Stony Brook University

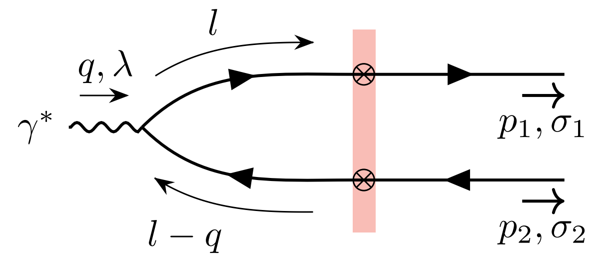
Center for Frontiers in Nuclear Science

BROOKHAVEN NATIONAL LABORATORY

Inclusive dijet/dihadron production beyond TMD framework at the EIC

Initial Stages 2021

Farid Salazar



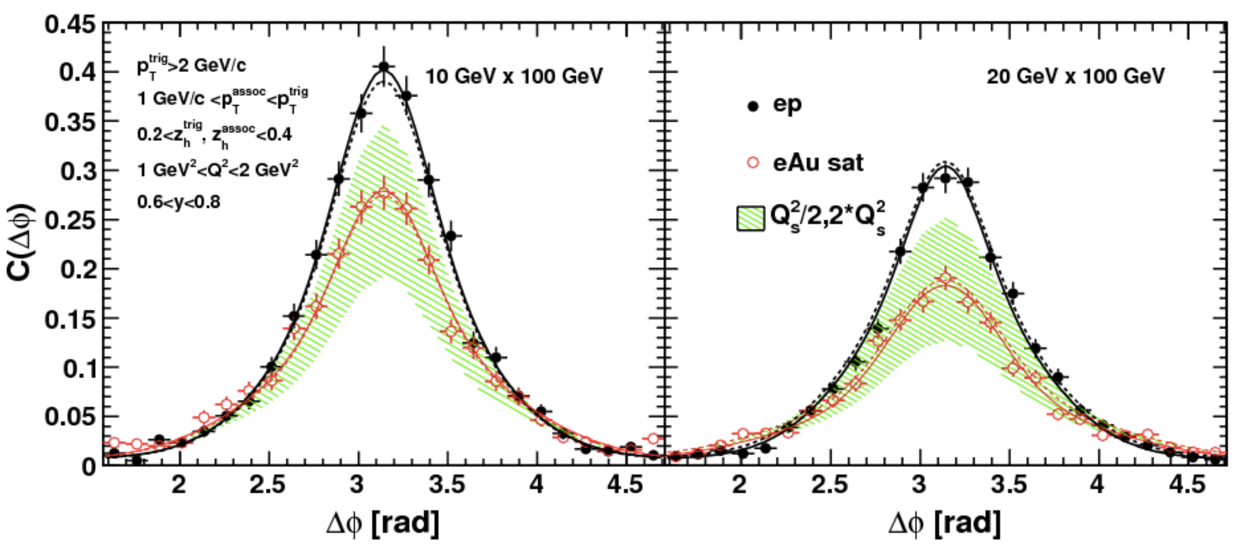
H. Mäntysaari, N. Mueller, FS, B. Schenke. 1912.05586 (PRL)

and work in progress with R. Boussarie, H. Mäntysaari, B. Schenke.

Previous studies at small-x

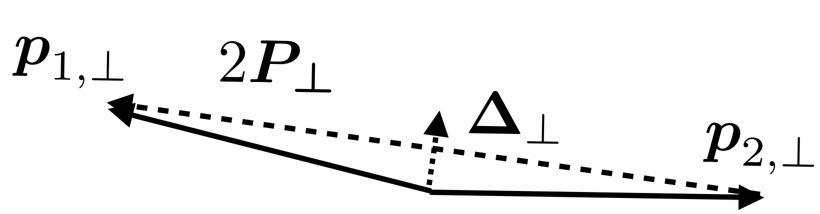
Two observables: back-to-back dihadrons, and dijet azimuthal correlations

