Small-x dijet/dihadron production beyond TMDs and progress towards NLO

QCD Evolution @ UCLA
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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. 2105.XXXXX

P. Caucal, FS, R. Venugopalan 210?.XXXXX

Outline

- Semi-inclusive observables at the EIC
  Dihadron and dijet azimuthal correlations

- TMD vs CGC framework:
  the WW gluon TMD
  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?

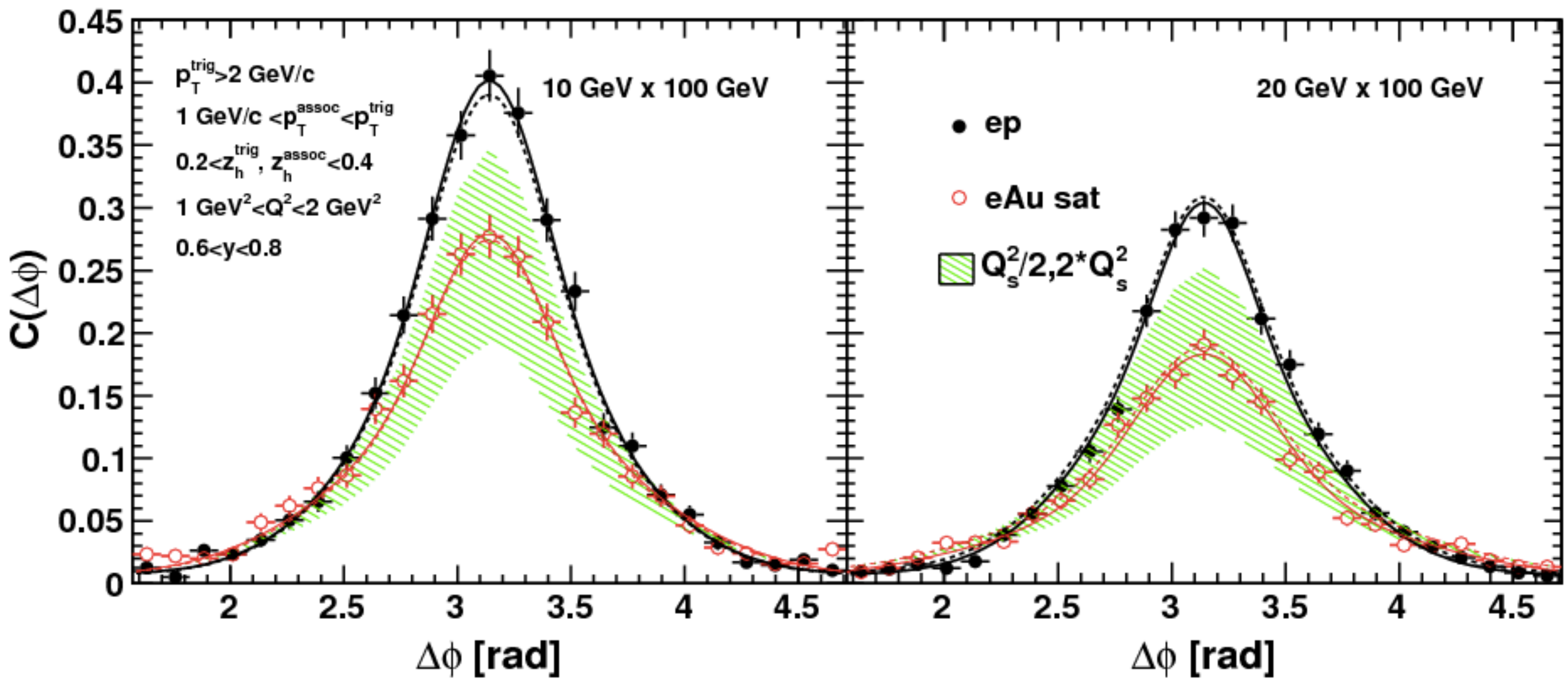
- *Towards full NLO computation in the CGC*:
  Cancellation of divergences at one loop, small-x factorization, and impact factor

- Summary and Outlook

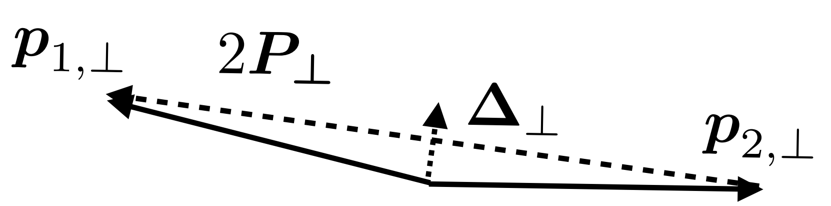
Dihadron and dijet studies at small-x

Forward dihadron azimuthal correlations and gluon saturation

Gluon saturation → Dihadron suppression of back-to-back peak



Zheng, Aschenauer, Lee, Xiao. 1403.2413



$\Delta\phi$ angle between $p_{1\perp}$ and $p_{2\perp}$

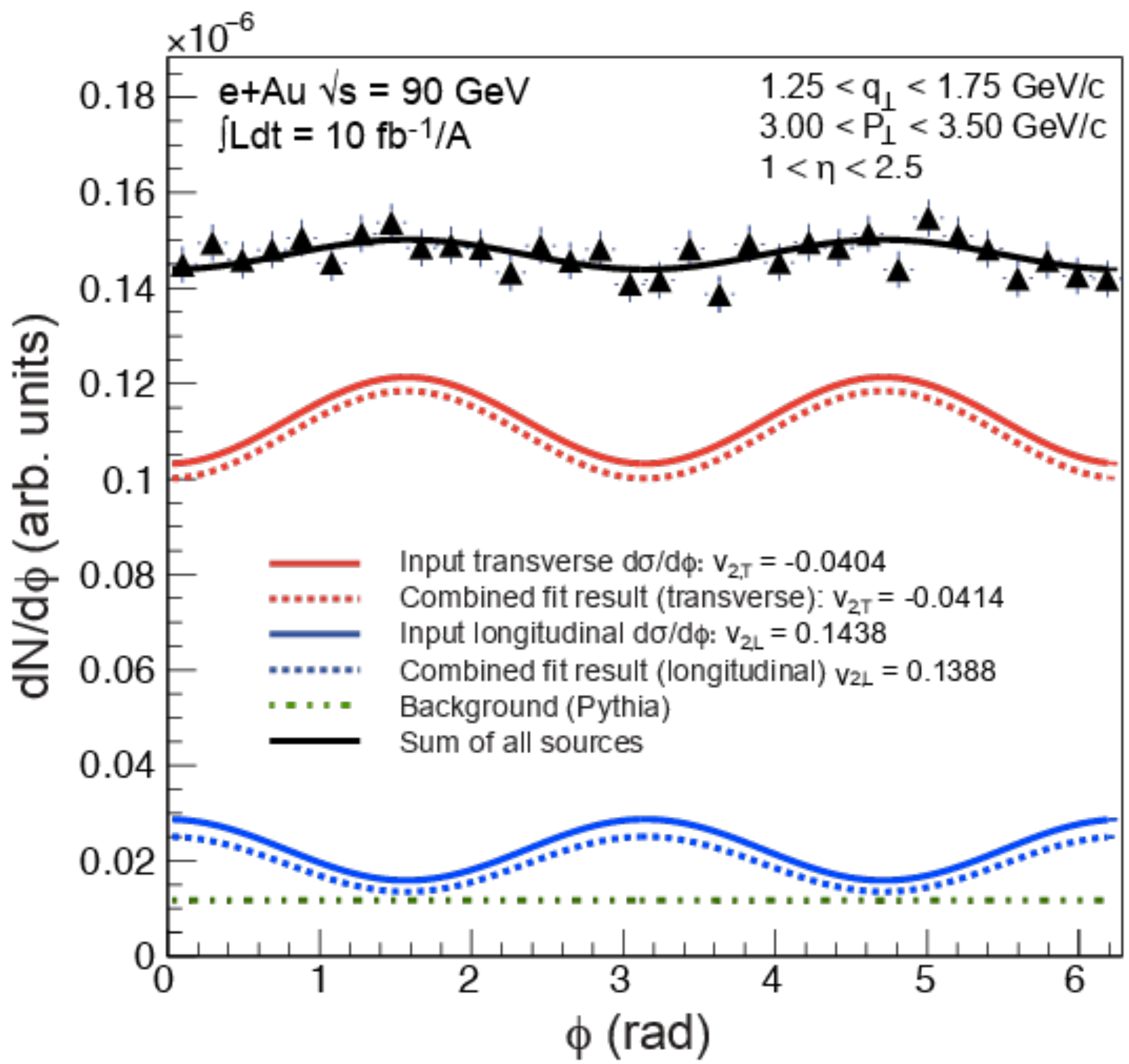
Typical momentum transfer from hadron/nucleus to

$$\Delta_\perp \sim Q_s$$

Dihadron and dijet studies at small-x

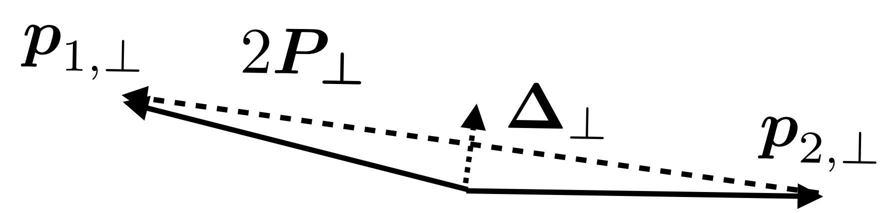
Forward dijet azimuthal asymmetries and WW gluon TMD

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

$$|\mathrm{v}_2| \sim \frac{x h_{\mathrm{WW}}}{x G_{\mathrm{WW}}}$$

$$\mathrm{v}_2 = \langle \cos(2\phi) \rangle$$

Beyond the TMD factorization

Previous studies:

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

Goal:

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

Observables:

