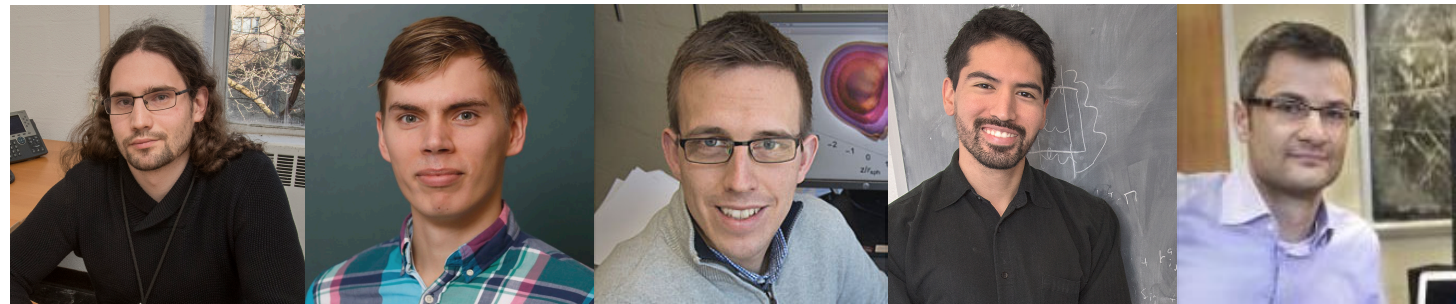


Small-x dijet/dihadron production beyond TMDs at the EIC

DIS 2021 @ Stony Brook
April 13th, 2021
Farid Salazar
faridsalazar03@gmail.com



H. Mäntysaari, N. Mueller, FS, B. Schenke. [1912.05586 \(PRL\)](#)

and work in progress with R. Boussarie, H. Mäntysaari, B. Schenke
[2104.XXXXX](#)



Outline

- Semi-inclusive observables at the EIC
Dihadron and dijet azimuthal correlations
- TMD factorization:
the WW gluon TMD
- CGC framework:
*from Wilson lines to TMDs and beyond
(kinematic vs genuine twists)*
- Numerical results:
*Where and what type of contributions beyond TMDs are
important for the EIC?*
- Summary and Outlook

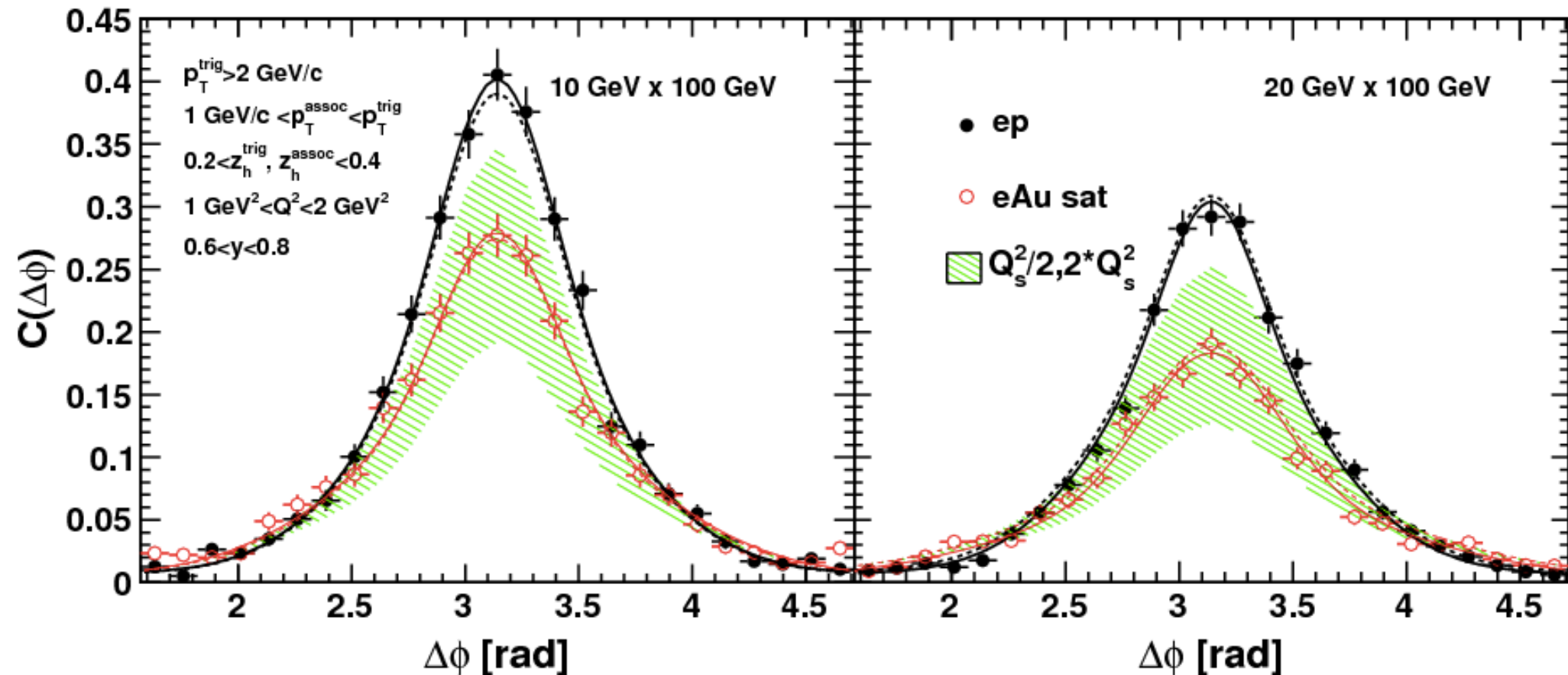
Dihadron and dijet studies at small-x

Forward dihadron azimuthal correlations and gluon saturation

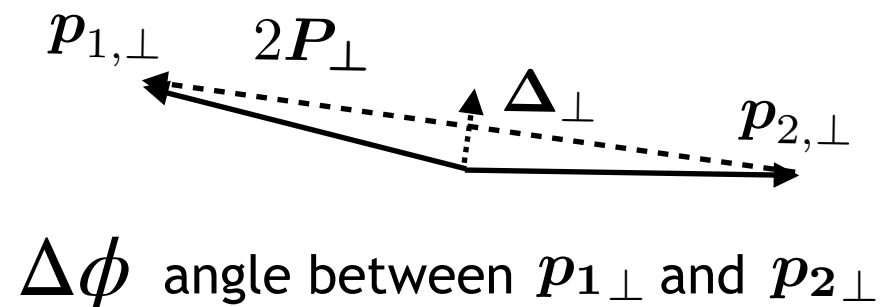
Gluon saturation



Dihadron suppression of back-to-back peak



Zheng, Aschenauer, Lee, Xiao. [1403.2413](#)



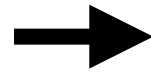
Typical momentum transfer from
hadron/nucleus to
 $\Delta_\perp \sim Q_s$

See also Xiaoxuan's talk tomorrow for dihadron correlations in pp and pA.

