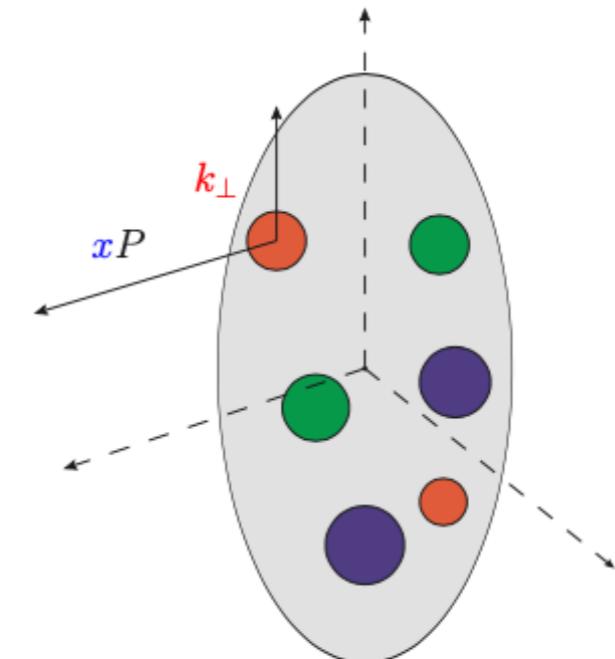
$$\mathcal{F}(x, \mathbf{k}_\perp) = 2 \int \frac{d\xi^+ d^2 \xi_\perp}{(2\pi)^3 P^-} e^{ixP^- \xi^+ - i\mathbf{k}_\perp \cdot \boldsymbol{\xi}_\perp} \left\langle P | F^{i-}(0) \mathcal{U}_{[0,\xi]}^{[\mathcal{C}]} F^{i-}(\xi) \mathcal{U}_{[0,\xi]}^{[\mathcal{C}']} | P \right\rangle$$



$\mathcal{U}^{[+]}$ future pointing gauge link

$\mathcal{U}^{[-]}$ past pointing gauge link

Characterize TMD by their gauge link structure



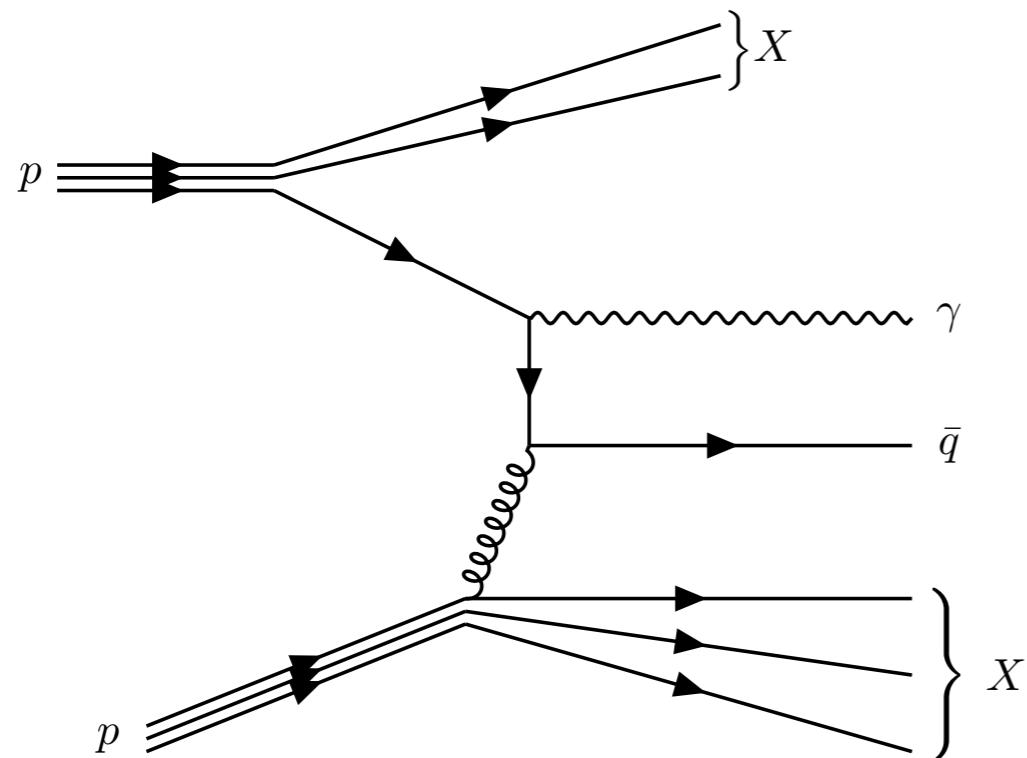
Credit: Renaud Boussarie

TMD factorization applicable for:

- SIDIS $k_\perp \ll Q$
- Dijet production $k_\perp \ll p_{1,\perp}, p_{2,\perp}$
- etc