Dihadron back-to-back suppression → Gluon saturation

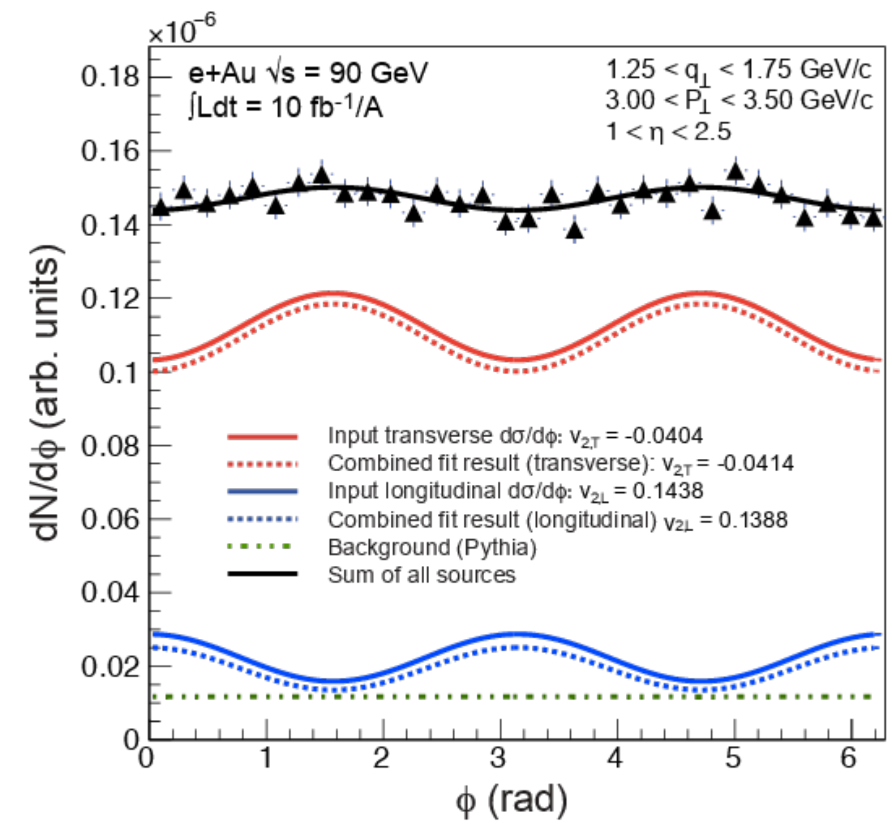


Zheng, Aschenauer, Lee, Xiao. 1403.2413

$\Delta\phi$ angle between $\boldsymbol{p_1}_\perp$ and $\boldsymbol{p_2}_\perp$



Dijet azimuthal asymmetries → Weizsäcker-Williams gluon TMD (linearly polarized)



Dumitru, Skokov, Ullrich. 1809.02615

$\Delta\phi$ angle between $\boldsymbol{P}_\perp$ and $\boldsymbol{\Delta}_\perp$

$$\boldsymbol{\Delta}_\perp = \boldsymbol{p_1}_\perp + \boldsymbol{p_2}_\perp$$

$$\boldsymbol{P}_\perp = z_2\boldsymbol{p_1}_\perp - z_1\boldsymbol{p_2}_\perp$$

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

Inclusive diparton production in DIS

At leading order in the CGC EFT and the (i)TMD factorization

Diparton cross-section in the CGC

Dominguez, Marquet, Xiao, Yuan. 1101.0715

$$d\sigma^{\gamma^* A\to q\bar{q}X} \sim \int_{\boldsymbol{l}_\perp,\bar{\boldsymbol{l}}_\perp} \Psi^{\gamma^*\to q\bar{q}}(\boldsymbol{P}_\perp - \boldsymbol{l}_\perp)\Psi^{\gamma^*\to q\bar{q}}(\boldsymbol{P}_\perp - \bar{\boldsymbol{l}}_\perp)\, \tilde{\Xi}_Y(\boldsymbol{\Delta}_\perp, \boldsymbol{l}_\perp, \bar{\boldsymbol{l}}_\perp)$$

$\tilde{\Xi}_Y(\boldsymbol{\Delta}_\perp, \boldsymbol{l}_\perp, \bar{\boldsymbol{l}}_\perp)$ Color structure containing **dipole** and **quadrupole** correlators.

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

TMD factorization: for (almost) back-to-back partons ($\Delta_\perp \ll P_\perp$)

Dominguez, Marquet, Xiao, Yuan. 1101.0715
Dumitru, Lappi, Skokov. 1508.04438

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

Weizsäcker-Williams (WW) gluon TMD

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

Improved TMD framework (resums kinematic power corrections $\Delta_\perp/P_\perp$):

Altinoluk, Boussarie, Kotko. 1901.01175 1902.07930
Boussarie, Mehtar-Tani. 2001-06449

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

Misses higher operators which are suppressed by powers of $Q_s/P_\perp$ and $Q_s/\Delta_\perp$ (genuine saturation corrections)