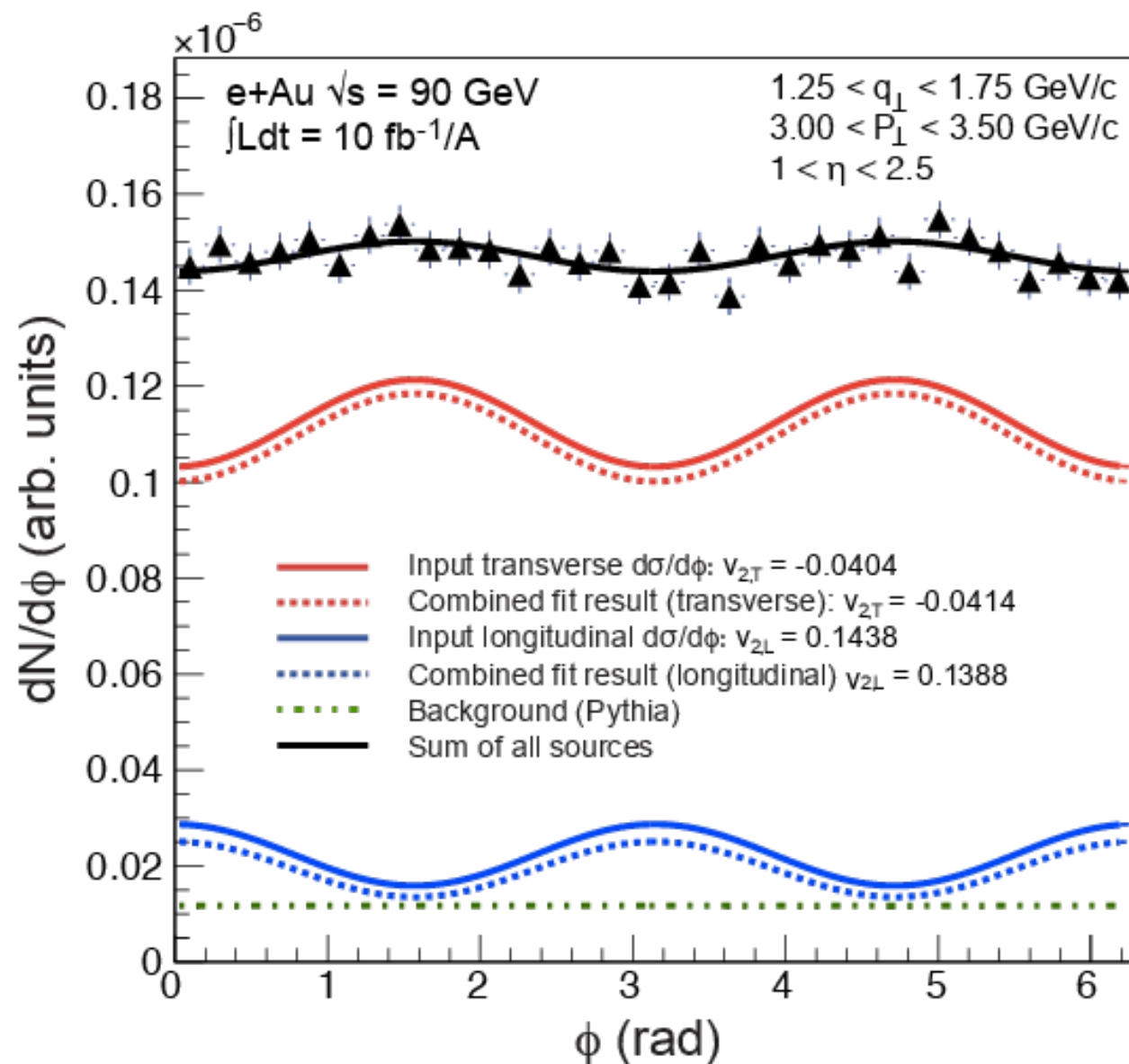
Dihadron and dijet studies at small-x

Forward dijet azimuthal asymmetries and WW gluon TMD

Dijet azimuthal asymmetries

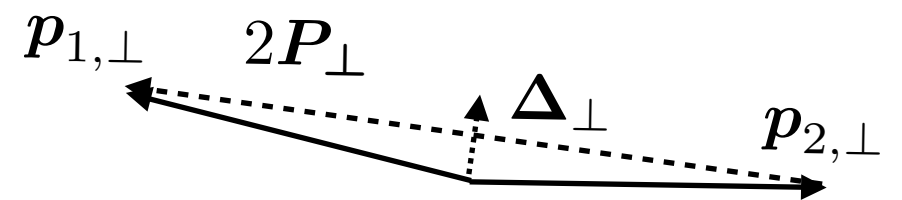


Weizsäcker-Williams gluon TMD (linearly polarized)



Dumitru, Skokov, Ullrich. [1809.02615](#)

Anisotropy in momentum imbalance



$\Delta\phi$ angle between $P_{\perp}$ and $\Delta_{\perp}$

$$\Delta_{\perp} = p_{1\perp} + p_{2\perp}$$

$$P_{\perp} = z_2 p_{1\perp} - z_1 p_{2\perp}$$

Azimuthal anisotropy is proportional to the ratio of linearly polarized to unpolarized WW gluon TMD

$$|v_2| \sim \frac{x h_{WW}}{x G_{WW}}$$

$$v_2 = \langle \cos(2\phi) \rangle$$

Beyond the TMD factorization

Previous studies:

Azimuthal correlations of back-to-back dijet/dihadron within the TMD factorization

Goal:

Assess the role of kinematic power corrections and genuine saturation.
How large are these corrections?

Observables:

Inclusive dijet/dihadron production for both e-p and e-Au (at EIC)

Study cross-section (including azimuthal anisotropies)
at and beyond the back-to-back limit

Approach:

CGC computation (Gaussian quadrupole + rcBK evolution).
Compare to TMD and iTMD framework

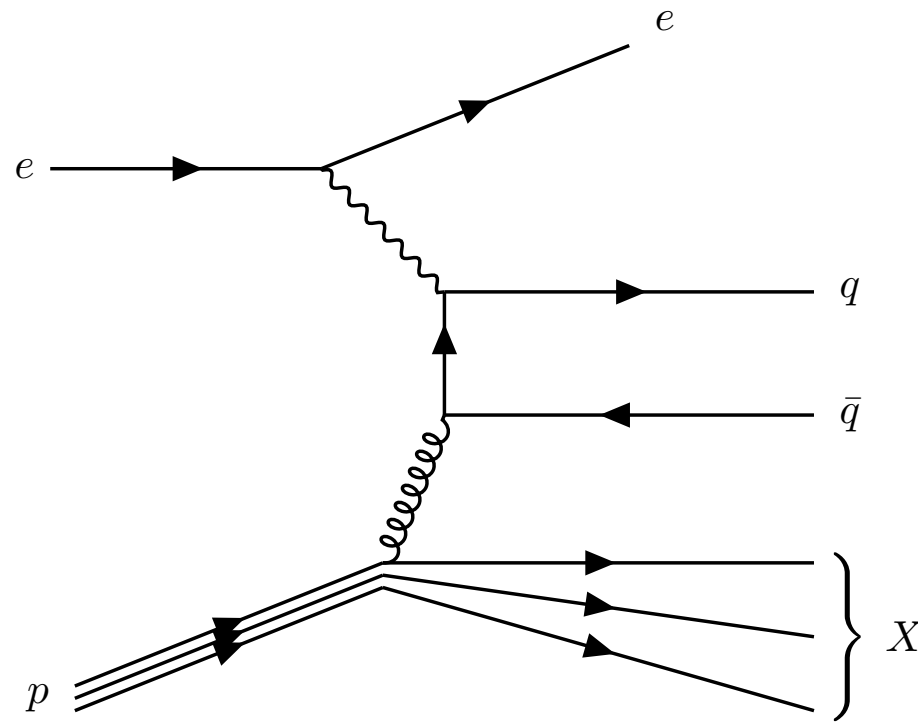
TMD factorization

$q\bar{q}$ production in DIS and Weizsäcker-Williams gluon TMD

Bomhof, Mulders, Pijlman 0601171

Dominguez, Marquet, Xiao, Yuan 1101.0715

Dominguez, Qiu, Xiao, Yuan. 1109.6293



LO diagram for $q\bar{q}$ production in pQCD

$$d\sigma^{\gamma^* A \rightarrow q\bar{q}} \sim \mathcal{H}_{\text{TMD}}^{ij}(\mathbf{P}_\perp) \alpha_s x G_{\text{WW}}^{ij}(\Delta_\perp, x)$$