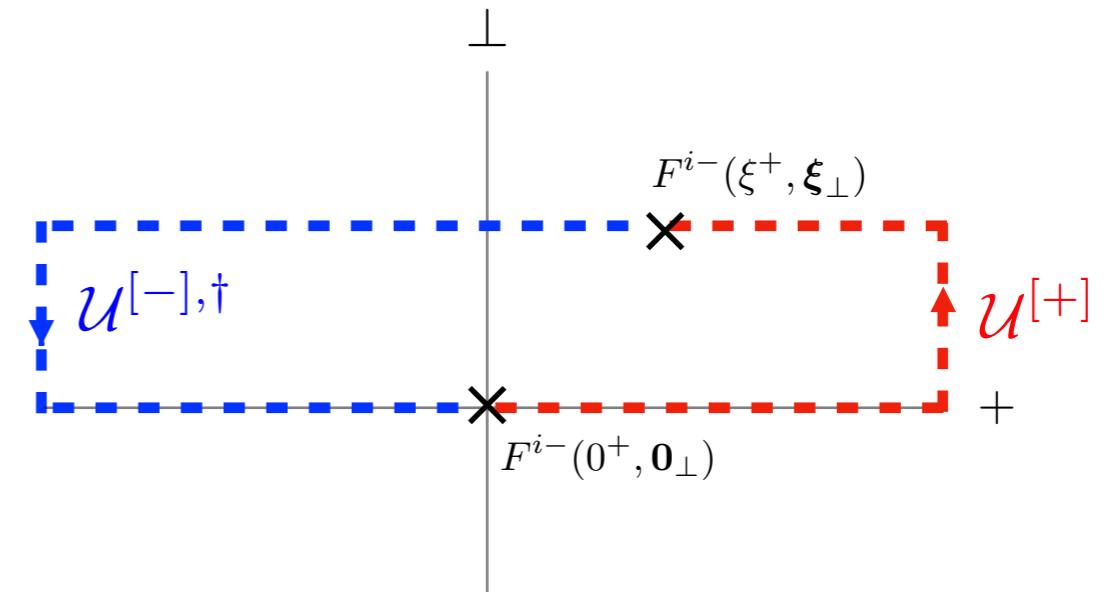
Transverse momentum dependent PDFs (TMDs)

Dipole gluon TMD



Forward photon-quark production in $p\bar{p}$ (pA)

$$\langle P | F^{i-}(0) \mathcal{U}^{[+]} F^{i-}(\xi) \mathcal{U}^{[-]\dagger} | P \rangle$$



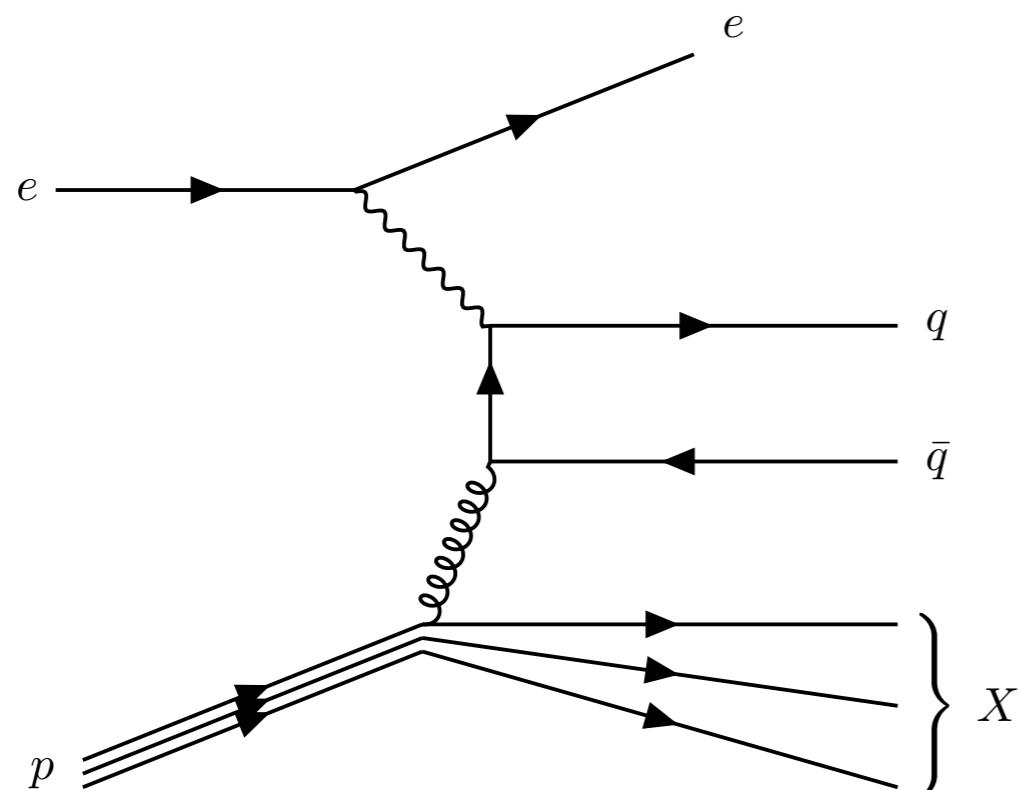
Non-universality due to color flow of underlying hard partonic process

Resummation of collinear gluons \longrightarrow Gauge invariance of TMDs

- Bomhof, Mulders, Pijlman (2006)
Dominguez, Marquet, Xiao, Yuan (2011)
Petreska (2018)