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

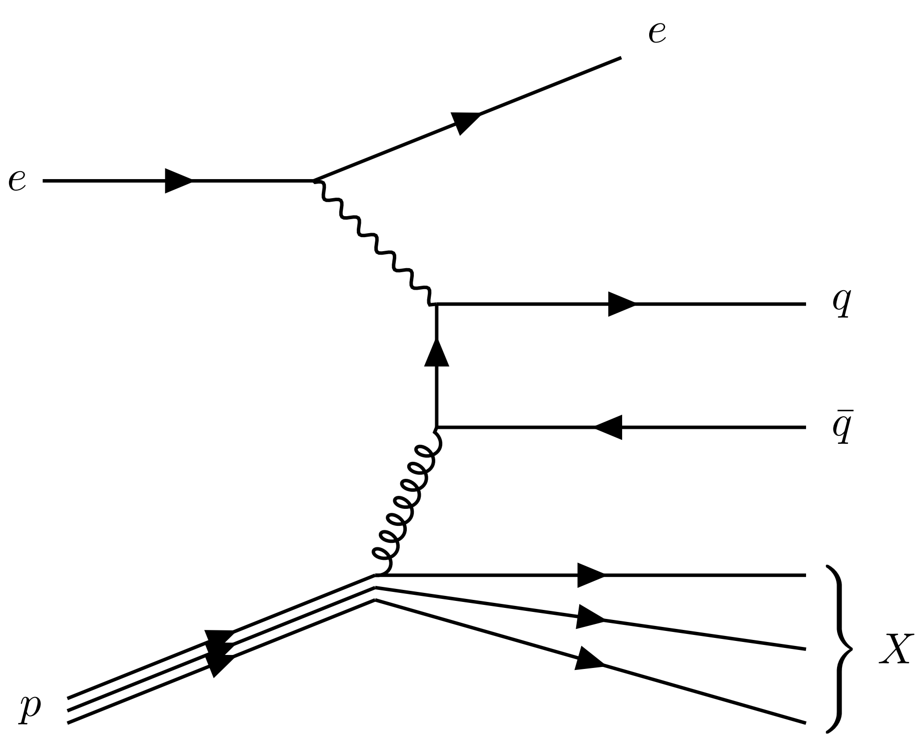
Study cross-section (including azimuthal anisotropies)
<u>at and beyond the back-to-back limit</u>

Approach:

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

TMD factorization

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



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

Bomhof, Mulders, Pijlman 0601171
Dominguez, Marquet, Xiao, Yuan 1101.0715
Dominguez, Qiu, Xiao, Yuan. 1109.6293

$$d\sigma^{\gamma^* A \to q\bar{q}} \sim \mathcal{H}^{ij}_{\mathrm{TMD}}(\boldsymbol{P}_\perp) \; \alpha_s x G^{ij}_{\mathrm{WW}}(\boldsymbol{\Delta}_\perp, x)$$

Perturbatively calculable

WW gluon TMD

Unpolarized part

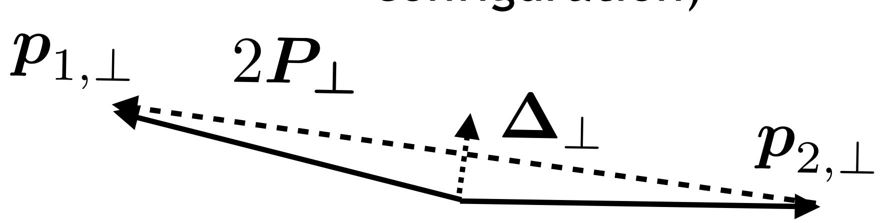
$$xG_{WW}(\boldsymbol{\Delta}_\perp, x) = \delta^{ij} x G^{ij}_{\mathrm{WW}}(\boldsymbol{\Delta}_\perp, x)$$

Linearly polarized part

$$xh_{WW}(\boldsymbol{\Delta}_\perp, x) = \left(2\frac{\boldsymbol{\Delta}^i_\perp \boldsymbol{\Delta}^j_\perp}{\boldsymbol{\Delta}^2_\perp} - \delta^{ij}\right) x G^{ij}_{\mathrm{WW}}(\boldsymbol{\Delta}_\perp, x)$$

Validity of TMD approach:

$\Delta_\perp \ll P_\perp$ (i.e. back-to-back configuration)

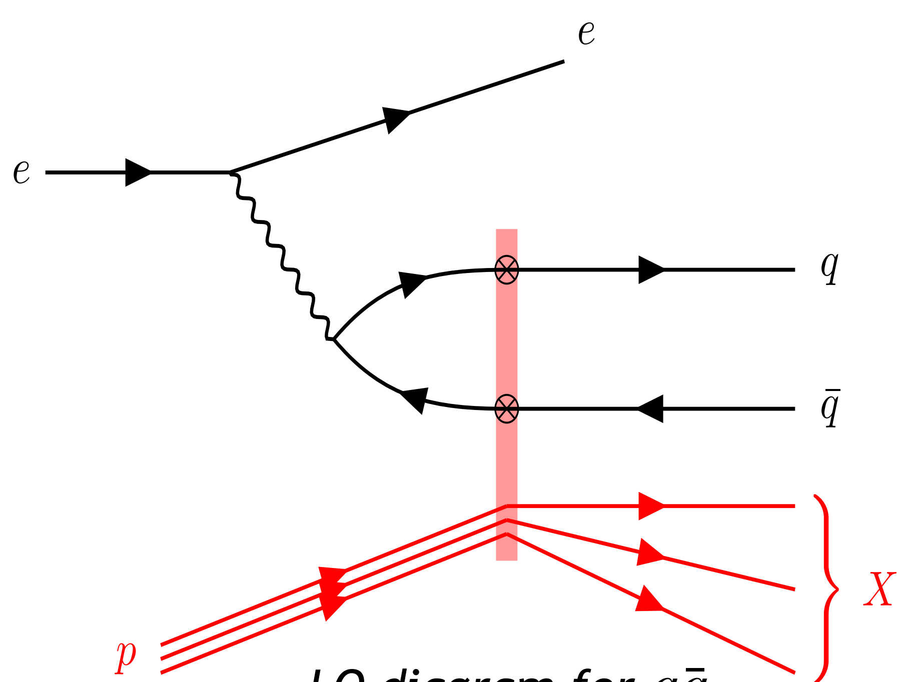


$$|\mathrm{v}_2| \sim \frac{xh_{\mathrm{WW}}}{xG_{\mathrm{WW}}}$$

in the angle $\phi \equiv \phi_{\boldsymbol{\Delta}_\perp} - \phi_{\boldsymbol{P}_\perp}$

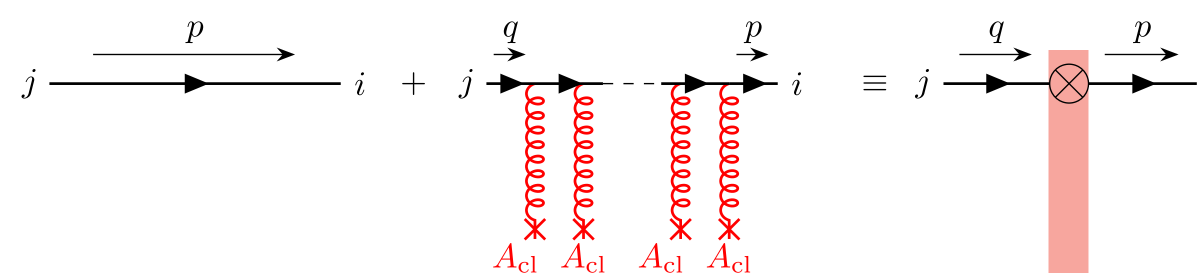
CGC framework: high energy correlators

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



LO diagram for $q\bar{q}$ production in the CGC EFT

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



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

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

Dijet cross-section in the CGC:

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

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

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

$$\frac{1}{N_c} \left\langle \mathrm{Tr}(V_{\boldsymbol{x}_{1\perp}} V^\dagger_{\boldsymbol{x}_{2\perp}}) \right\rangle_Y \qquad \frac{1}{N_c} \left\langle \mathrm{Tr}(V_{\boldsymbol{x}_{1\perp}} V^\dagger_{\boldsymbol{x}_{2\perp}} V_{\bar{\boldsymbol{x}}_{2\perp}} V^\dagger_{\bar{\boldsymbol{x}}_{1\perp}}) \right\rangle_Y$$

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

$$d\sigma^{\gamma^* A \to q\bar{q}} \sim \mathcal{H}^{ij}_{\mathrm{TMD}}(\boldsymbol{P}_\perp)\, \alpha_s x G^{ij}_{\mathrm{WW}}(\boldsymbol{\Delta}_\perp, x) + \mathcal{O}(\Delta_\perp/P_\perp) + \mathcal{O}(Q_s/P_\perp)$$

Hard factor

Weizsäcker-Williams gluon TMD

See also **Krysztof's talk** on ITMDs before this talk!

Kotko, Kutak, Marquet, Petreska, Sapeta, van Hameren. 1503.03421

Altinoluk, Boussarie, Kotko. 1901.01175

Altinoluk, Marquet, Taels. 2103.14495

$$d\sigma^{\gamma^* A \to q\bar{q}} \sim \mathcal{H}^{ij}_{\mathrm{iTMD}}(\boldsymbol{P}_\perp, \boldsymbol{\Delta}_\perp)\, \alpha_s x G^{ij}_{\mathrm{WW}}(\boldsymbol{\Delta}_\perp, x) + \mathcal{O}(Q_s/P_\perp)$$

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

Genuine higher twist contributions

Important for nuclei (EIC)?

Weizsäcker-Williams gluon TMD

$$\alpha_s x G^{ij}_{\mathrm{WW}}(\boldsymbol{\Delta}_\perp, x) \sim \int_{\boldsymbol{b}_\perp, \bar{\boldsymbol{b}}_\perp} e^{-i\boldsymbol{\Delta}_\perp \cdot (\boldsymbol{b}_\perp - \bar{\boldsymbol{b}}_\perp)} \left\langle \mathrm{Tr}(V_{\boldsymbol{b}_\perp} \partial^i V^\dagger_{\boldsymbol{b}_\perp} V_{\bar{\boldsymbol{b}}_\perp} \partial^j V^\dagger_{\bar{\boldsymbol{b}}_\perp}) \right\rangle_Y$$

Can be computed from Wilson lines!