Perturbatively
calculable

WW gluon TMD

Unpolarized part

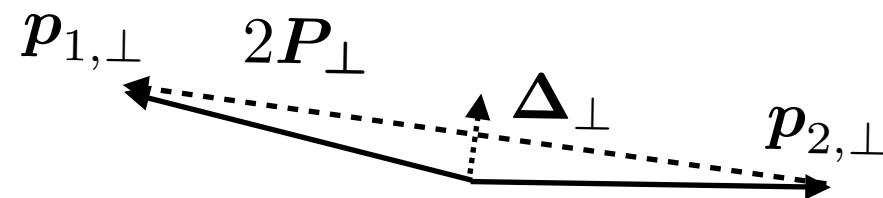
$$xG_{\text{WW}}(\Delta_\perp, x) = \delta^{ij} xG_{\text{WW}}^{ij}(\Delta_\perp, x)$$

Linearly polarized part

$$xh_{\text{WW}}(\Delta_\perp, x) = \left(2 \frac{\Delta_\perp^i \Delta_\perp^j}{\Delta_\perp^2} - \delta^{ij} \right) xG_{\text{WW}}^{ij}(\Delta_\perp, x)$$

Validity of TMD approach:

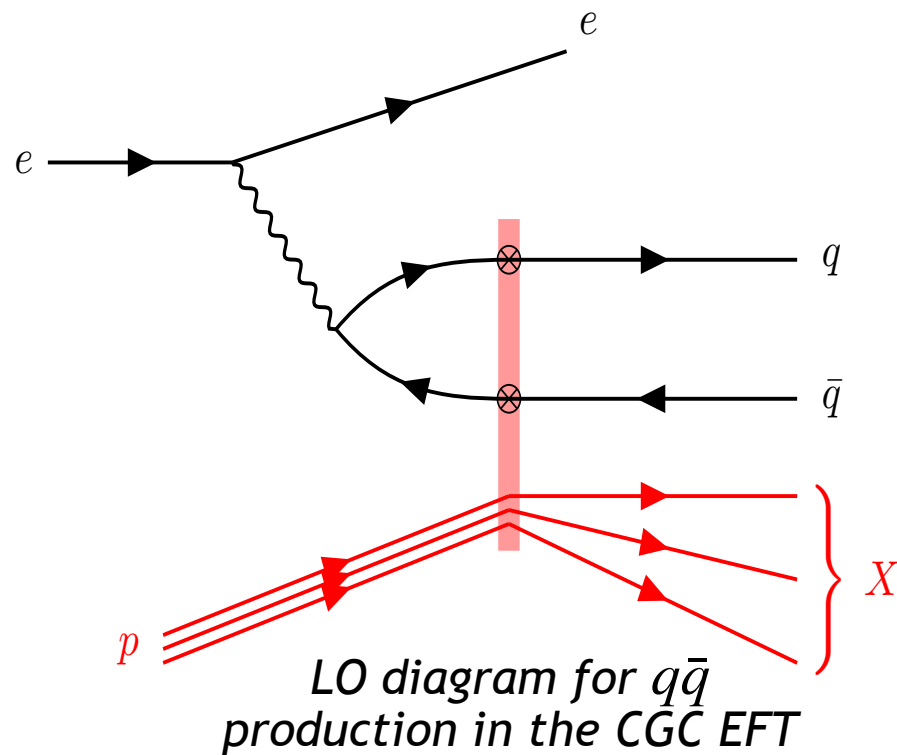
$$\Delta_\perp \ll P_\perp \quad (\text{i.e. back-to-back configuration})$$



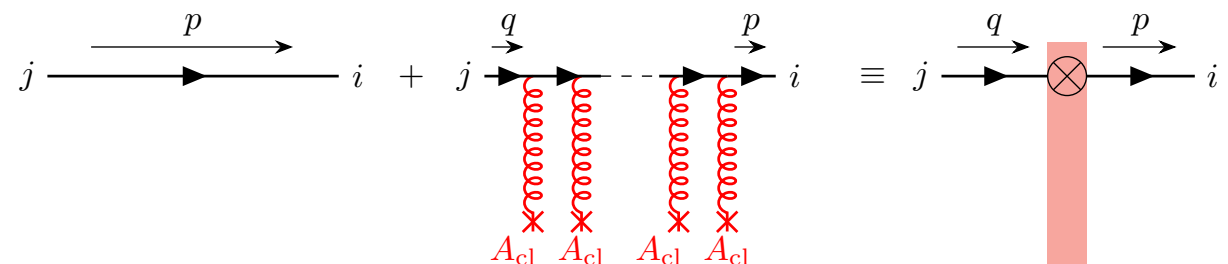
$$|v_2| \sim \frac{xh_{\text{WW}}}{xG_{\text{WW}}} \quad \text{in the angle } \phi \equiv \phi_{\Delta_\perp} - \phi_{P_\perp}$$

CGC framework: high energy correlators

$q\bar{q}$ production in DIS and quadrupole Wilson line correlator



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



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

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

Dijet cross-section in the CGC:

$$d\sigma^{\gamma^* A \rightarrow q\bar{q}X} \sim \int_{l_{\perp}, l'_{\perp}} \Psi^{\gamma^* \rightarrow q\bar{q}}(P_{\perp} - l_{\perp}) \Psi^{\gamma^* \rightarrow q\bar{q}}(P_{\perp} - l'_{\perp}) \tilde{\Xi}_Y(\Delta_{\perp}, l_{\perp}, l'_{\perp})$$

$$\tilde{\Xi}_Y(\Delta_{\perp}, l_{\perp}, l'_{\perp})$$

Color structure containing **dipole** and **quadrupole** operators.

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

For bridging the gap between large x and low x see also **Jamal's talk** in the afternoon.

For non-eikonal corrections see **Guillaume's talk** in the afternoon.

TMD, improved TMD and CGC

The TMD and improved TMD limit as an expansion

Dominguez, Marquet, Xiao, Yuan. [1101.0715](#)

Dumitru, Lappi, Skokov. [1508.04438](#)

$$d\sigma^{\gamma^* A \rightarrow q\bar{q}} \sim \mathcal{H}_{\text{TMD}}^{ij}(\mathbf{P}_\perp) \alpha_s x G_{\text{WW}}^{ij}(\Delta_\perp, x) + \mathcal{O}(\Delta_\perp/P_\perp) + \mathcal{O}(Q_s/P_\perp)$$

Hard factor

Weizsäcker-Williams gluon TMD

Kotko et al. [1503.03421](#)

Altinoluk, Marquet, Tael. [2103.14495](#)

Altinoluk, Boussarie, Kotko. [1901.01175](#)

$$d\sigma^{\gamma^* A \rightarrow q\bar{q}} \sim \mathcal{H}_{\text{iTMD}}^{ij}(\mathbf{P}_\perp, \Delta_\perp) \alpha_s x G_{\text{WW}}^{ij}(\Delta_\perp, x) + \mathcal{O}(Q_s/P_\perp)$$

Hard factor resums
kinematic powers $\Delta_\perp/P_\perp$

Genuine higher twist
contributions

Weizsäcker-Williams gluon TMD

Important for nuclei
(EIC)?

$$\alpha_s x G_{\text{WW}}^{ij}(\Delta_\perp, x) \sim \int_{\mathbf{b}_\perp, \bar{\mathbf{b}}_\perp} e^{-i\Delta_\perp \cdot (\mathbf{b}_\perp - \bar{\mathbf{b}}_\perp)} \left\langle \text{Tr}(V_{\mathbf{b}_\perp} \partial^i V_{\mathbf{b}_\perp}^\dagger V_{\bar{\mathbf{b}}_\perp} \partial^j V_{\bar{\mathbf{b}}_\perp}^\dagger) \right\rangle_Y$$

Can be computed from Wilson lines!