See also Dumitru, Skokov. 1605.02739

*See back-up slides for details

See Pietr Taels' plenary on Sunday

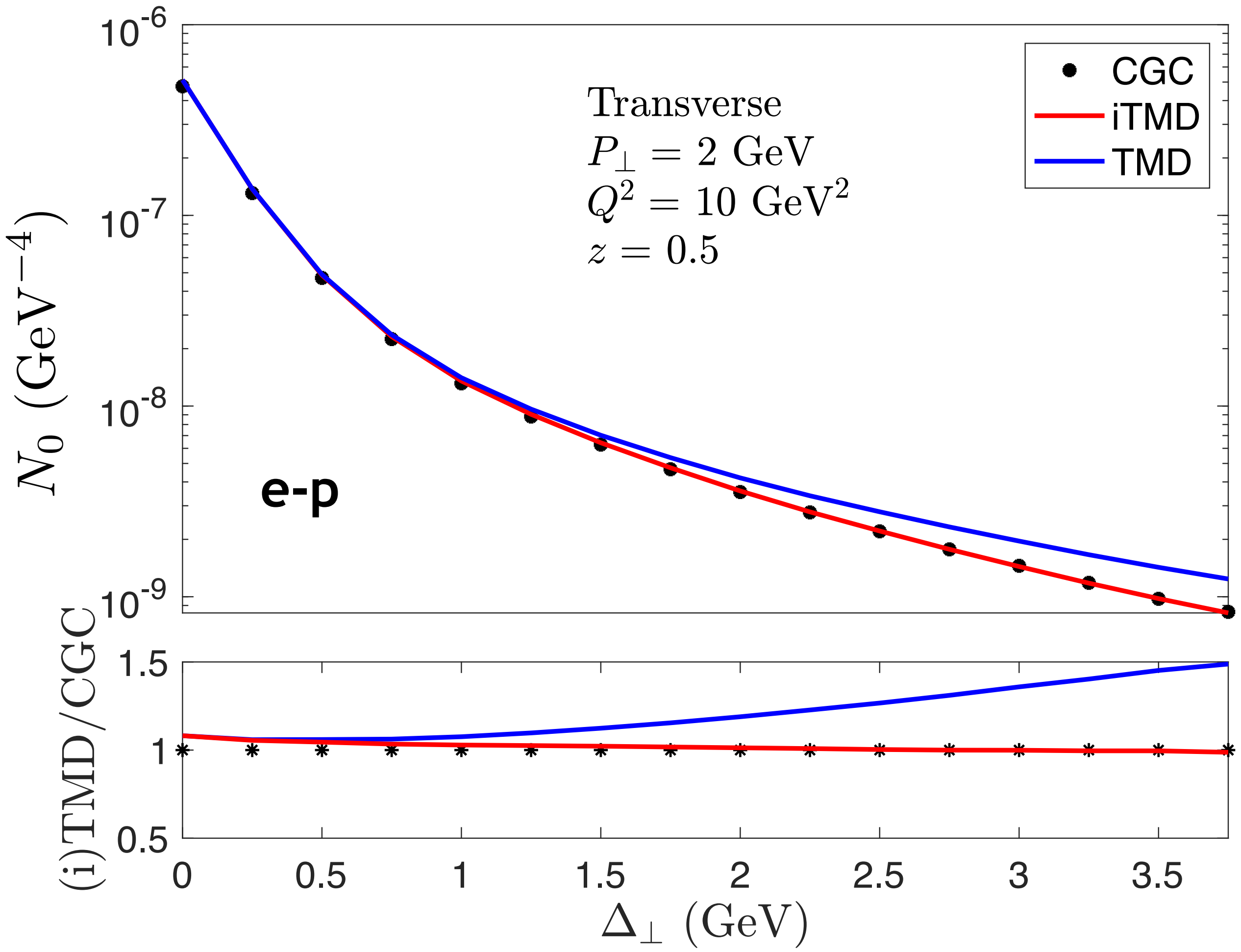
Inclusive diparton production in DIS

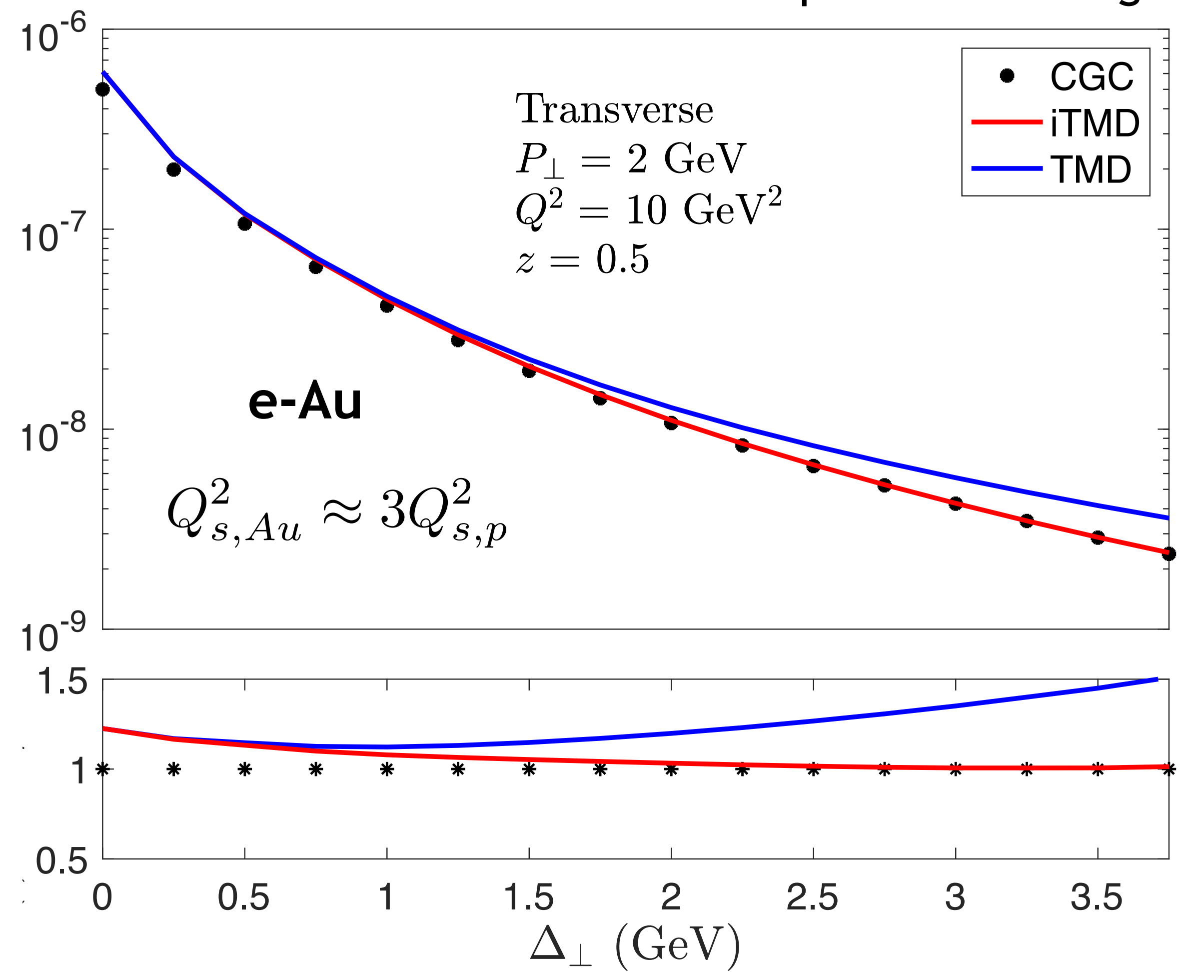
Numerical results for differential yield (transverse virtual photon pol)

$$N_0 \equiv \int_0^{2\pi} d\phi_{\boldsymbol{P}_\perp \boldsymbol{\Delta}_\perp} \frac{1}{S_\perp} \frac{d\sigma}{d^2\boldsymbol{P}_\perp d^2\boldsymbol{\Delta}_\perp}$$

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

*See back-up slides for longitudinal





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

For pA look at: Fujii, Marquet, Watanabe. 2006.16279

Inclusive diparton production in DIS

Numerical results for azimuthal anisotropy (transverse virtual photon pol)

$$v_2 \equiv \frac{1}{N_0} \int_0^{2\pi} d\phi_{\boldsymbol{P}_\perp \boldsymbol{\Delta}_\perp} \cos(2\phi_{\boldsymbol{P}_\perp \boldsymbol{\Delta}_\perp}) \frac{1}{S_\perp} \frac{d\sigma}{d^2\boldsymbol{P}_\perp d^2\boldsymbol{\Delta}_\perp}$$