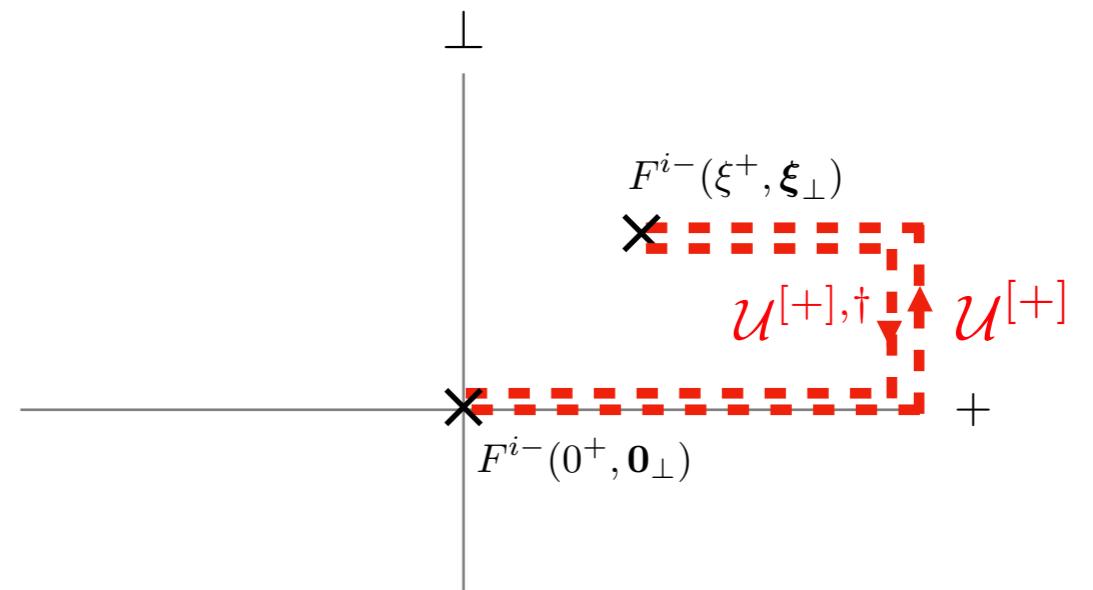
Transverse momentum dependent PDFs (TMDs)

Weizsäcker-Williams gluon TMD



Forward quark anti-quark production in DIS

$$\langle P | F^{i-}(0) \mathcal{U}^{[+]} F^{i-}(\xi) \mathcal{U}^{[+]^\dagger} | P \rangle$$



Non-universality due to color flow of underlying hard partonic process

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- Dominguez, Marquet, Xiao, Yuan (2011)
- Petreska (2018)

Transverse momentum dependent PDFs (TMDs)

Semi-inclusive processes at the EIC

Dipole gluon

- Hadron/jet production [Iancu, Mueller, Triantafyllopoulos, Wei \(2020\)](#)
- Hadron/jet + photon production [Kolb  , Roy, FS, Schenke, Venugopalan \(2020\)](#)

Weizs  cker-Williams

- Dihadron/dijet production* [Dominguez, Marquet, Xiao, Yuan \(2011\)](#)
 - Trijet production* [Altinoluk, Boussarie, Marquet, Taels \(2020\)](#)
 - Heavy quark pair production* [Bacchetta, Boers, Pisano, Taels \(2018\)](#)
 - Heavy quarkonium production** [Bacchetta, Boers, Pisano, Taels \(2018\)](#)
 - Heavy quarkonium + jet production [D'Alesio, Murgia, Pisano, Taels \(2019\)](#)
- $\left. \right\} \text{Extract color octet LDME's}$

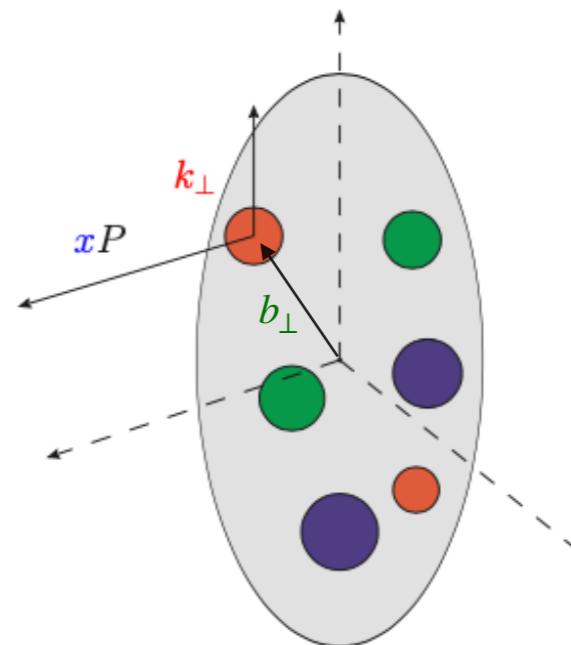
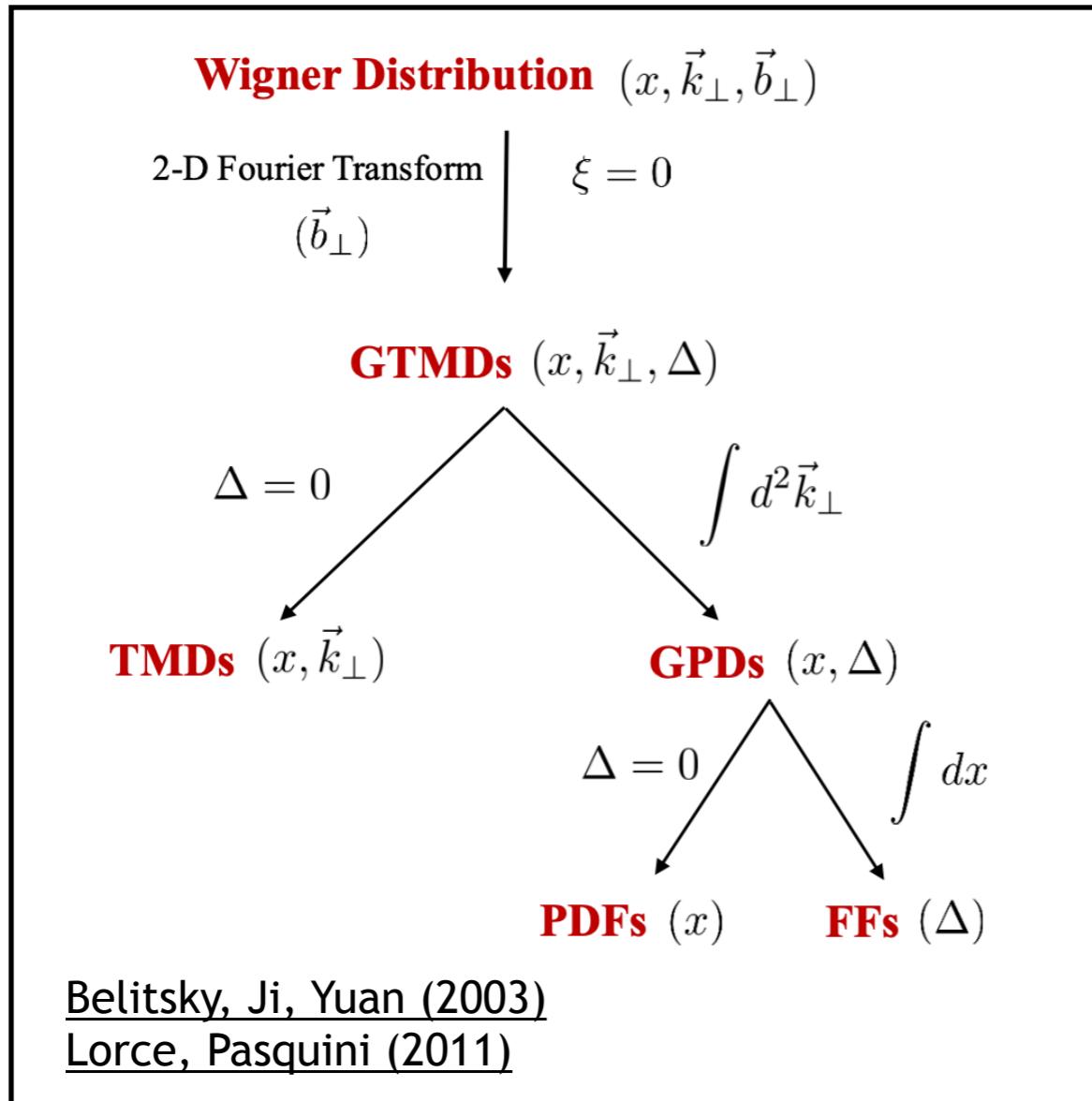
*correlation/back-to-back limit