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

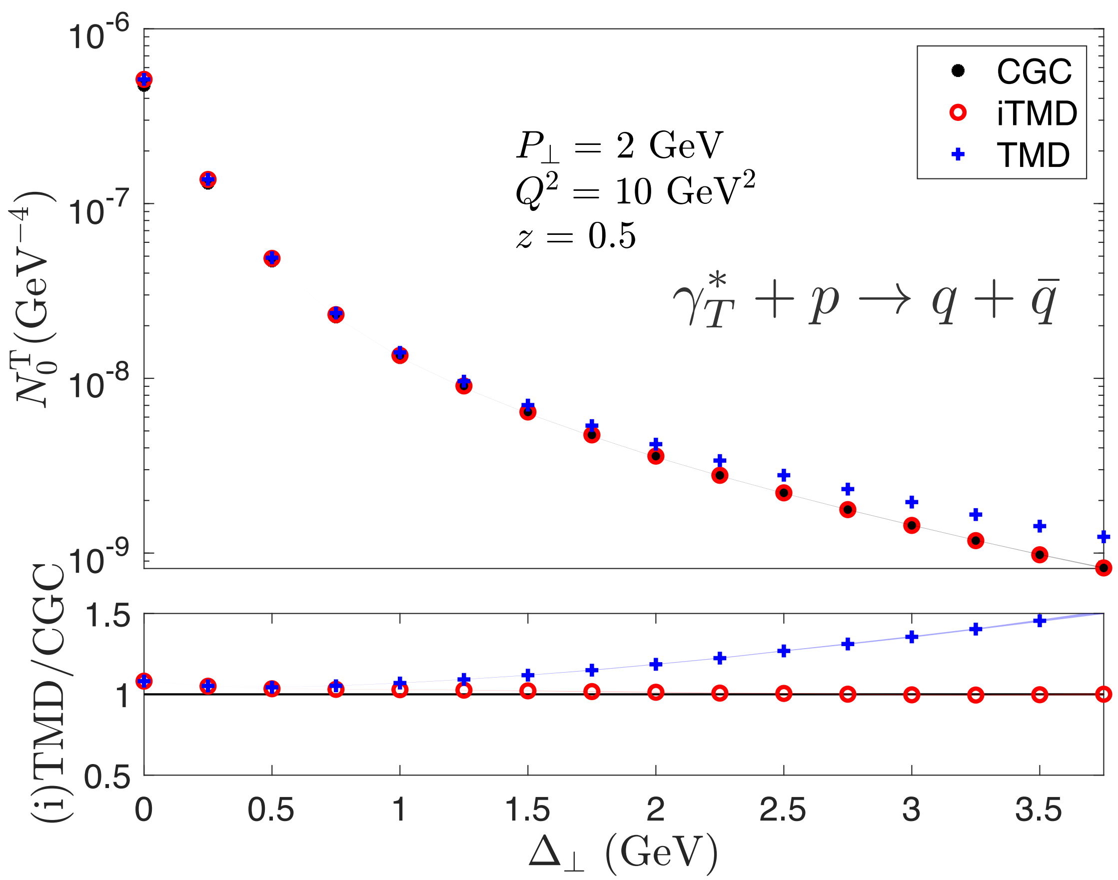
Boussarie, Mäntysaari, FS, Schenke. 2105.XXXX

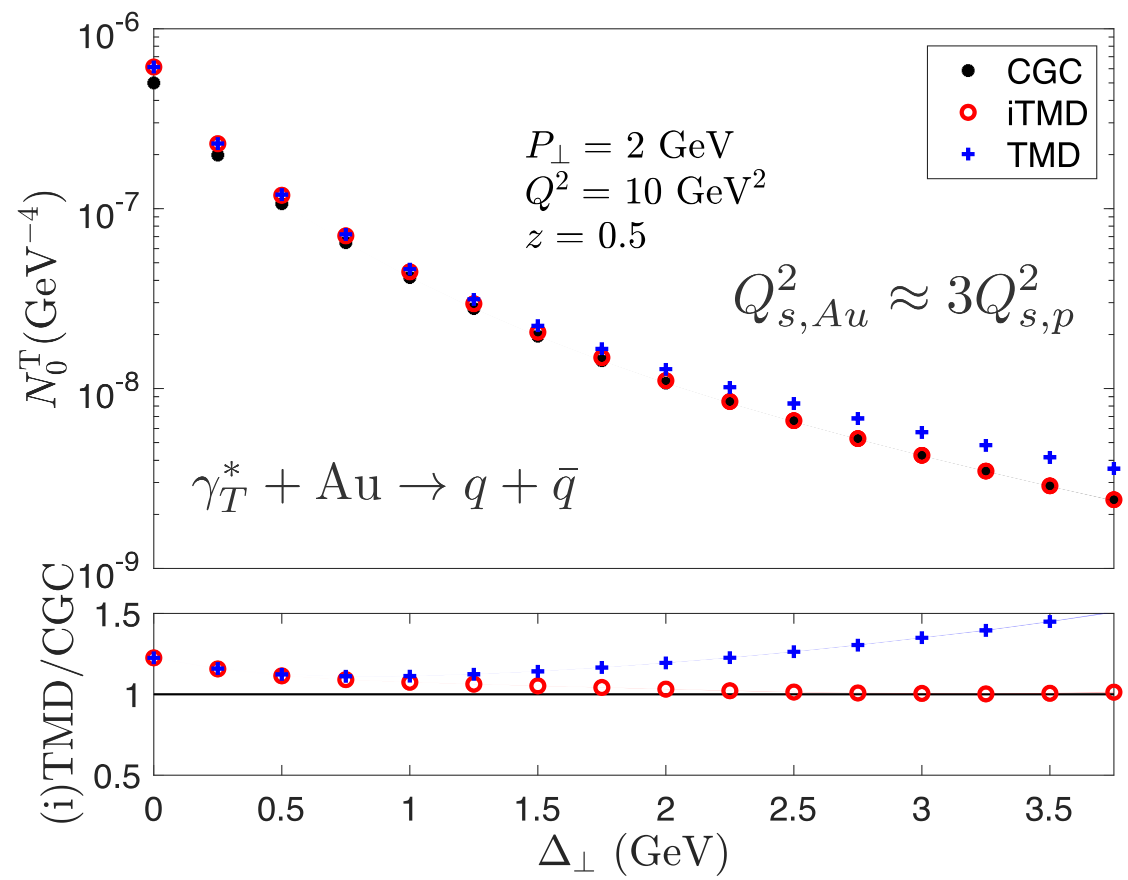
Numerical results

Differential yield (transverse virtual photon pol)

$$N_0^T \equiv \int_0^{2\pi} d\phi_{\boldsymbol{P}_\perp \boldsymbol{\Delta}_\perp} \frac{1}{S_\perp} \frac{d\sigma^{\gamma_T^* + A \to q\bar{q}} + X}{dy_1 dy_2 d^2\boldsymbol{P}_\perp d^2\boldsymbol{\Delta}_\perp}$$