H. Mäntysaari, N. Mueller, FS, B. Schenke, 1912.05586
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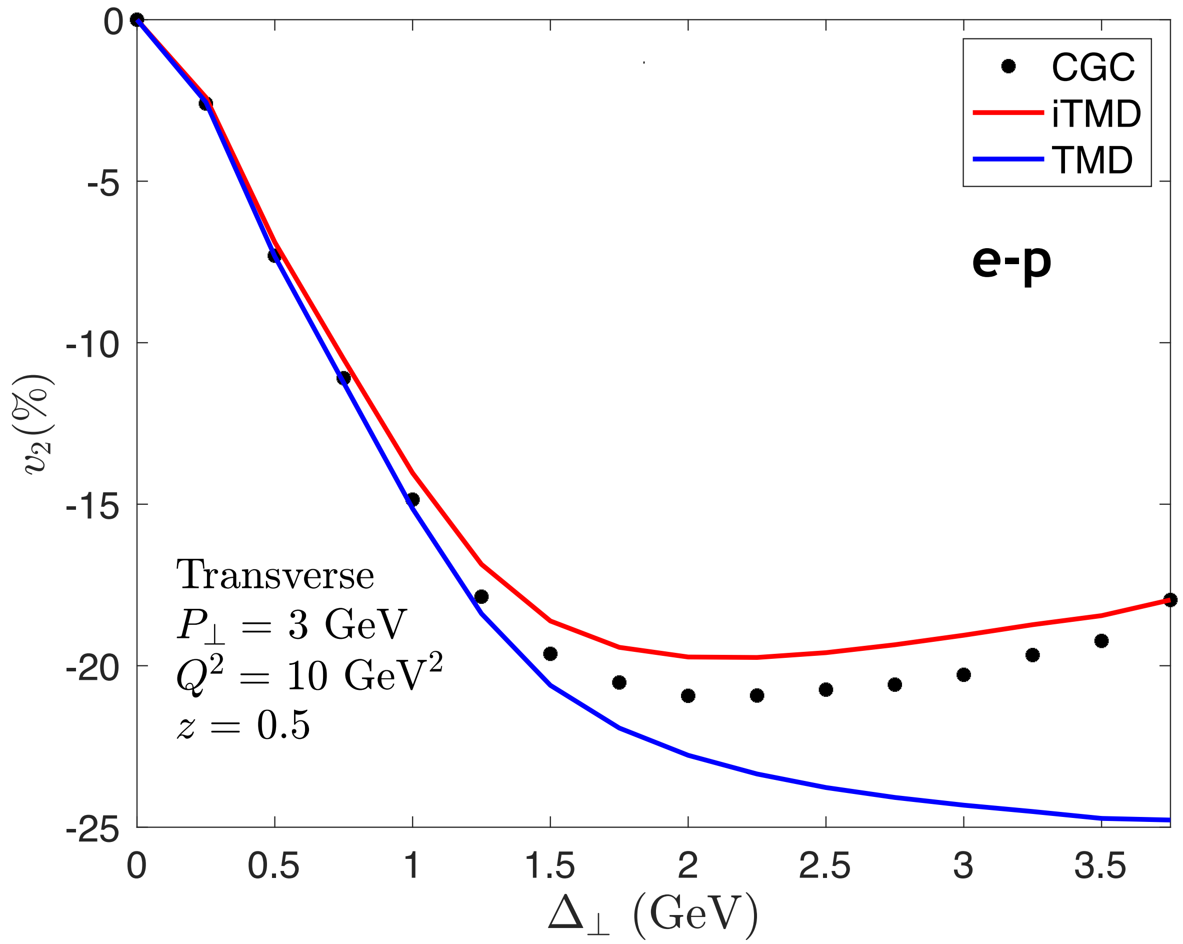