H. Mäntysaari, N. Mueller, FS, B. Schenke. [1912.05586](#) (PRL)

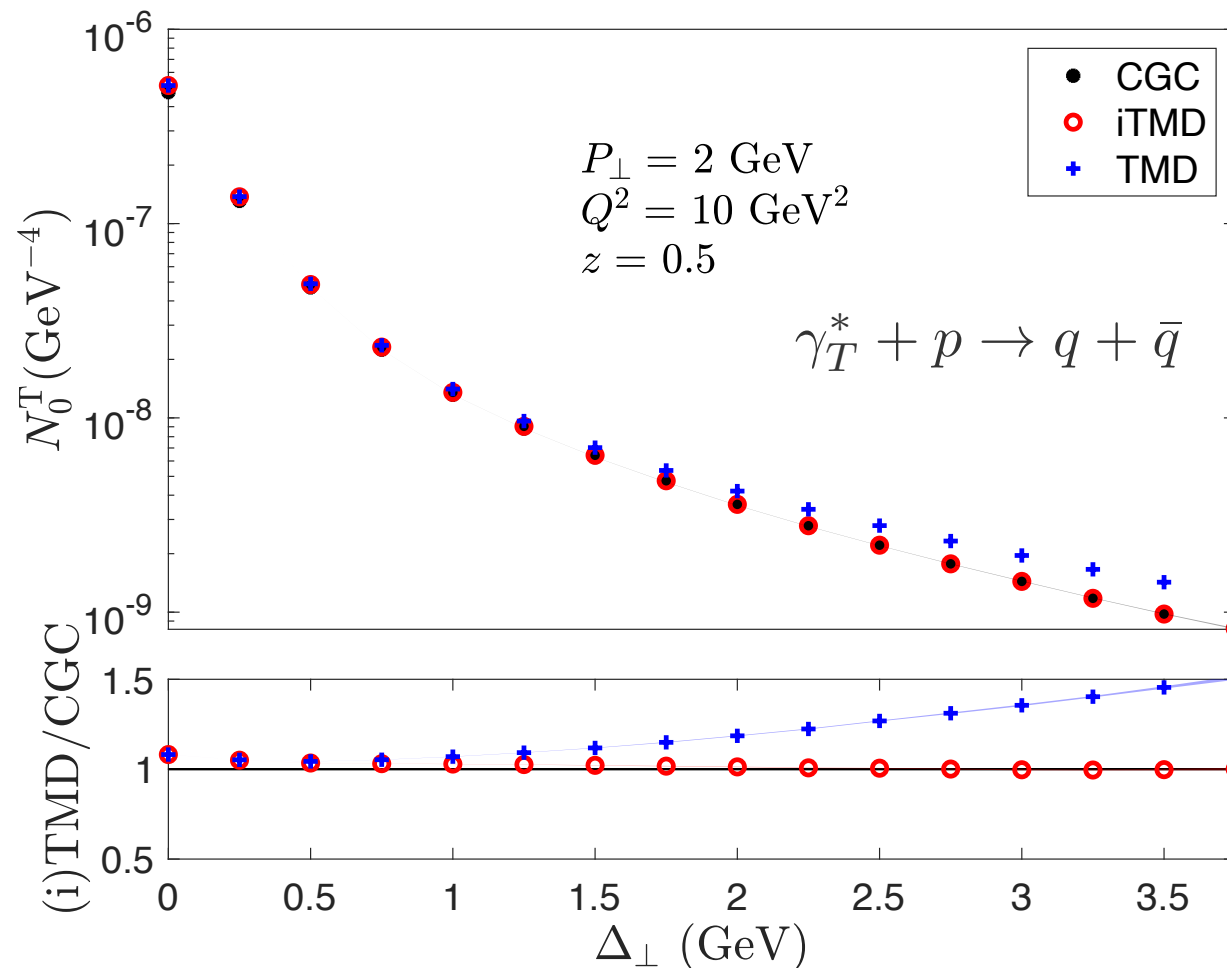
Boussarie, Mäntysaari, FS, Schenke. [2104.XXXX](#)

Numerical results

Differential yield (transverse virtual photon pol)

$$N_0^T \equiv \int_0^{2\pi} d\phi \mathbf{P}_\perp \Delta_\perp \frac{1}{S_\perp} \frac{d\sigma^{\gamma_T^* + A \rightarrow q\bar{q} + X}}{dy_1 dy_2 d^2\mathbf{P}_\perp d^2\Delta_\perp}$$

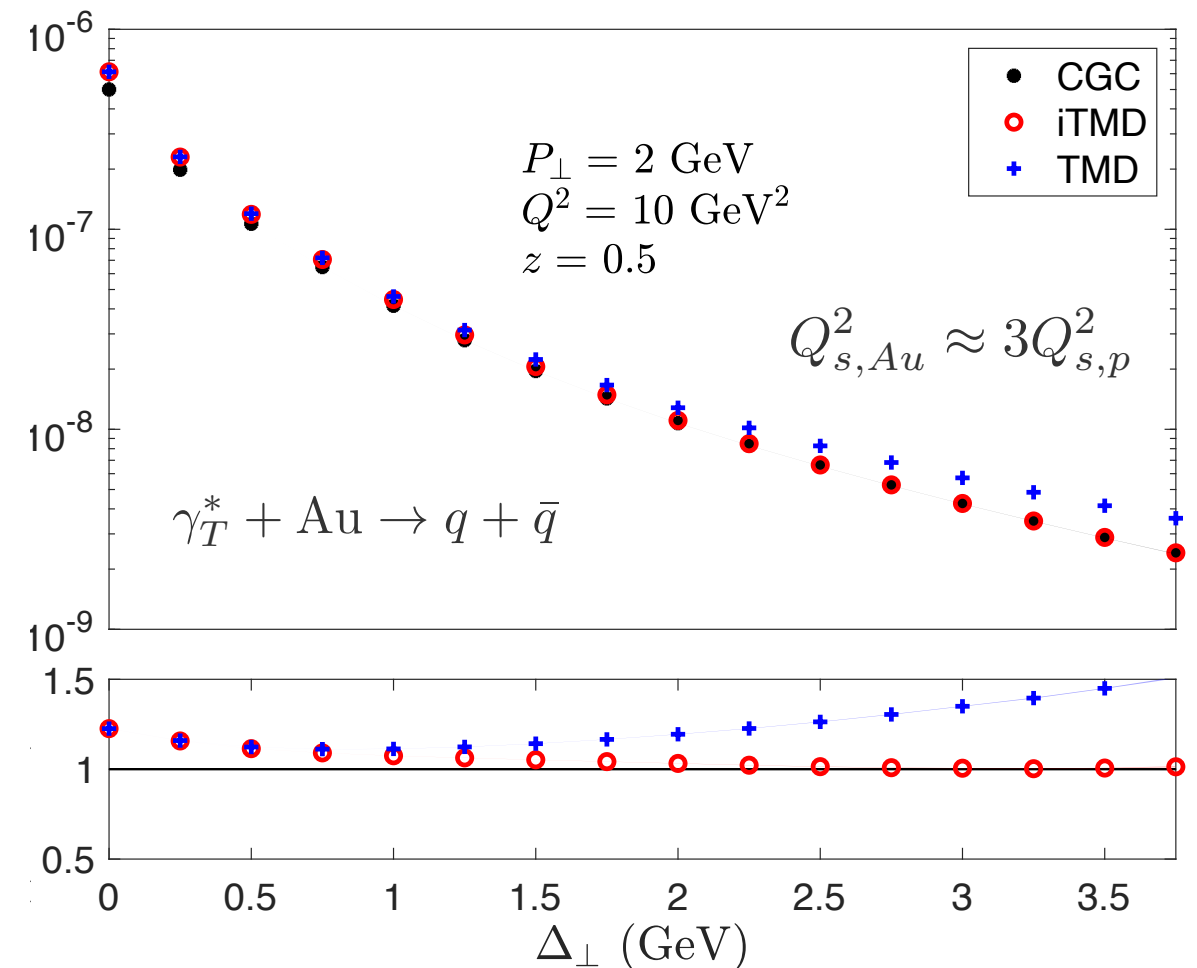
H. Mäntysaari, N. Mueller, FS, B. Schenke. 1912.05586
and work in progress with Boussarie, Mäntysaari, Schenke



proton ~ smaller Q_s^2

TMD framework provides good agreement
for back-to-back jets $\Delta_\perp \lesssim P_\perp$