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 $\Delta_\perp$

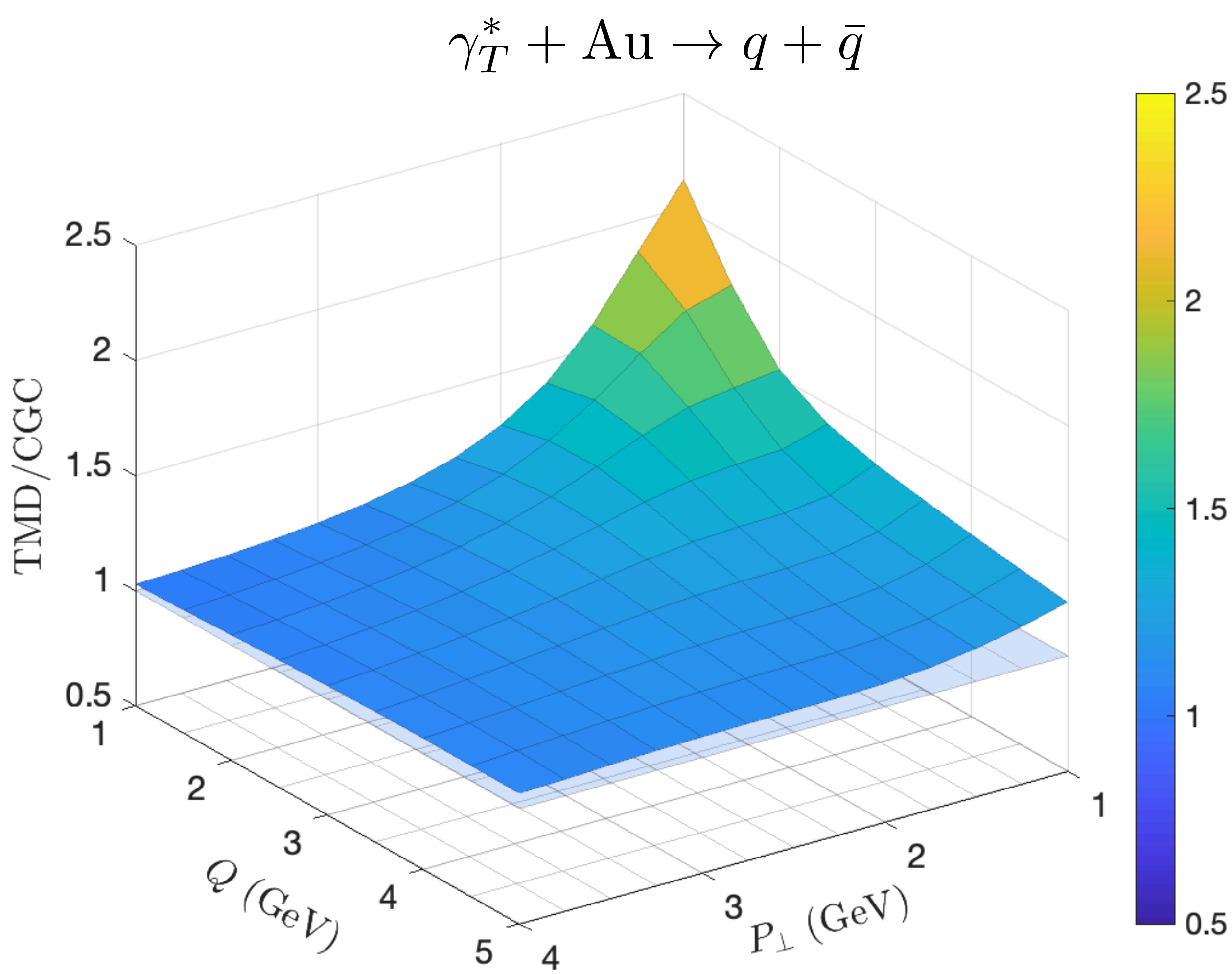
Genuine higher twist contributions

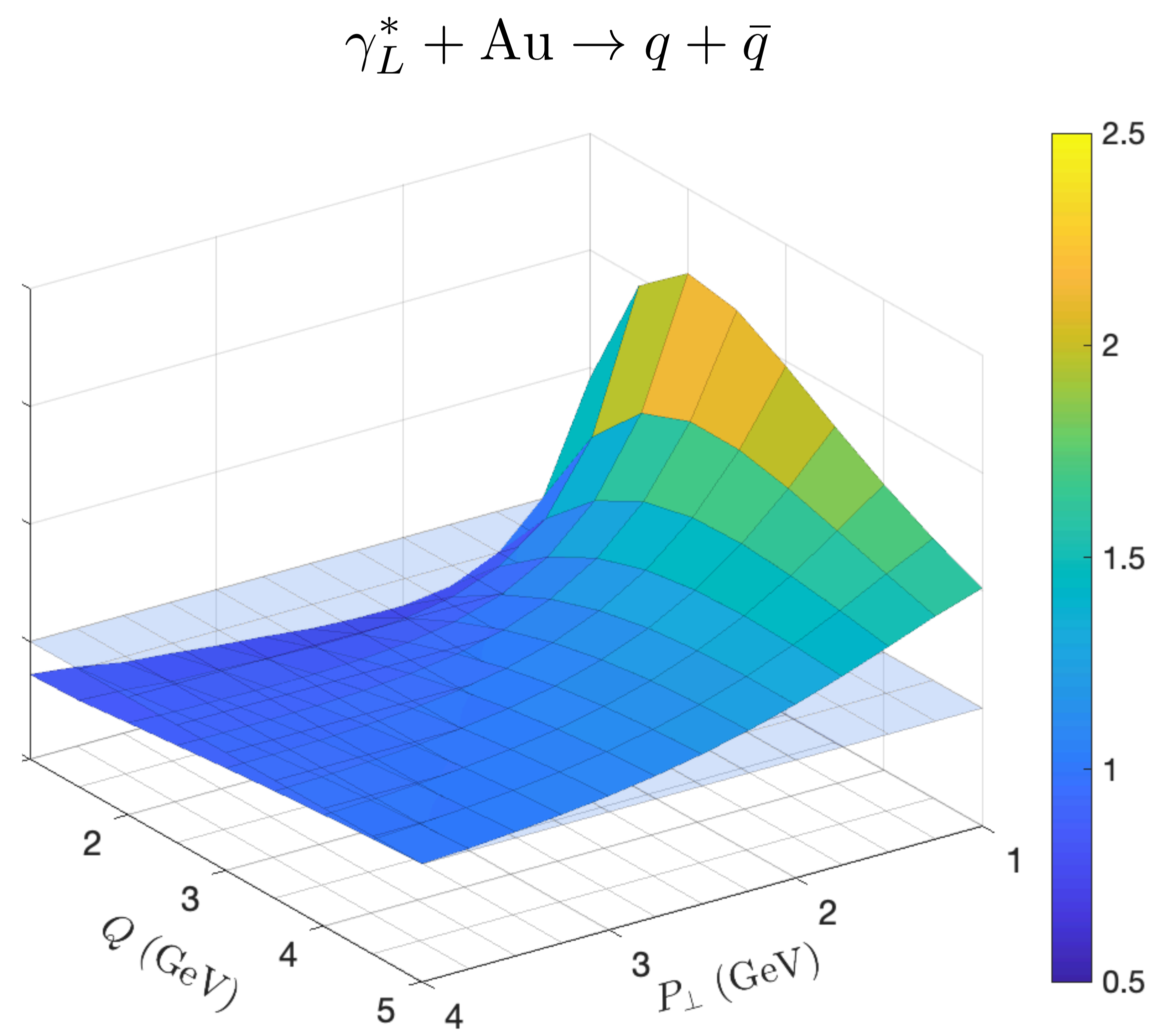
Impact on back-to-back dihadrons in e-Au collisions

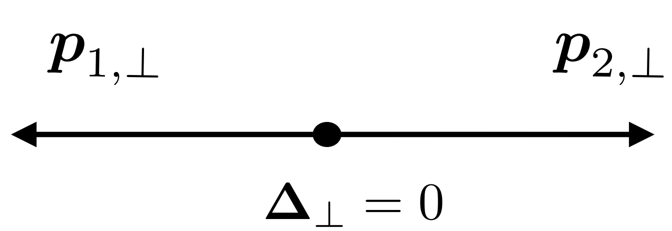
Numerical results

Q^2 and $P_\perp$ dependence of genuine twists

At exactly back-to-back $\Delta_\perp = 0$ the ratio of CGC/TMD is sensitive to genuine twists







Back-to-back (in transverse space)

Genuine higher twist contributions grow at low Q^2 and low $P_\perp$

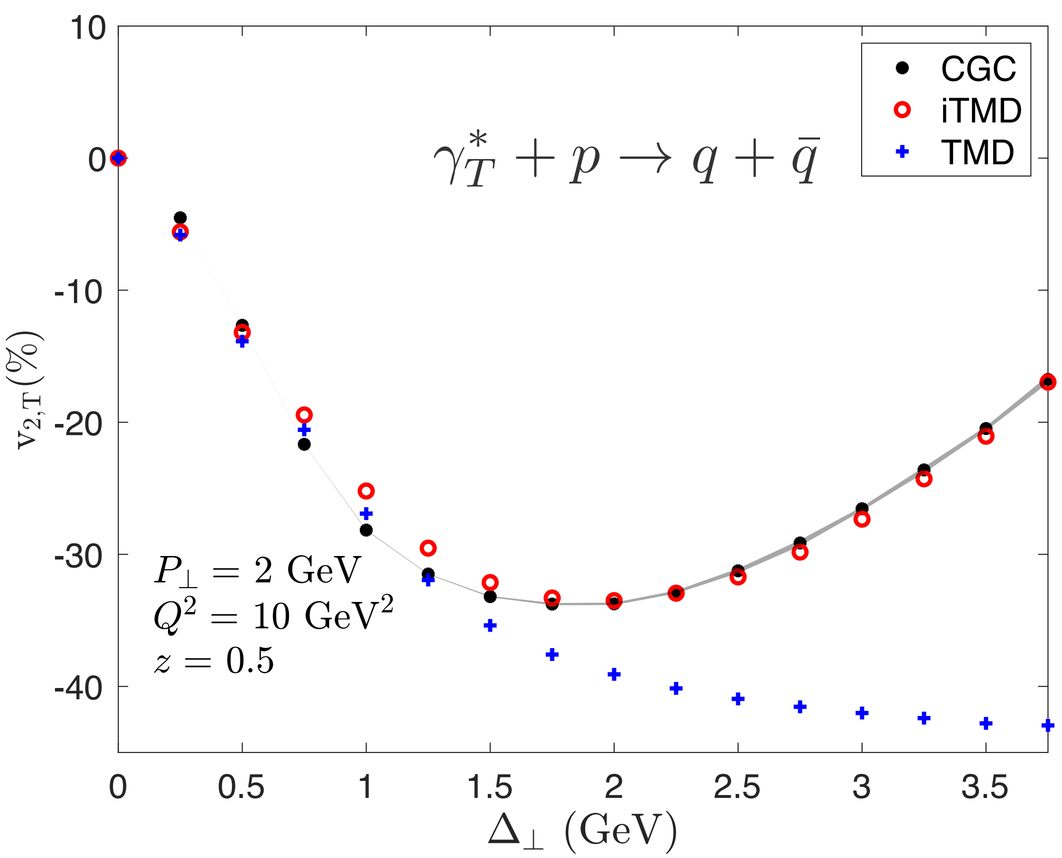
If one these scales is large then CGC converges to TMD as expected.