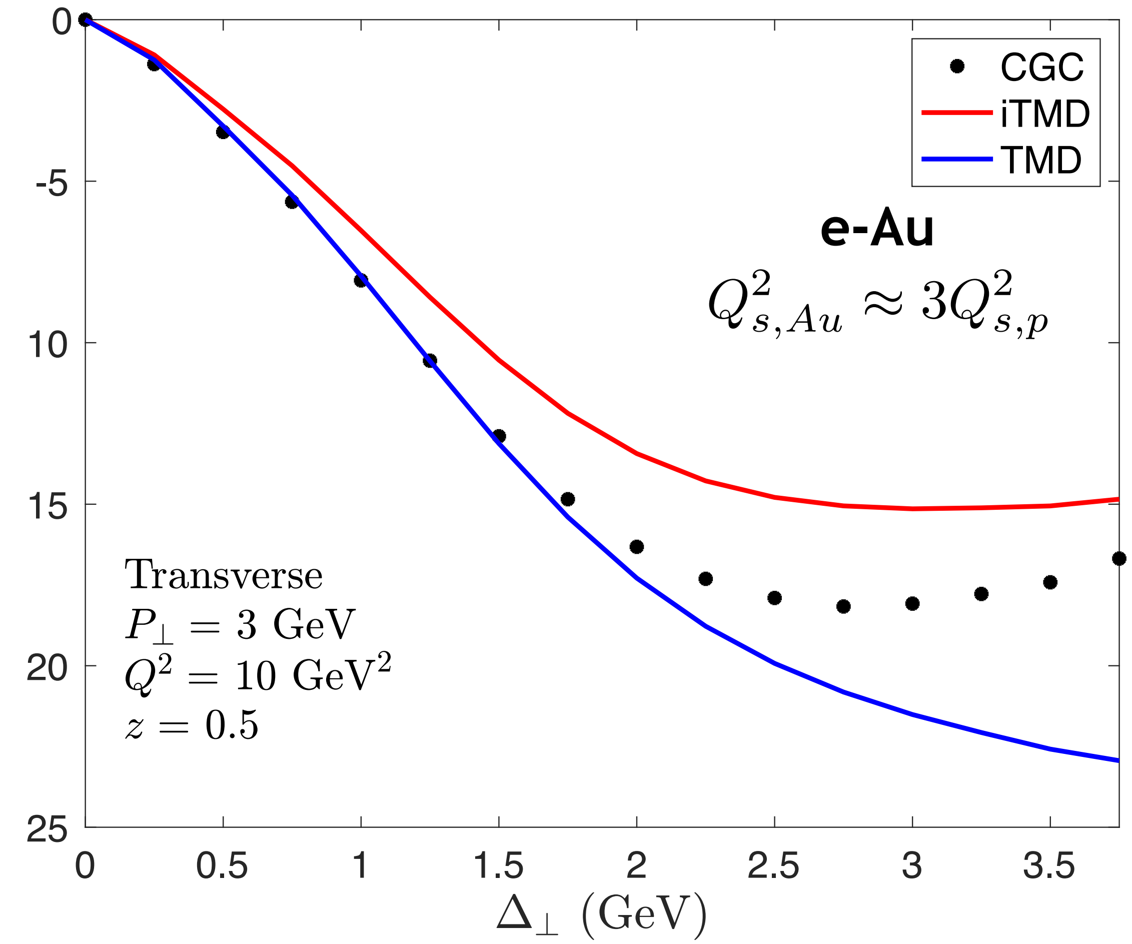

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iTMD improves agreement with CGC computation of v_2
Kinematic power corrections contribute to v_2 and might be necessary for the proper extraction of linearly polarized TMD

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Deviations from iTMD and CGC signal the possibility to access genuine saturation effects

Summary

- Good quantitative agreement between CGC and iTMD at broad range of kinematics for small Q_s^2
- Genuine saturation could be observable even in back-to-back jets for sufficiently large Q_s^2 (large nucleus at EIC)
- Proper extraction of linearly polarized WW gluon TMD from azimuthal dijet correlations will need to account for correlations due to kinematic twists in the iTMD framework

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

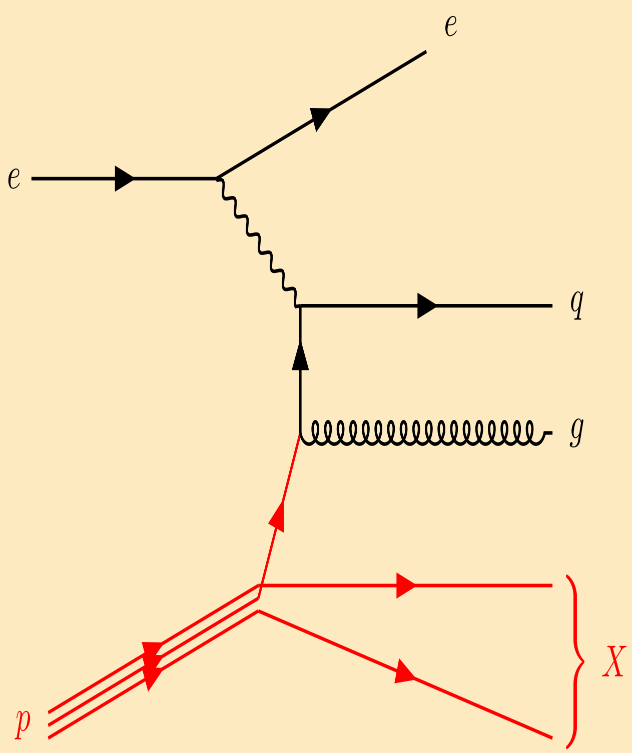
  Small-x JIMWLK at NLO
  Balistky, Chirlli. 1309.7644
  Kovner, Lublinky, Mulian. 1310.0378

  Impact factor
  Roy, Venugopalan. (for dijet+photon) 1911.04530
  Iancu, Mullian. (dijet in pA) 2009.11930