Improved TMD framework provides
excellent agreement with CGC



Gold nucleus ~ larger Q_s^2

Improved TMD framework shows
significant deviations at low $\Delta_\perp$
Genuine higher twist contributions

Impact on back-to-back dihadrons in
e-Au collisions

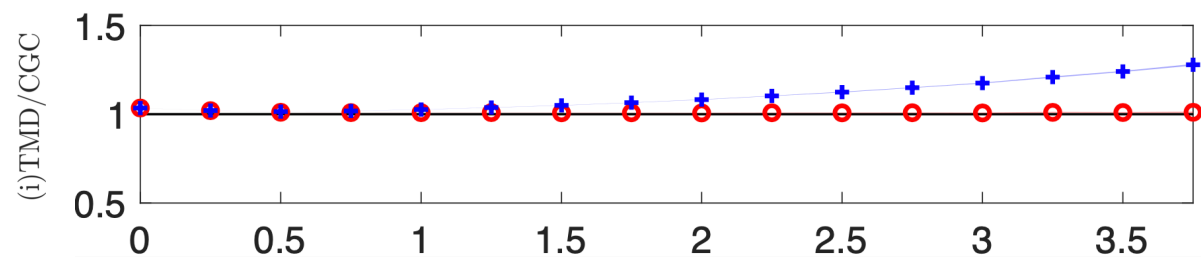
Numerical results

Accessing genuine twists with Q^2 dependence

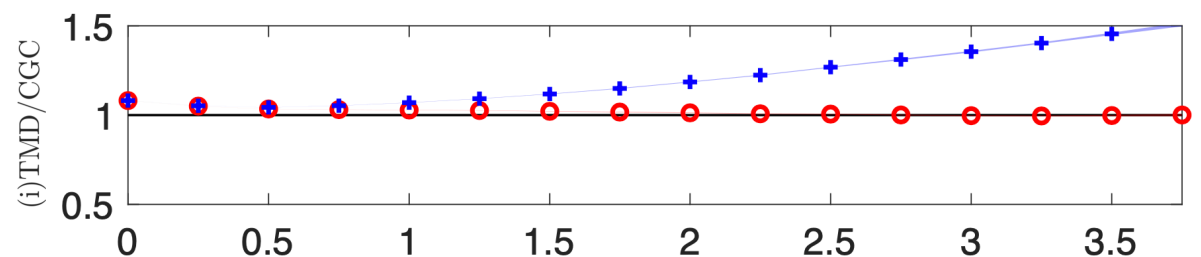
$$\gamma_T^* + p \rightarrow q + \bar{q}$$

$$\gamma_T^* + \text{Au} \rightarrow q + \bar{q}$$

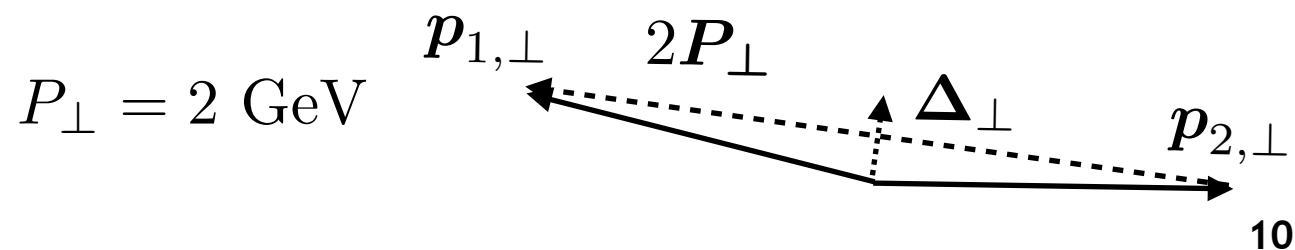
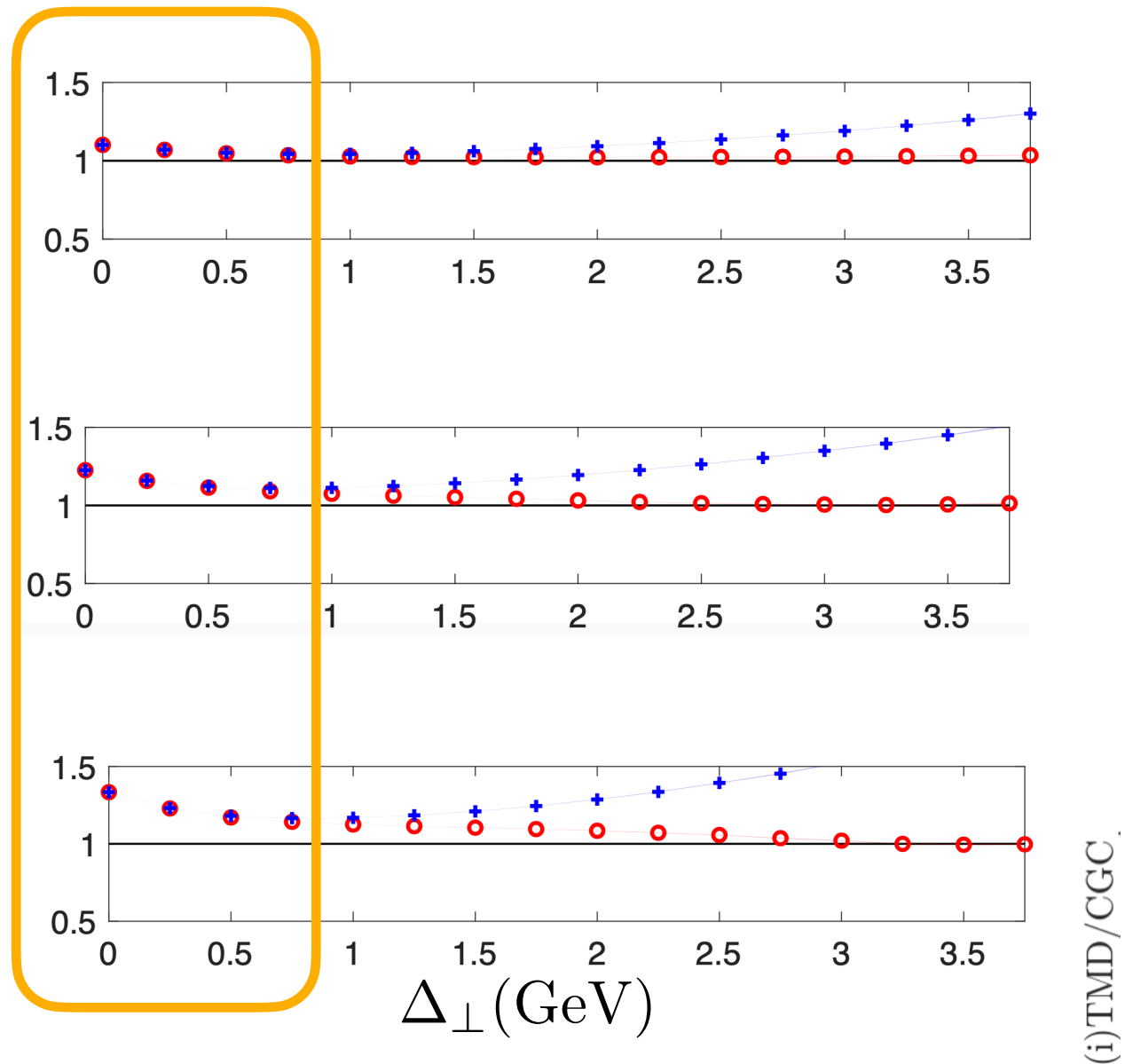
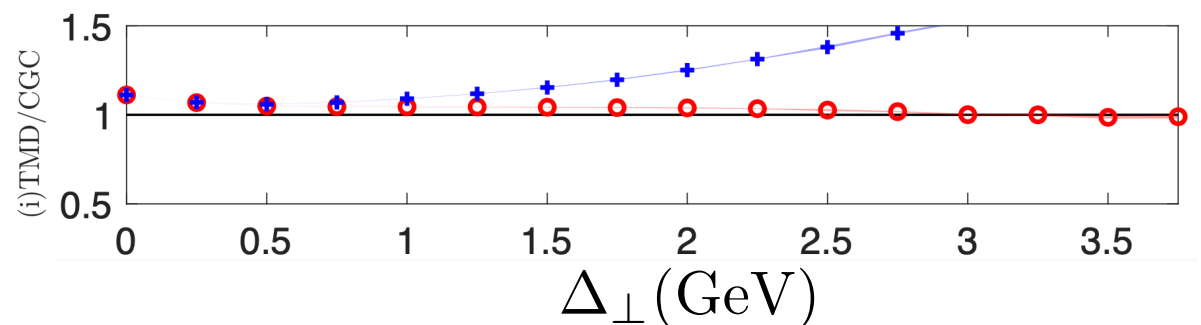
$$Q^2 = 25 \text{ GeV}^2$$