**color octet channel dominant

Generalized TMDs (GTMDs)

5 dimensional tomography of hadrons and nuclei

$$\mathcal{F}(x, \mathbf{k}_\perp, \Delta_\perp) = 2 \int \frac{d\xi^+ d^2 \xi_\perp}{(2\pi)^3 P^-} e^{ixP^- \xi^+ - i\mathbf{k}_\perp \cdot \xi_\perp} \left\langle P - \frac{\Delta_\perp}{2} \left| F^{i-}(0) \mathcal{U}_{[0,\xi]}^{[\mathcal{C}]} F^{i-}(\xi) \mathcal{U}_{[0,\xi]}^{[\mathcal{C}']} \right| P + \frac{\Delta_\perp}{2} \right\rangle$$



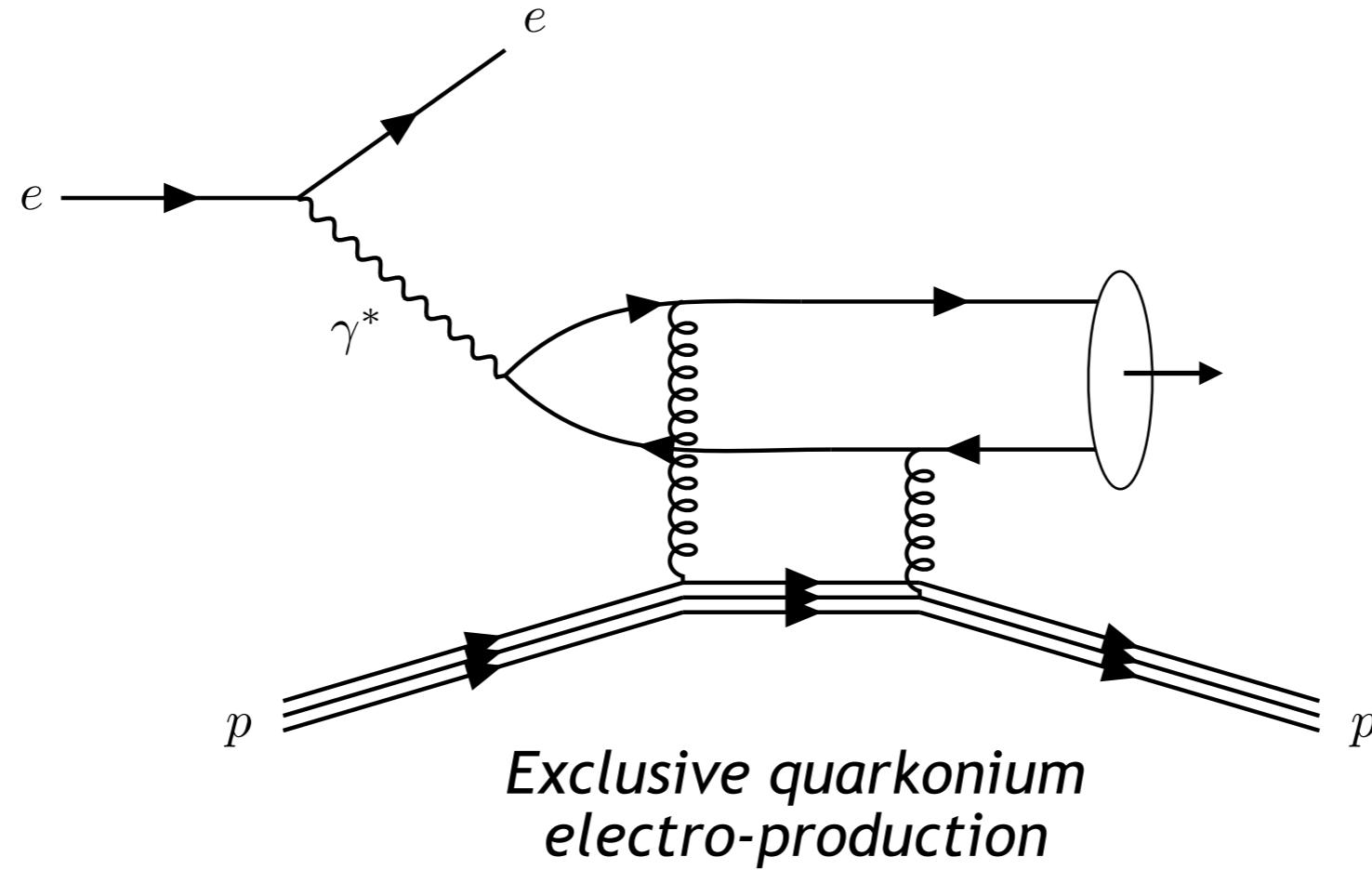
Encodes orbital angular momentum