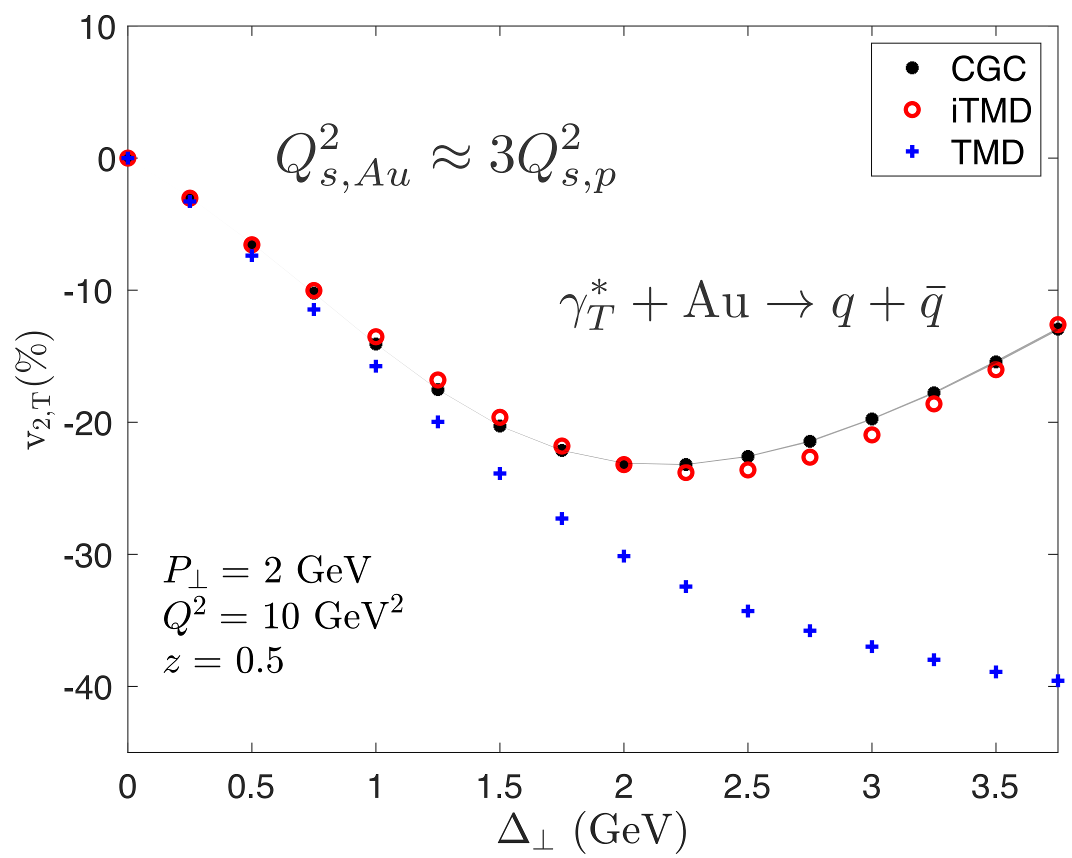
Numerical results

Elliptic anisotropy (transverse virtual photon pol)

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

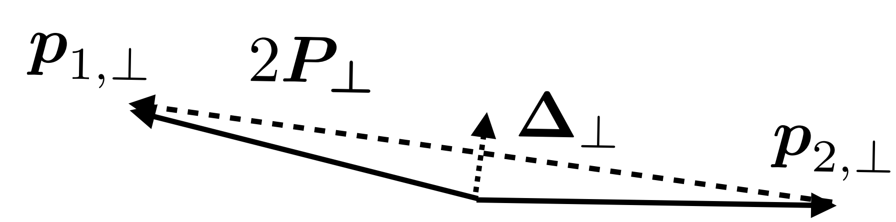
H. Mäntysaari, N. Mueller, FS, B. Schenke, 1912.05586
and work in progress with Boussarie, Mäntysaari, Schenke





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



v_2 in the angle

$$\phi \equiv \phi_{\boldsymbol{\Delta}_\perp} - \phi_{\boldsymbol{P}_\perp}$$

See also **Feng's talk** on Monday for contribution from soft gluon emissions to v_2!

Towards full NLO computation in the CGC

Current studies at NLO in the CGC in DIS:

- Structure functions (fully inclusive DIS)
  Beuf. 1708.06557
  Hänninen, Lappi, Paatelainen. 1711.08207
  Beuf, Hänninen, Lappi, Mäntysaari. 2007.01645
- Exclusive dijet
  Boussarie, Grabovsky, Szymanowski, Wallon. 1606.00419 1905.07371
- Exclusive J/Ψ
  Mäntysaari, Penttala. 2104.02349
- Semi-inclusive photon+dijet
  Roy, Venugopalan. 1911.04530
- Sudakov resummation for semi-inclusive back-to-back dijets/dihadrons
  Mueller, Xiao, Yuan. 1308.2993

See also **Feng's talk** on Monday!

For semi-inclusive production of dijets in p-A at NLO see **Yair's talk** after this one!

Goal:

Full NLO computation of semi-inclusive dijets in the CGC

- *Cancellation of divergences: UV, soft and collinear*
- *Factorization of small-x: Leading Log JIMWLK evolution*
- *Numerically tractable expressions for impact factor*

Approach:

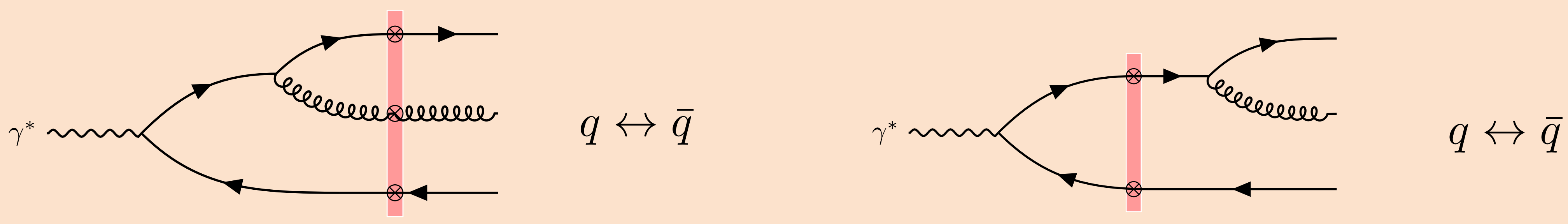
CGC momentum space Feynman rules

- *Dimensional regularization for transverse momenta*
- *Longitudinal momentum (rapidity) cut-off*
- *Small cone algorithm*

Semi-inclusive dijets in DIS at NLO

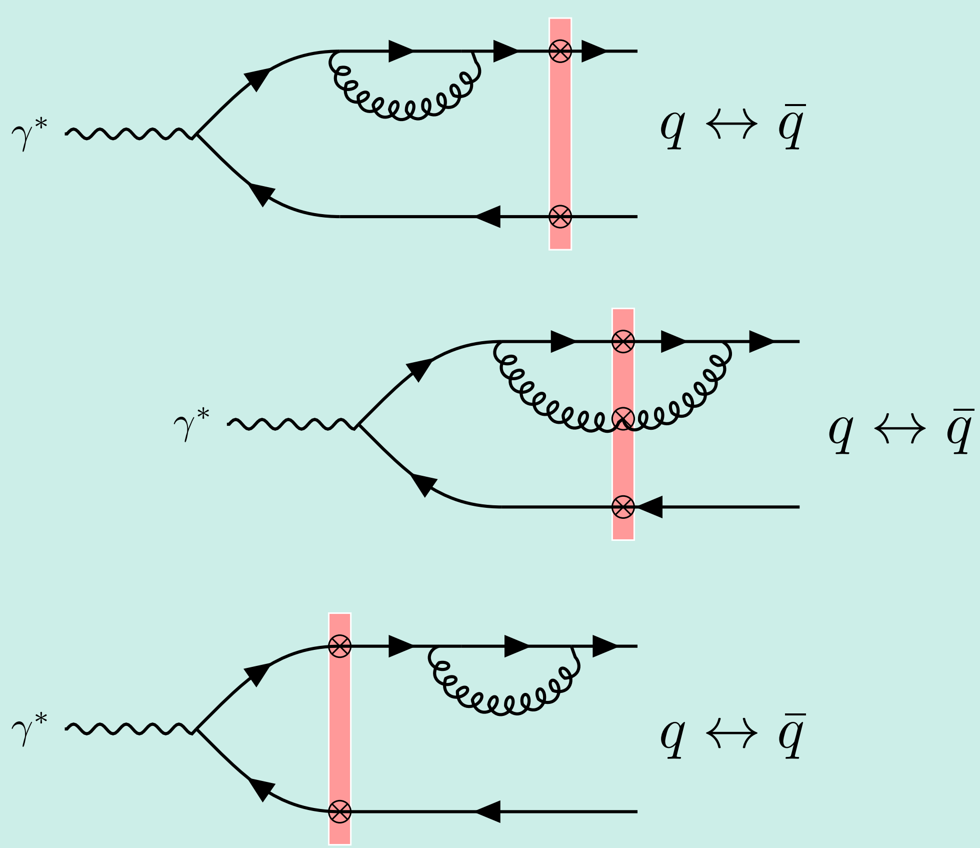
Feynman diagrams: real and virtual

Real emission diagrams (loop opens in DA and closes in the CCA)

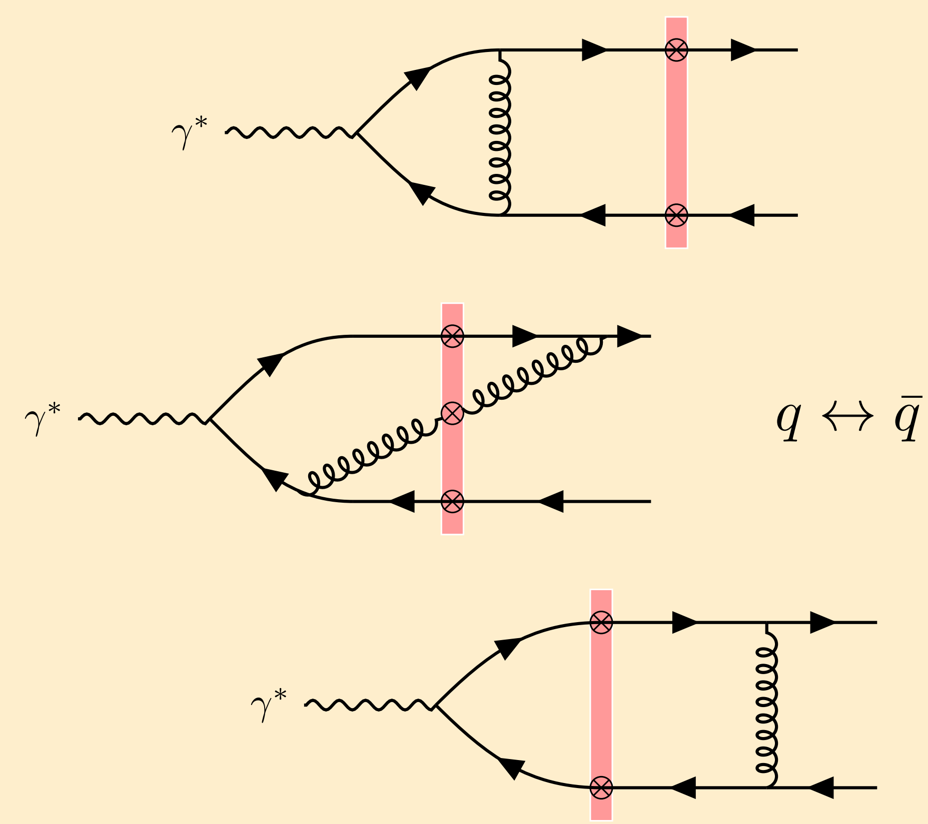


Virtual emission (loop open and closes in DA or CCA)