$$Q^2 = 10 \text{ GeV}^2$$



$$Q^2 = 4 \text{ GeV}^2$$



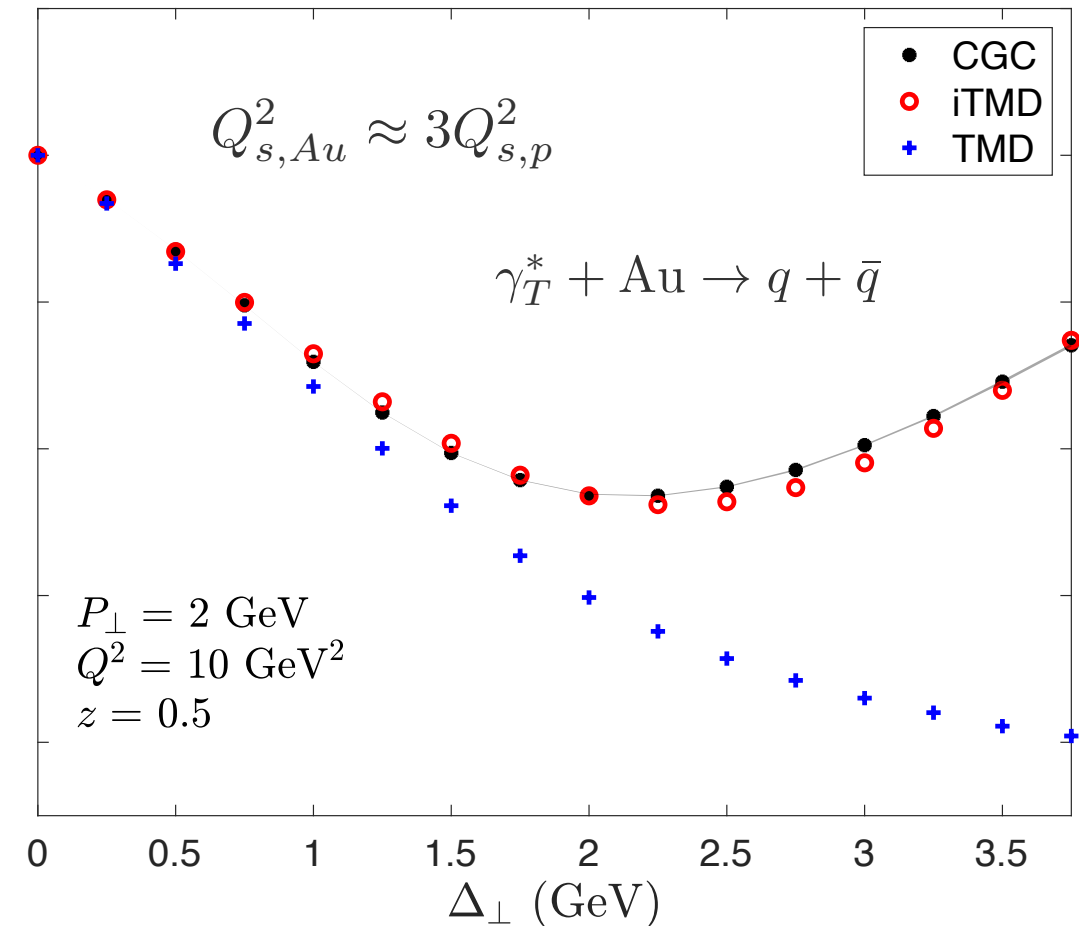
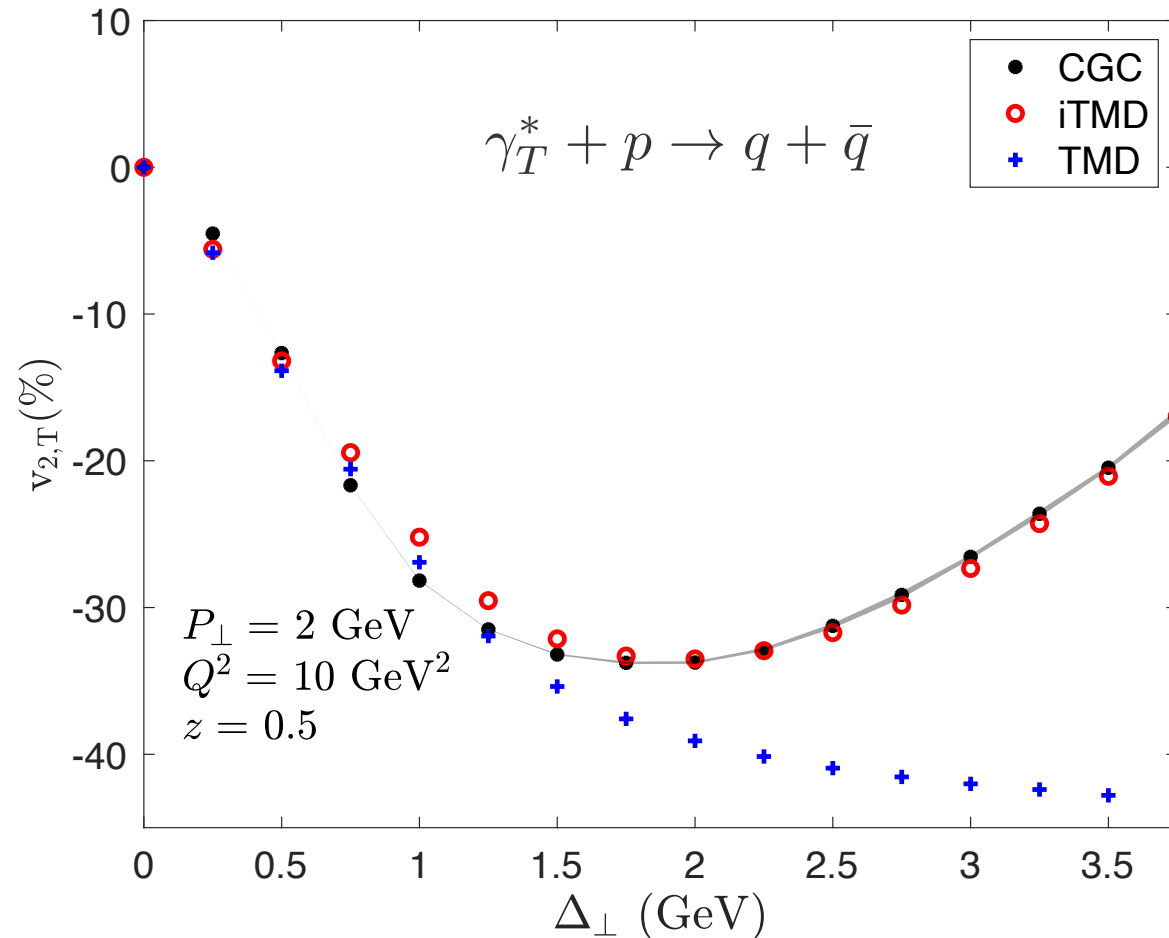
Genuine higher twist contributions grow at low Q^2