Back-up Slides

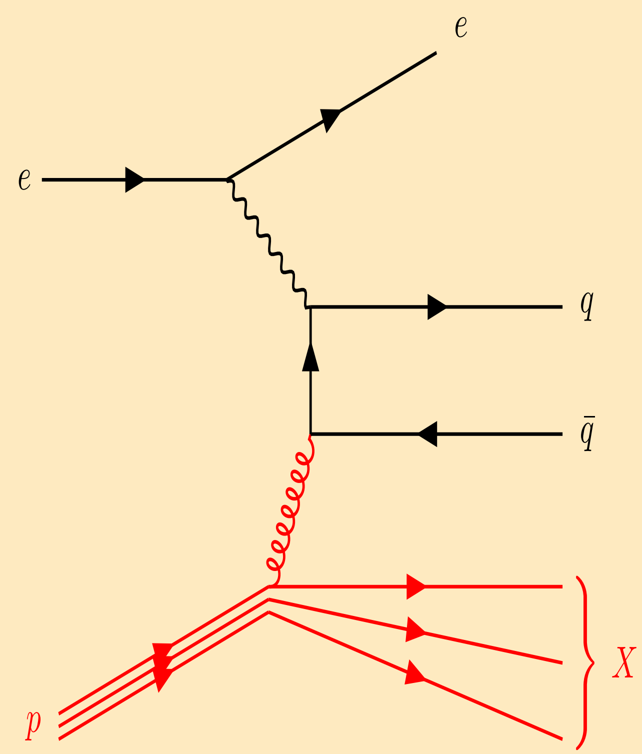
Inclusive diparton production in DIS

Collinear pQCD: quark initiated vs gluon initiated



QCD Compton scattering

~ quark PDF



Photon-gluon fusion

~ gluon PDF

dominant channel at small-x

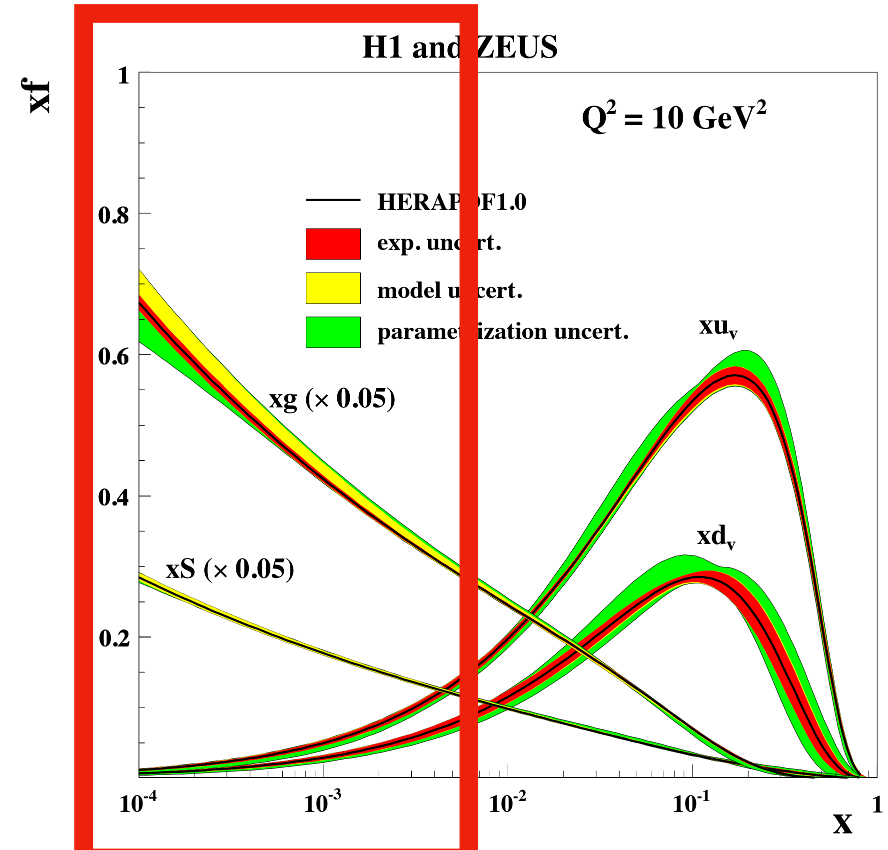


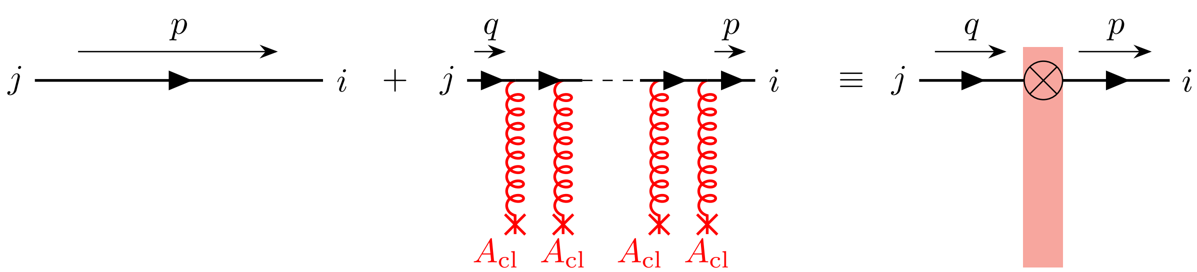
Image source: H1Zeus

Inclusive diparton production in DIS

CGC EFT and Multiple scattering

McLerran, Venugopalan.
hep-ph/9309289, hep-ph/9311205

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