GTMDs depend on gauge link structure $\mathcal{U}^{[+]}$ $\mathcal{U}^{[-]}$

Access through exclusive processes

Generalized TMDs (GTMDs)

Accessing the Dipole gluon GPD at the EIC



Exclusive single quarkonium production is sensitive to gluon dipole GPD

Sensitive only to color singlet

Some recent development on LFWF see [Lappi, Mäntysaari, Penttala \(2017\)](#)

Need 2 particles in final state for sensitivity to GTMD

One can access elliptic part of GPD in J/ψ correlation with scattered DIS electron

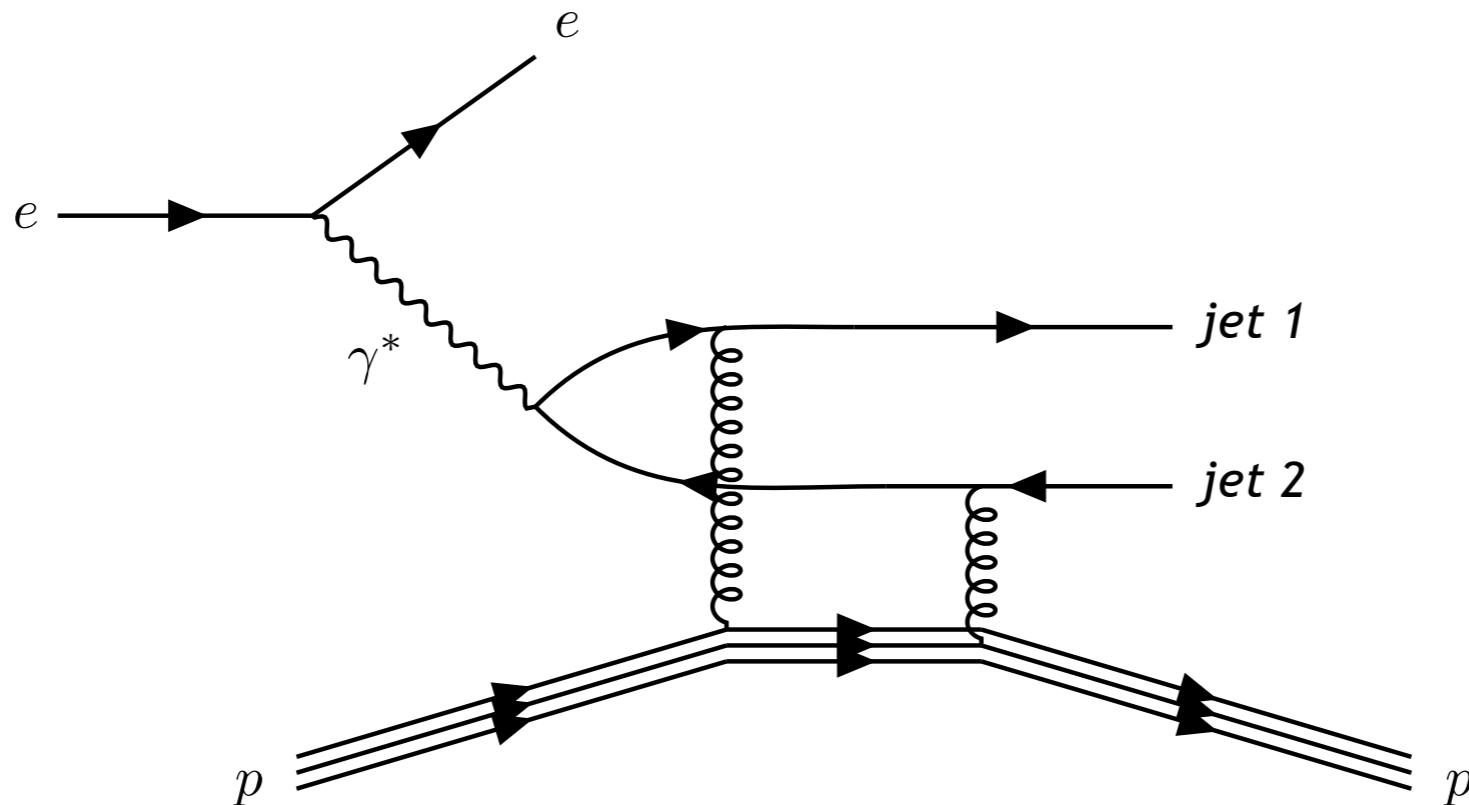
[Hatta, Yuan, Xiao \(2017\)](#)