Numerical results

Elliptic anisotropy (transverse virtual photon pol)

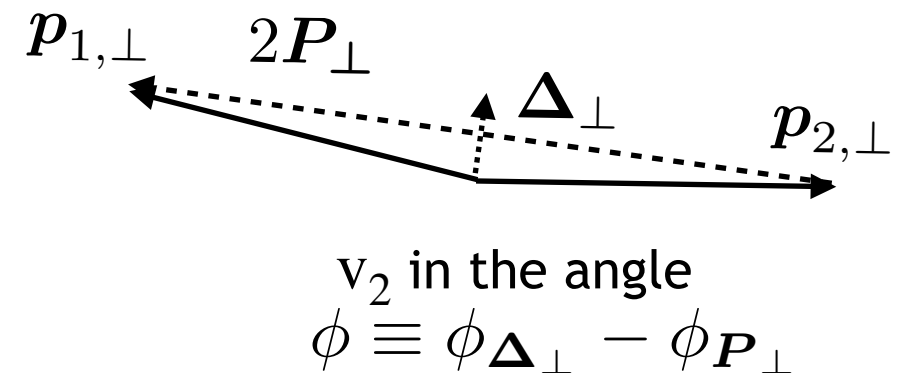
$$v_{2,T} \equiv \frac{1}{N_0} \int_0^{2\pi} d\phi_{\mathbf{P}_\perp \Delta_\perp} \cos(2\phi_{\mathbf{P}_\perp \Delta_\perp}) \frac{1}{S_\perp} \frac{d\sigma^{\gamma_T^* + A \rightarrow q\bar{q} + X}}{dy_1 dy_2 d^2\mathbf{P}_\perp d^2\Delta_\perp}$$

H. Mäntysaari, N. Mueller, FS. B. Schenke. 1912.05586
and work in progress with Boussarie, Mäntysaari, Schenke



iTMD improves agreement with CGC
computation of v_2

Kinematic power corrections contribute to
 v_2 and might be necessary for the proper
extraction of linearly polarized TMD

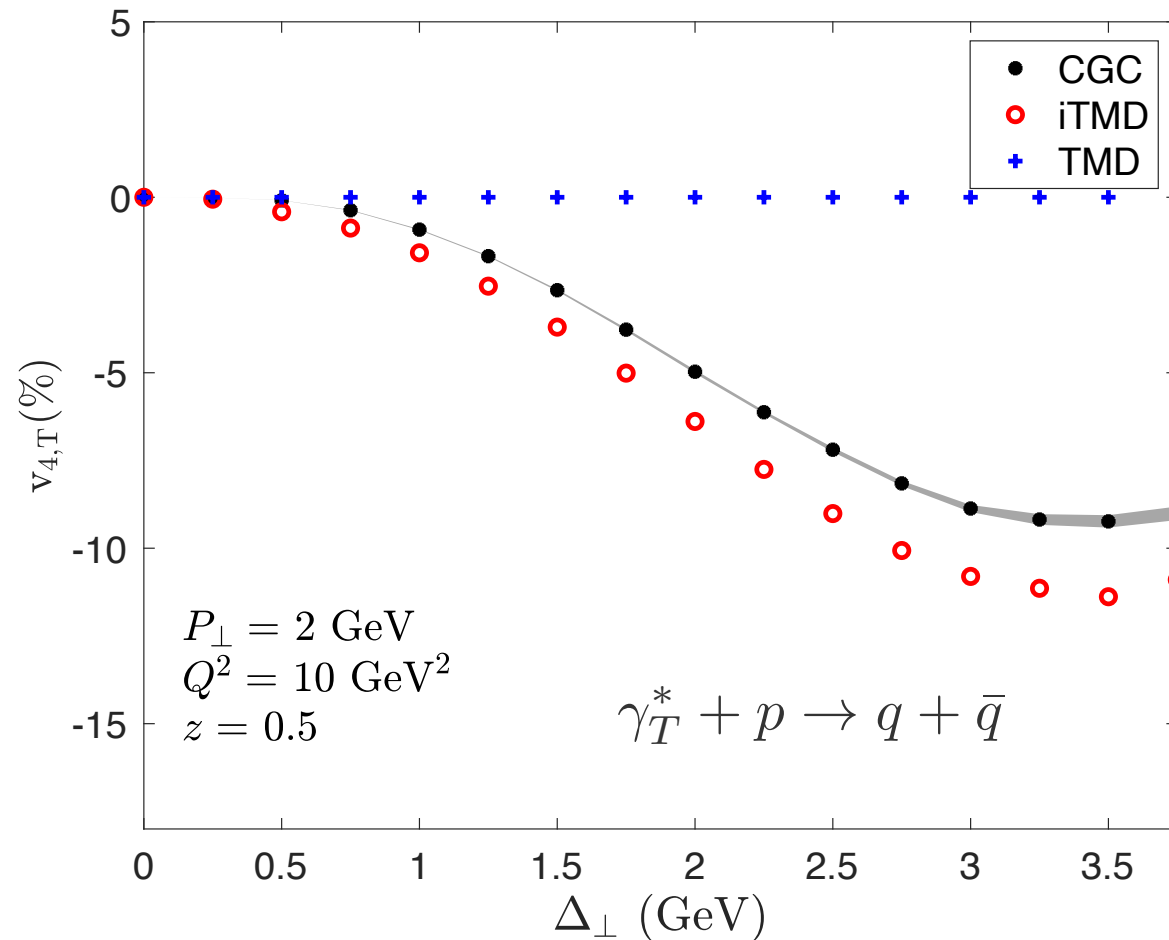


Numerical results

Quadrangular anisotropy (transverse virtual photon pol)

$$v_{4,T} \equiv \frac{1}{N_0} \int_0^{2\pi} d\phi_{\mathbf{P}_\perp \mathbf{\Delta}_\perp} \cos(4\phi_{\mathbf{P}_\perp \mathbf{\Delta}_\perp}) \frac{1}{S_\perp} \frac{d\sigma^{\gamma_T^* + A \rightarrow q\bar{q} + X}}{dy_1 dy_2 d^2\mathbf{P}_\perp d^2\mathbf{\Delta}_\perp}$$