Self-energy contributions

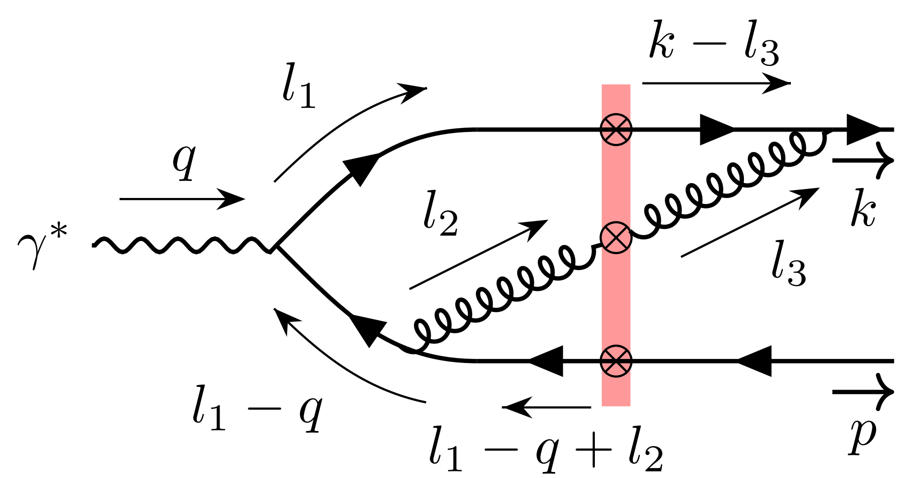


Vertex contributions



Semi-inclusive dijets in DIS at NLO

An example: vertex contribution with gluon crossing the shock-wave



From momentum space Feynman rules:

$$S^{\lambda}_{\mathrm{V},3} = \mu^{3\varepsilon}\int \frac{\mathrm{d}^{4-\varepsilon}l_1}{(2\pi)^{4-\varepsilon}}\frac{\mathrm{d}^{4-\varepsilon}l_2}{(2\pi)^{4-\varepsilon}}\frac{\mathrm{d}^{4-\varepsilon}l_3}{(2\pi)^{4-\varepsilon}}\left[\bar{u}(k)(ig\gamma^{\mu}t^a)S^0(k-l_3)\mathcal{T}^q(k-l_3,l_1)S^0(l_1)(-ie\not{\epsilon}(\lambda,q))S^0(l_1-q)(ig\gamma^{\nu}t^b)\right.$$
$$\left.S^0(l_1-q+l_2)\mathcal{T}^q(l_1-q+l_2,-p)v(p)\right]G^{0,ac}_{\mu\rho}(l_3)G^{0,db}_{\sigma\nu}(l_2)\mathcal{T}^{g,\rho\sigma}_{cd}(l_3,l_2)$$

Free Feynman propagator

Effective CGC vertices

After working out Dirac/vector structure and loop integration, we find (for longitudinally polarized photon):

$$\mathcal{M}^{\lambda=0}_{\mathrm{V},3} = \frac{ee_f q^-}{\pi}\int \mathrm{d}^2\boldsymbol{x}_\perp \mathrm{d}^2\boldsymbol{y}_\perp \mathrm{d}^2\boldsymbol{z}_\perp e^{-i\boldsymbol{k}_\perp\cdot\boldsymbol{x}_\perp}e^{-i\boldsymbol{p}_\perp\cdot\boldsymbol{y}_\perp}\left[t^aV(\boldsymbol{x}_\perp)V^\dagger(\boldsymbol{z}_\perp)t_aV(\boldsymbol{z}_\perp)V^\dagger(\boldsymbol{y}_\perp)-t^at_a\right]$$

Wilson line color structure

$$\frac{\alpha_s}{\pi^2}\int_{z_0}^{z_q}\frac{\mathrm{d}z_g}{z_g}e^{-i\boldsymbol{k}_\perp\cdot z_g/z_q\boldsymbol{r}_{zx}}(z_{\bar{q}}+z_g)(z_q-z_g)QK_0\left(\Delta_{\mathrm{V},3}\sqrt{\left(\boldsymbol{r}_{xy}-\frac{z_g\boldsymbol{r}_{zy}}{z_{\bar{q}}+z_g}\right)^2+\omega_{\mathrm{V},3}\boldsymbol{r}^2_{zy}}\right)$$

Wave-function at NLO

Gluon longitudinal momentum cut-off

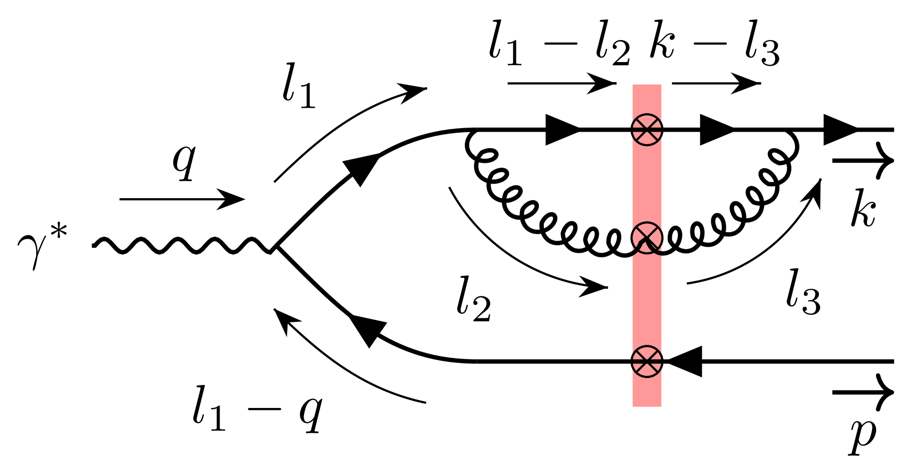
$$\left\{\left[1-\frac{z_g}{2z_q}-\frac{z_g}{2(z_{\bar{q}}+z_g)}\right]\frac{\boldsymbol{r}_{zx}\cdot\boldsymbol{r}_{zy}}{\boldsymbol{r}^2_{zx}\boldsymbol{r}^2_{zy}}\frac{[\bar{u}(k)\gamma^-v(p)]}{q^-}+\frac{1}{4}\left[\frac{z_g}{z_q}-\frac{z_g}{(z_{\bar{q}}+z_g)}\right]\frac{\boldsymbol{r}_{zx}\times\boldsymbol{r}_{zy}}{\boldsymbol{r}^2_{zx}\boldsymbol{r}^2_{zy}}\frac{[\bar{u}(k)\gamma^-\left[\gamma^1,\gamma^2\right]v(p)]}{q^-}\right\}$$

JIMWLK kernel

Full expression for this diagram!

Semi-inclusive dijets in DIS at NLO

Another example: self-energy contribution with gluon crossing the shock-wave



Self-energy contains a UV singularity, must subtract UV limit ($z_\perp \to x_\perp$) to isolate finite piece (longitudinally pol photon):

$$\mathcal{M}^{\lambda=0}_{\mathrm{SE},2} - \mathcal{M}^{\lambda=0}_{\mathrm{SE},2,\mathrm{UV}} = -\frac{ee_f q^-}{\pi} \int \mathrm{d}^2\boldsymbol{x}_\perp \mathrm{d}^2\boldsymbol{y}_\perp e^{-i\boldsymbol{k}_\perp\boldsymbol{x}_\perp - i\boldsymbol{p}_\perp\boldsymbol{y}_\perp} \frac{\alpha_s}{\pi^2} \int_{z_0}^{z_q} \frac{\mathrm{d}z_g}{z_g} z_q z_{\bar{q}} Q \left[1 - \frac{z_g}{z_q} + \frac{z_g^2}{2z_q^2}\right] \frac{[\bar{u}(k)\gamma^- v(p)]}{q^-}$$

$$\int \frac{\mathrm{d}^2\boldsymbol{z}_\perp}{\boldsymbol{r}_{zx}^2} \left\{ e^{-i\frac{z_g}{z_q}\boldsymbol{k}_\perp\boldsymbol{r}_{zx}} K_0\left(\bar{Q}\sqrt{\left(\boldsymbol{r}_{xy} + \frac{z_g}{z_q}\boldsymbol{r}_{zx}\right)^2 + \omega_{\mathrm{SE},2}\boldsymbol{r}_{zx}^2}\right) \mathcal{C}_{\mathrm{SE},2}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp, \boldsymbol{z}_\perp) - \boxed{\exp\left(-\frac{\boldsymbol{r}_{zx}^2}{2\xi}\right) K_0\left(\bar{Q} r_{xy}\right) \mathcal{C}_{\mathrm{SE},1}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp)} \right\}$$

Subtraction term* as in 1711.08207

Subtraction term can be computed in dimensional regularization

$$\mathcal{M}^{\lambda=0}_{\mathrm{SE},2,\mathrm{UV}} = \frac{ee_f q^-}{\pi} \mu^{-2\varepsilon} \int \mathrm{d}^{2-\varepsilon}\boldsymbol{x}_\perp \mathrm{d}^{2-\varepsilon}\boldsymbol{y}_\perp e^{-i\boldsymbol{k}_\perp\boldsymbol{x}_\perp - i\boldsymbol{p}_\perp\boldsymbol{y}_\perp} \mathcal{C}_{\mathrm{LO}}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp) \mathcal{N}^{\lambda=0}_{\mathrm{LO},\varepsilon}(\boldsymbol{r}_{xy}) \frac{\alpha_s C_F}{2\pi} \left\{ \left(2\ln\left(\frac{z_q}{z_0}\right) - \frac{3}{2}\right) \left(\frac{2}{\varepsilon} + \ln(2\pi\mu^2\xi)\right) - \frac{1}{2} \right\}$$

combined with other virtual contributions.