[Mäntysaari, Roy, FS, Schenke \(2020\)](#)

*For incoherent diffraction and fluctuations
(see Heikki's talk Tuesday morning)

Generalized TMDs (GTMDs)

Accessing the Dipole gluon GTMD at the EIC



Exclusive dijet electro-production

Hatta, Yuan, Xiao (2016)

Mäntysaari, Mueller, Schenke (2019)

FS, Schenke (2019)

At EIC energies, the small- x constrain
the invariant mass of dijet system

$$\rightarrow p_{\perp} \lesssim 5 \text{ GeV}$$

Challenging to reconstruct
experimentally

Include effects of soft-gluon radiation

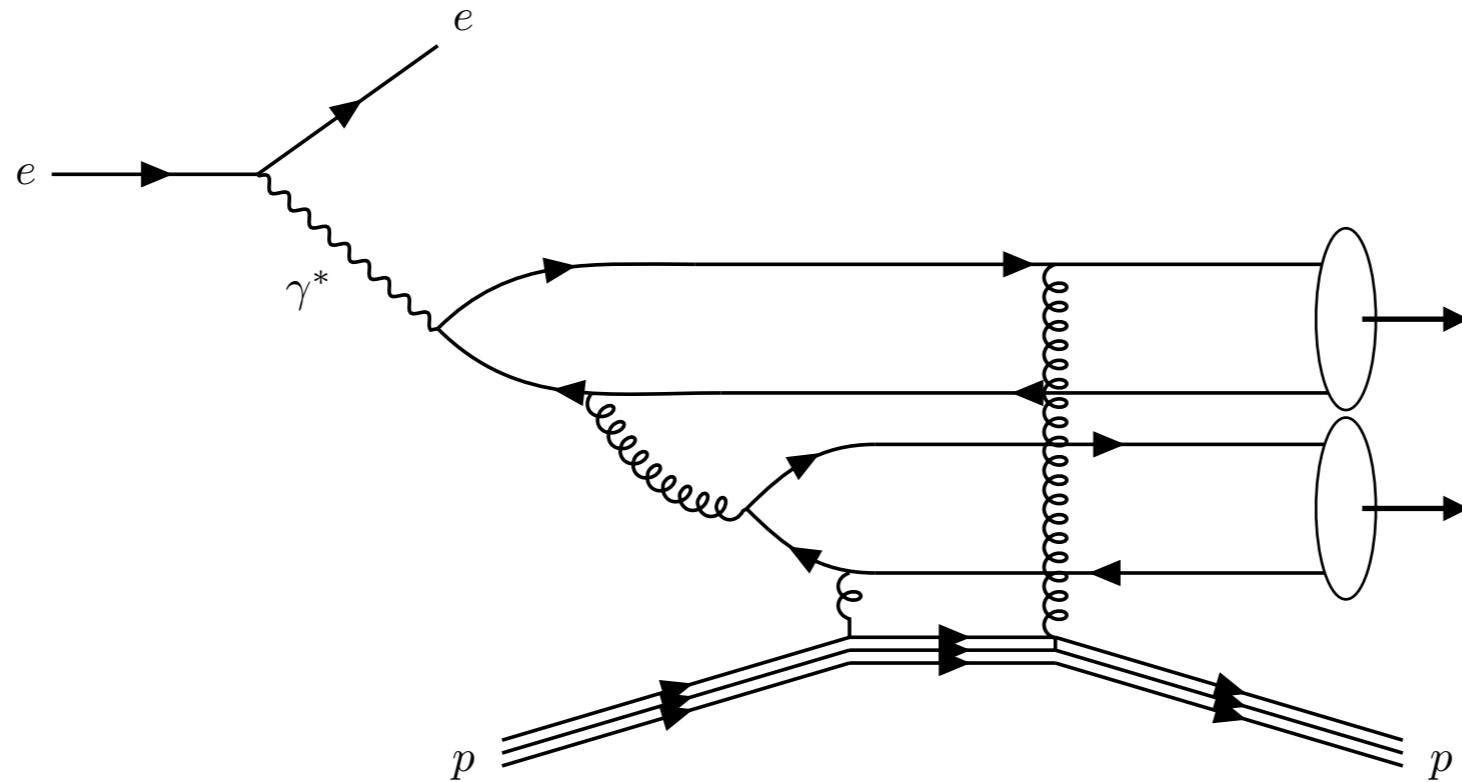
\rightarrow Better to measure recoiled
target

Hatta, Mueller, Ueda, Yuan (2019)
Hatta, Yuan, Xiao, Zhou (2020)

Maybe worth studying heavy quark pair via charm fragmentation function $c \rightarrow D$

Generalized TMDs (GTMDs)

Accessing the Weizsäcker Williams GTMD at the EIC



Quarkonia pair electro-production

Suggested by Feng Yuan

To access WW GTMD need 2 quark anti-quark pairs!