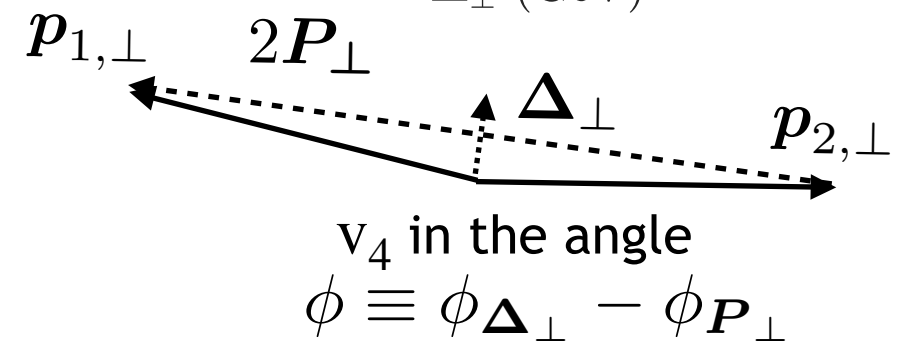
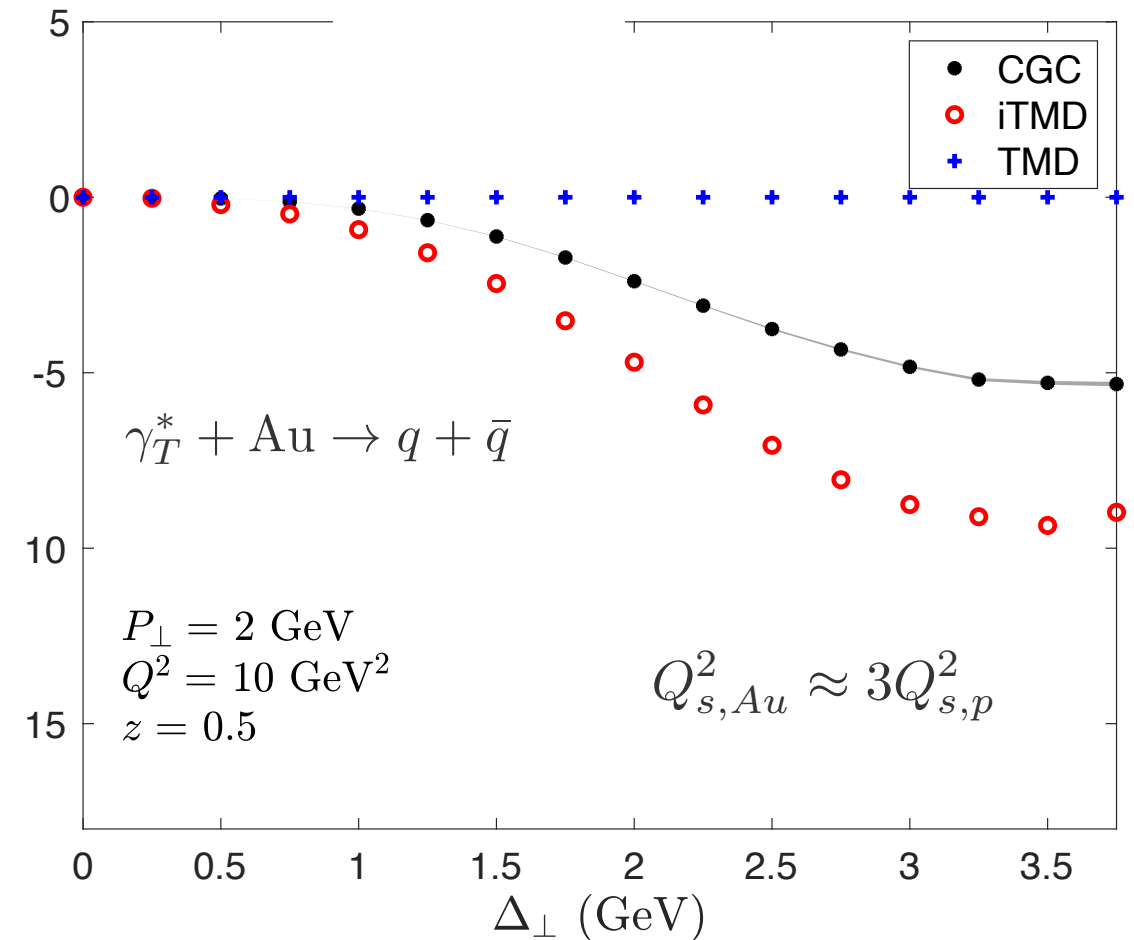
H. Mäntysaari, N. Mueller, FS, B. Schenke. 1912.05586
and work in progress with Boussarie, Mäntysaari, Schenke



TMD framework: $v_4 \equiv 0$

Kinematic corrections in the iTMD
induce v_4

**Genuine twists lead to a reduction in
 v_4 (more strongly for e-Au)**



See also Dumitru, Skokov. 1605.02739

Summary

- In proton- γ^* collisions: improved TMD framework is sufficient for wide range of kinematics. Only WW gluon TMD (G_{WW}^{ij}) is necessary.

Suitable form for coupling to event generator.

See also Piotr's talk right after this one.

- Azimuthal anisotropies in $\phi_{P\Delta}$ have contributions both from linearly polarized gluon TMD (h_{WW}) and from kinematic corrections.

Need kinematic correction to properly extract h_{WW} .

- In Au- γ^* collisions: genuine twists (beyond WW TMD) might be important and could be accessed in back-to-back measurements.

Genuine twists more important at low Q^2 and $P_\perp$

Outlook

- **From partons to hadrons/jets**

MC sampler of partonic cross-section
Fragmentation/hadronization
Jet reconstruction

Within the TMD factorization:

Dumitru, Skokov, Ullrich. [1809.02615](#)

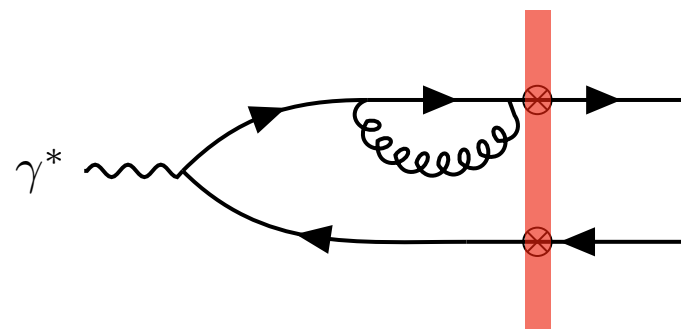
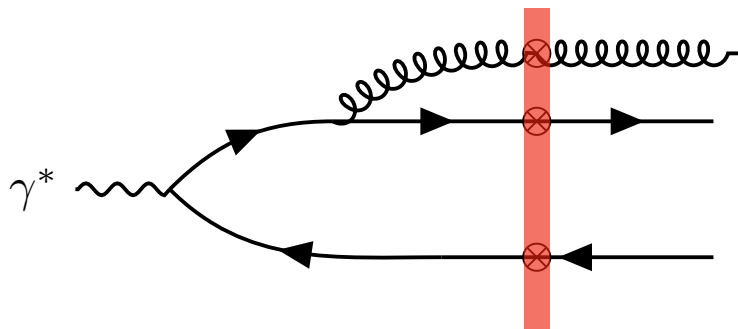
Zheng, Aschenauer, Lee, Xiao. [1403.2413](#)

- **Include NLO contributions**

Sudakov and soft gluon resummation
Mueller, Xiao, Yuan. [1308.2993](#), [2010.10744](#)

Impact factor
Roy, Venugopalan. (for dijet+photon) [1911.04530](#)
Iancu, Mulian. (dijet in pA) [2009.11930](#)

Small-x JIMWLK at NLO
Balitsky, Chirlli. [1309.7644](#)
Kovner, Lublinsky, Mulian. [1310.0378](#)



**NLO corrections to dihadron/
dijet in the CGC coming soon!**
(in progress with Caucal and
Venugopalan)