UV pole

Color structure of Wilson lines

$$\mathcal{C}_{\mathrm{SE},1}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp) = C_F \left[V(\boldsymbol{x}_\perp)V^\dagger(\boldsymbol{y}_\perp) - 1\right]$$

$$\mathcal{C}_{\mathrm{SE},2}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp, \boldsymbol{z}_\perp) = \left[t^a V(\boldsymbol{x}_\perp)V^\dagger(\boldsymbol{z}_\perp) t_a V(\boldsymbol{z}_\perp)V^\dagger(\boldsymbol{y}_\perp) - t^a t_a\right]$$

Semi-inclusive dijets in DIS at NLO

Cancellation of divergences: UV and rapidity

Rapidity (aka slow) divergence $z_g \to z_0$

- Introduce factorization scale z_f

- UV and IR divergences are absent (cancel among real and virtual) in $\mathcal{H}_{\rm LL}$

- First step in JIMWLK leading log evolution

$$\left\langle |\mathcal{M}_{\rm NLO}|^2 \right\rangle \sim \alpha_s \ln\left(\frac{z_f}{z_0}\right) \mathcal{H}_{\rm LL} \left\langle |\mathcal{M}_{\rm LO}|^2 \right\rangle$$

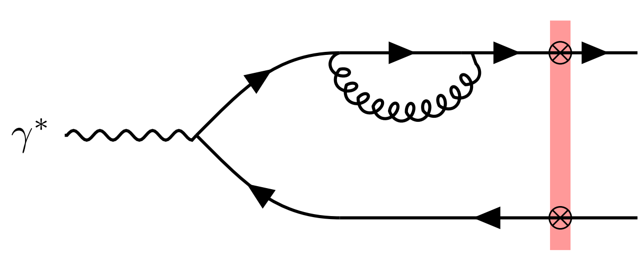
JIMWLK LL Hamiltonian

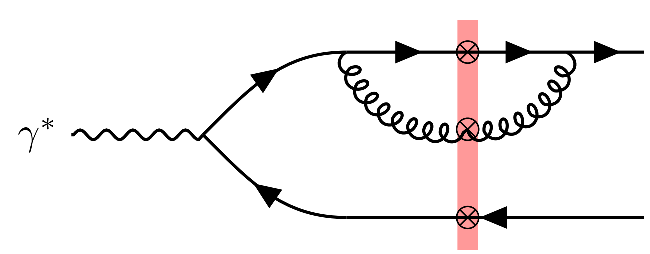
Log squared in rapidity cancel out!

Cancellation of UV divergences

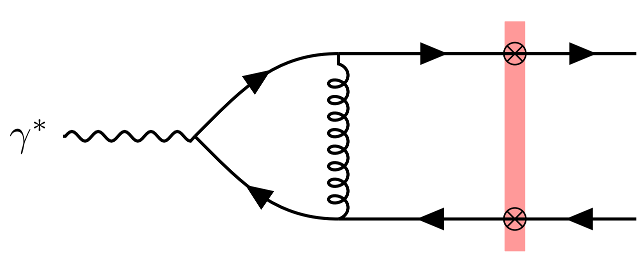
- No UV divergences in real emission (unless one of the jets is integrated out)

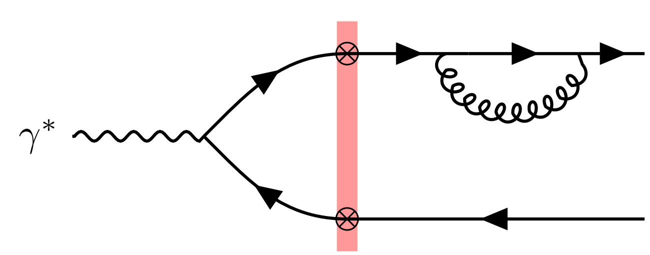
- UV divergences cancel among self energies contributions (before SW and crossing SW)





- UV divergence cancel in vertex contribution before SW and self energy contribution after SW





$+ \quad q \leftrightarrow \bar{q}$

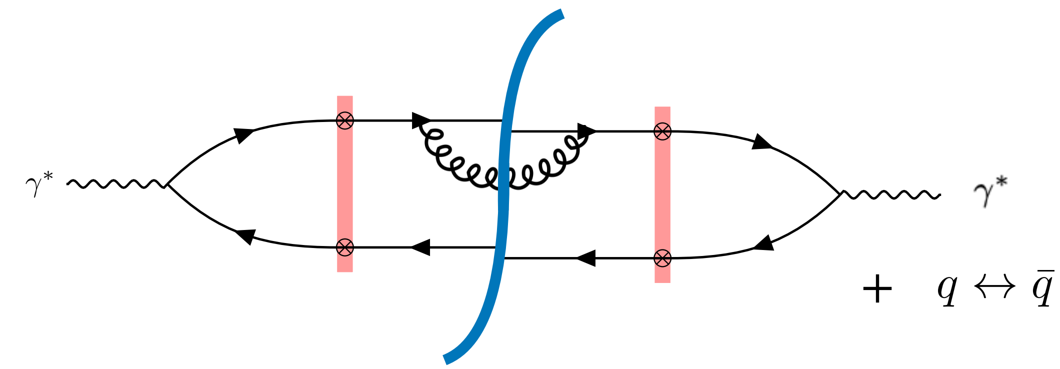
Self-energy contribution vanishes exactly in dim reg (IR and UV pole cancel each other out)
<u>turns UV divergences into IR</u> (massless quarks)

Semi-inclusive dijets in DIS at NLO

Cancellation of divergences: collinear and soft divergences

Collinear non-slow divergences

- Implement a jet algorithm (small cone) <u>excluding slow gluon divergence</u>



$+ \quad q \leftrightarrow \bar{q}$

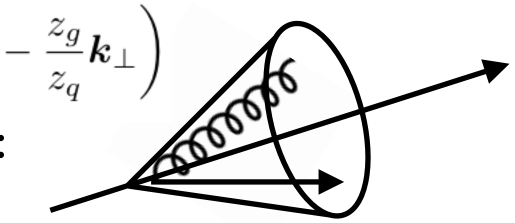
Phase space for collinear non-slow gluon

$$\int_{z_f}^{z_j} \frac{\mathrm{d}z_g}{z_g}\mu^{\varepsilon} \int \frac{\mathrm{d}^{2-\varepsilon}\mathcal{C}_{qg,\perp}}{(2\pi)^{2-\varepsilon}} \frac{1}{\mathcal{C}^2_{qg,\perp}}$$

Collinearity variable:

$$\mathcal{C}_{qg,\perp} = \frac{z_q}{z_j}\left(\boldsymbol{k}_{\boldsymbol{g}\perp} - \frac{z_g}{z_q}\boldsymbol{k}_{\perp}\right)$$

Small-cone condition:

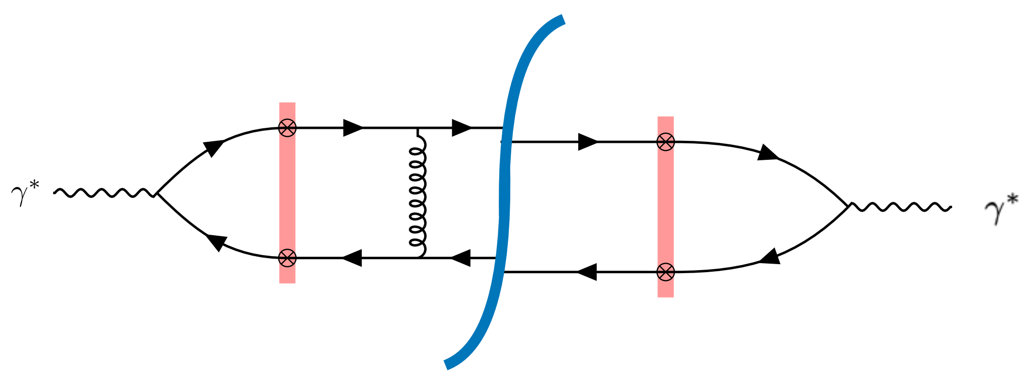


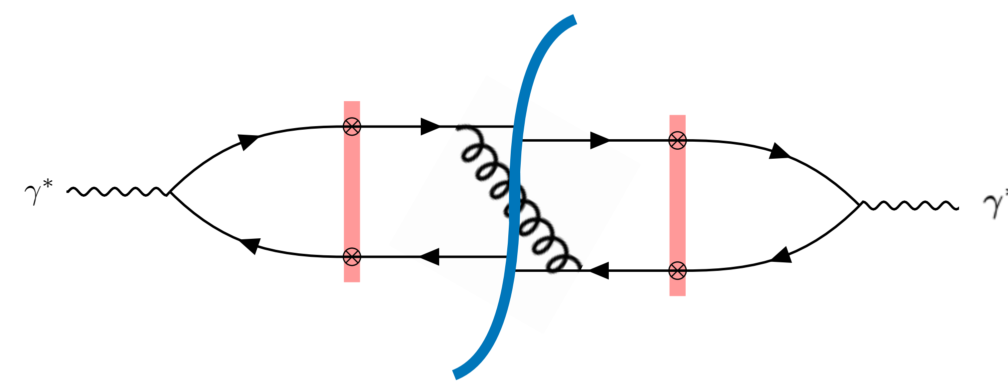
$$\mathcal{C}^2_{qg,\perp} \leq \mathcal{C}^2_{qg,\perp}\big|_{\max} = R^2 \boldsymbol{p}_j^2 \min\left(\frac{z_g^2}{z_j^2}, \frac{(z_j - z_g)^2}{z_j^2}\right)$$

- Collinear divergence cancels against IR divergence left in virtual contributions

Soft divergence

- Remaining soft divergence cancel between vertex correction after SW, and cross term real gluon emission after SW





Note they posses same color structure (cross-section level)

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.