Sensitive to color singlet and octet

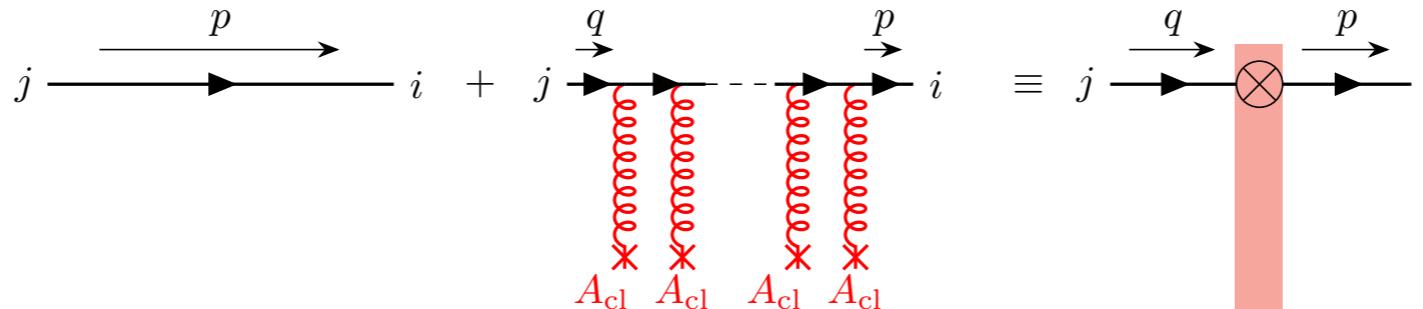
Process has been studied in pp collisions [Boussarie, Hatta, Yuan, Xiao \(2018\)](#)

Not worked out in DIS yet!

The Color Glass Condensate EFT

Multiple scattering and Wilson line correlators

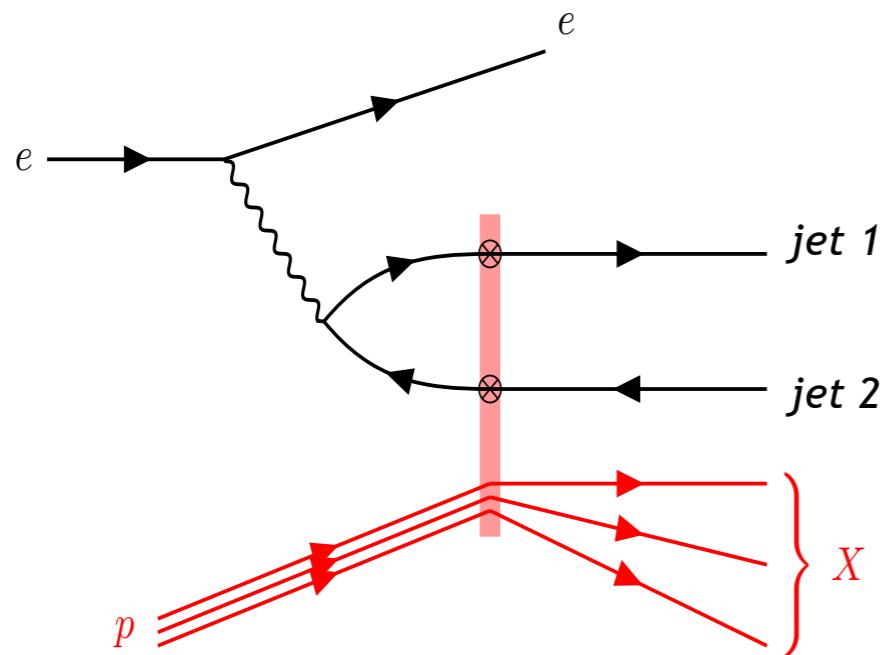
Dense gluon field $A_{cl} \sim 1/g$ needs resummation of multiple gluon interactions



**Light-like
Wilson line:**

$$V_{ij}(x) = P \exp \left\{ ig \int dx^- A_{cl}^{+,a}(x, x^-) t^a \right\}$$

Classical
small-x field $A_{cl}^{+,a} = -\frac{\rho^a}{\nabla_\perp^2}$ large-x
sources



LO CGC diagram for dijet production

Dipole

$$\frac{1}{N_c} \langle \text{Tr}(V_{\mathbf{x}_{1\perp}} V_{\mathbf{x}_{2\perp}}^\dagger) \rangle_Y$$

Quadrupole

$$\frac{1}{N_c} \langle \text{Tr}(V_{\mathbf{x}_{1\perp}} V_{\mathbf{x}_{2\perp}}^\dagger V_{\bar{\mathbf{x}}_{2\perp}} V_{\bar{\mathbf{x}}_{1\perp}}^\dagger) \rangle_Y$$

Initial conditions via:
McLerran Venugopalan (MV) model

[McLerran Venugopalan \(1993\)](#)

Color charge correlators from LCWF

[Dumitru, Miller, Venugopalan \(2018\)](#)

[Dumitru, Mäntysaari, Paatelainen \(2021\)](#)

Small-x evolution via:
BK or JIMWLK equations

[Balitsky \(1996\)](#)