- 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 $P_\perp$.

- Showed exact cancellation of divergences for the semi-inclusive production of dijets in DIS at NLO and verified the small-x factorization.

  No need for UV counter-terms, no dependence on μ scale

  Obtained a numerically tractable expression for impact factor (depends on rapidity scale z_f)

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

- **Numerical results for dijets/dihadrons at NLO**

  Isolate impact factor and evaluate numerically:

  Couple to NLL JIMWLK/BK+Gaussian

  How large are NLO corrections?

  What's their impact on saturation searches at the EIC?

  Consider to back-to-back kinematics, then consider more general kinematics

Recent progress on numerical computations in the CGC at NLO

Structure functions
Beuf, Hänninen, Lappi, Mäntysaari. 2007.01645

Exclusive vector meson production
Mäntysaari, Penttala. 2104.02349

Our results can be applied to dijet photo-production at NLO (need to compute transversely polarized photon), e.g. UPCs

faridsalazar03@gmail.com

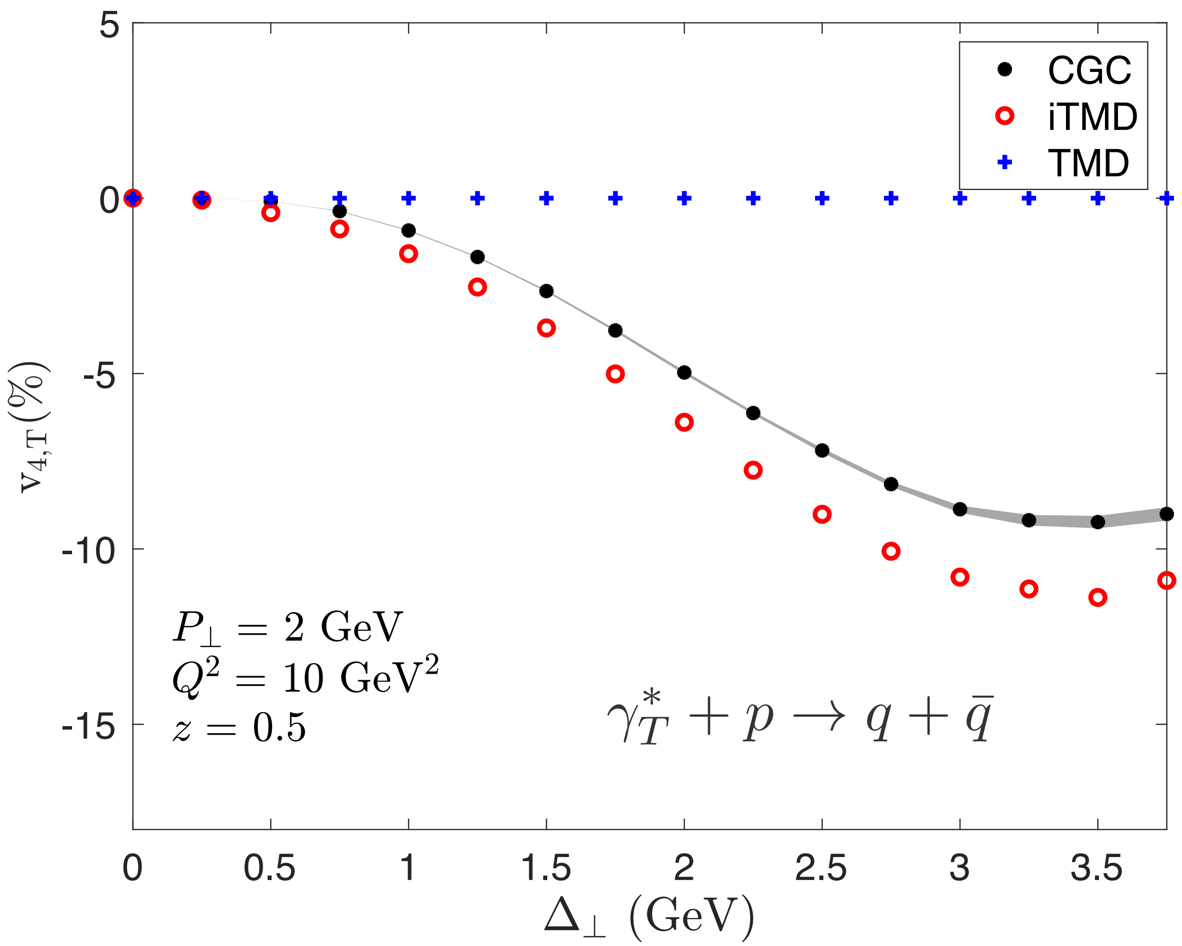
Back-up

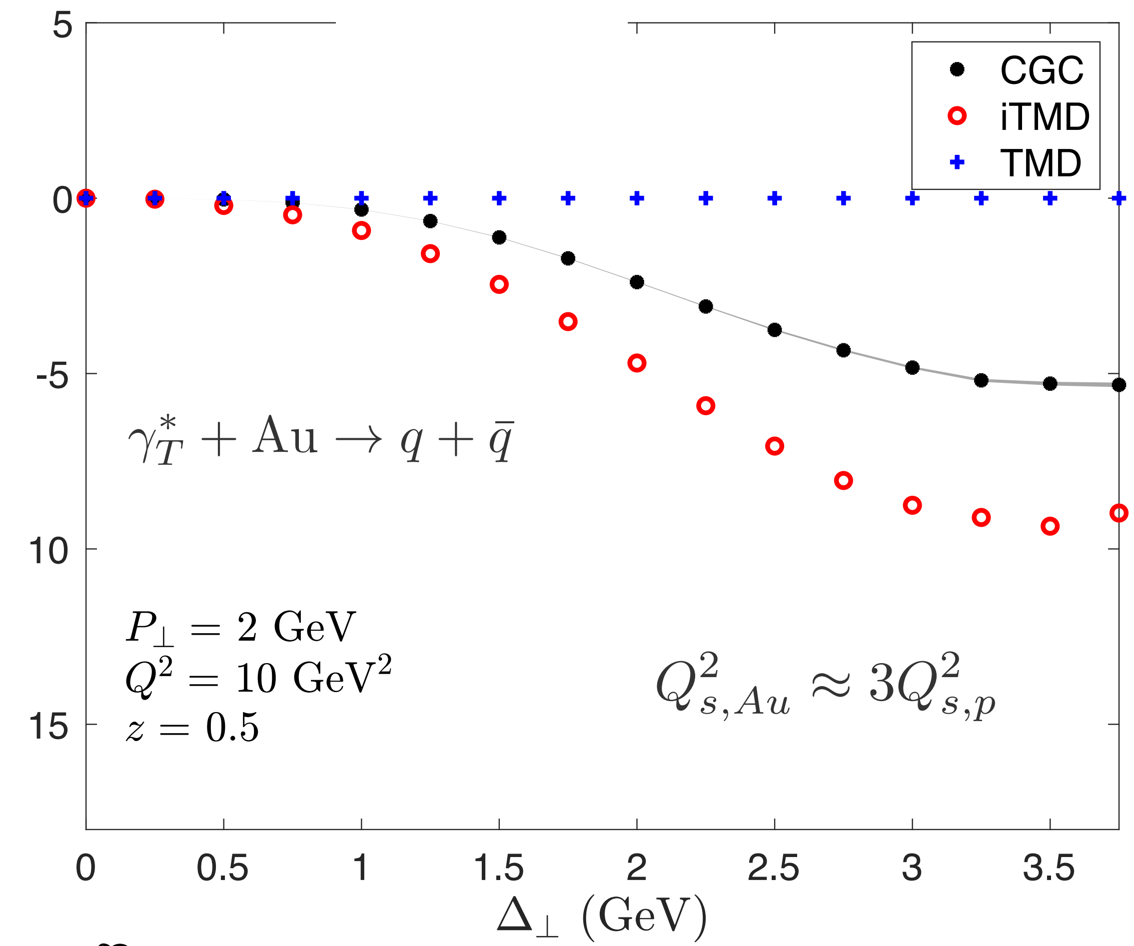
Numerical results

Quadrangular anisotropy (transverse virtual photon pol)

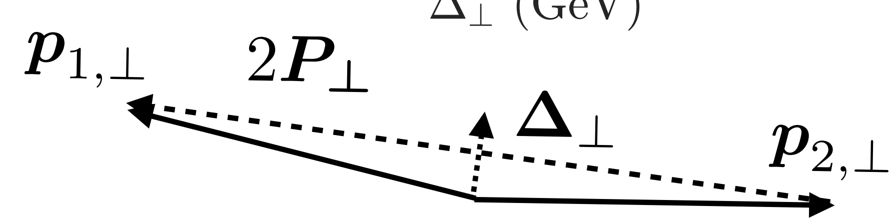
$$\mathrm{v}_{4,\mathrm{T}} \equiv \frac{1}{N_0}\int_0^{2\pi} d\phi_{\boldsymbol{P}_\perp \boldsymbol{\Delta}_\perp} \cos(4\phi_{\boldsymbol{P}_\perp \boldsymbol{\Delta}_\perp}) \frac{1}{S_\perp} \frac{d\sigma^{\gamma_T^* + A \to q\bar{q} + X}}{dy_1 dy_2 d^2\boldsymbol{P}_\perp d^2\boldsymbol{\Delta}_\perp}$$

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





TMD framework: $\mathrm{v}_4 \equiv 0$



Kinematic corrections in the iTMD induce v_4

v_4 in the angle $\phi \equiv \phi_{\boldsymbol{\Delta}_\perp} - \phi_{\boldsymbol{P}_\perp}$

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

See also Dumitru, Skokov. 1605.02739