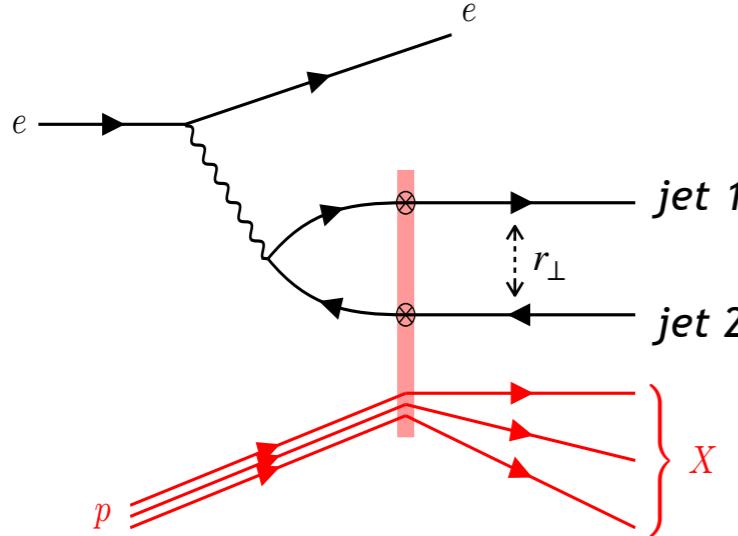
[Kovchegov \(1999\)](#)

[Jalilian-Marian, Kovner, Weigert \(1999\)](#)

[Iancu, McLerran, Leonidov \(2000\)](#)

The Color Glass Condensate EFT

From Wilson line correlators to (G)TMDs



Dominguez, Marquet, Xiao, Yuan (2011)

Derivative expansion (small r_\perp) one can recover TMDs at small- x (leading power of k_\perp/P_\perp)

$$\left\langle \text{Tr}(V_{b_\perp} \partial^i V_{b_\perp}^\dagger V_{\bar{b}_\perp} \partial^j V_{\bar{b}_\perp}^\dagger) \right\rangle_{Y=\log(1/x)} \xrightarrow{\text{F.T.}} \mathcal{F}_{WW}(x, k_\perp)$$

Improved TMD framework

Resummation of kinematic power corrections k_\perp/P_\perp

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

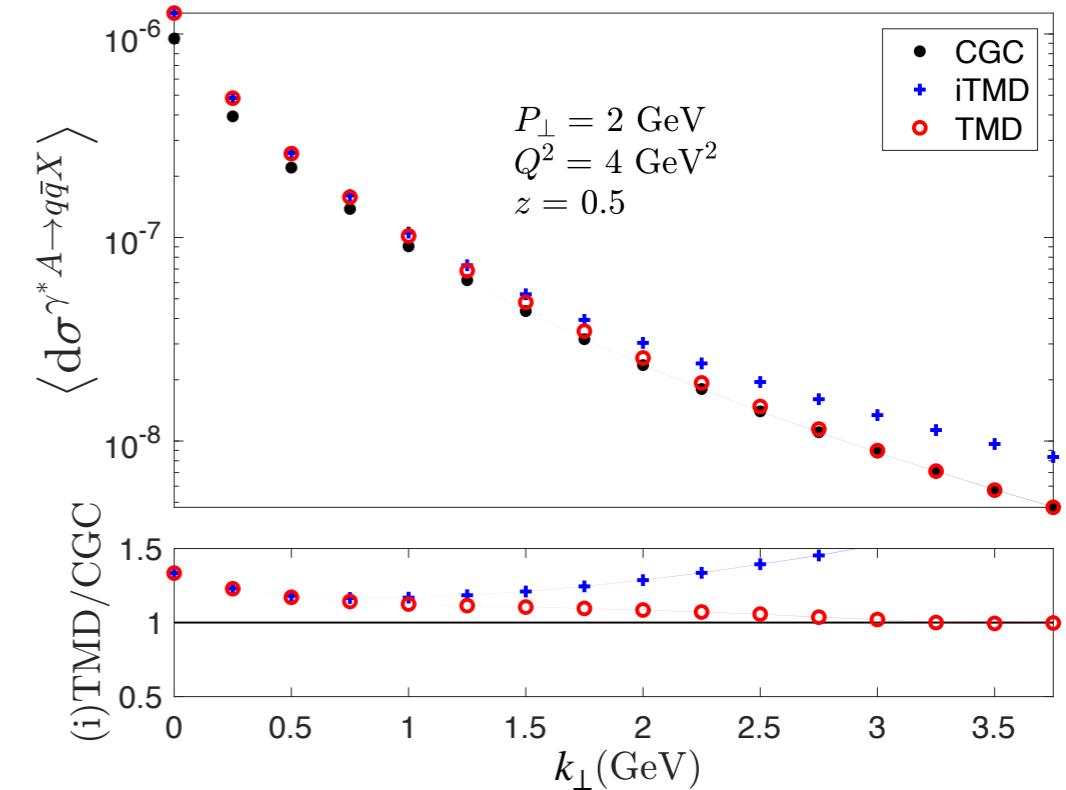
Matching CGC and (G)TMD framework to all orders

Includes higher genuine twists Q_s/P_\perp in the form of higher twist operators

Altinoluk, Boussarie, Kotko (2019)

Altinoluk, Boussarie (2019)

Comparison between CGC, iTMD and TMD for dipartion production in nuclear DIS



Mäntysaari, Mueller, FS, Schenke (2019)

Boussarie, Mäntysaari, FS, Schenke (in preparation)

Conclusions

- Measurement of dijets vs quarkonia pairs are complementary (access different GTMD)
- Jets at small- x have small p_{\perp} (difficult to reconstruct). Look at heavy quark pair instead?
- (G)TMDs can be computed from Wilson line correlators in the CGC (MV model, or color charge correlators)
- The CGC contains kinematic power corrections and genuine saturation corrections beyond the limits of validity of the TMD framework

Thanks!