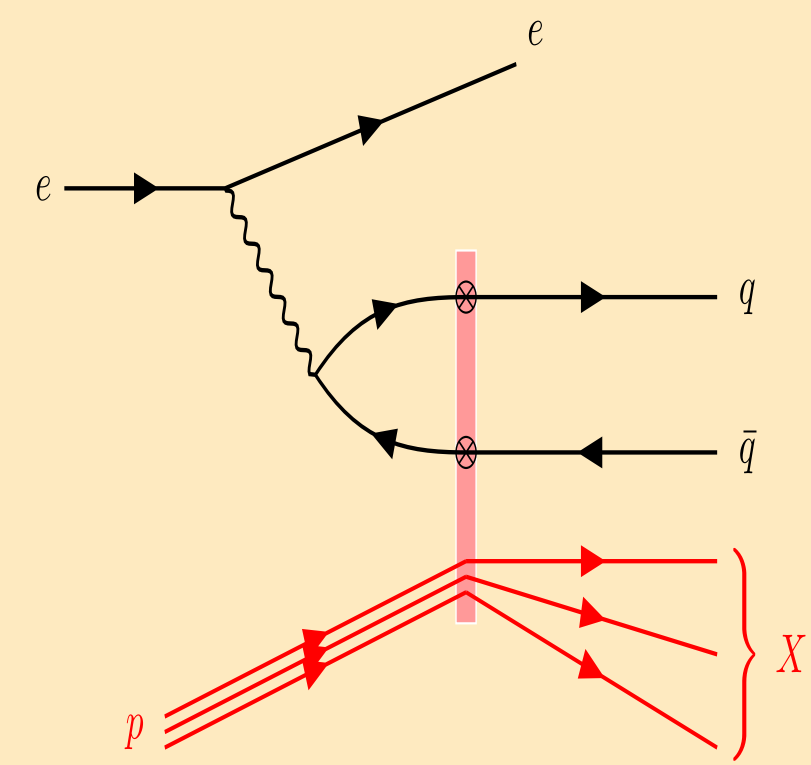
Effective CGC eikonal vertex:

$$\mathcal{T}_{ij}(p,q) = (2\pi)\delta(p^- - q^-)\gamma^- \mathrm{sign}(p^-) \int_{\boldsymbol{z}_\perp} e^{-i(\boldsymbol{p}_\perp - \boldsymbol{q}_\perp)\cdot \boldsymbol{z}_\perp} V_{ij}^{\mathrm{sign}(p^-)}(\boldsymbol{z}_\perp)$$

Light-like Wilson line:

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

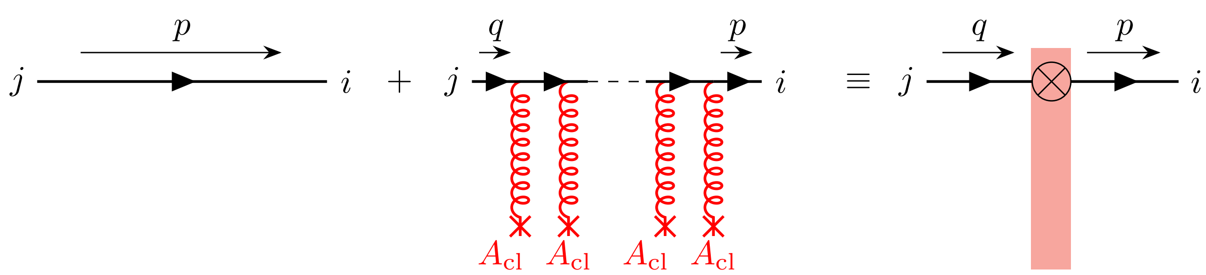
Classical → $A_{cl}^{+,a} = -\dfrac{\rho^a}{\nabla_\perp^2}$ ← large-x



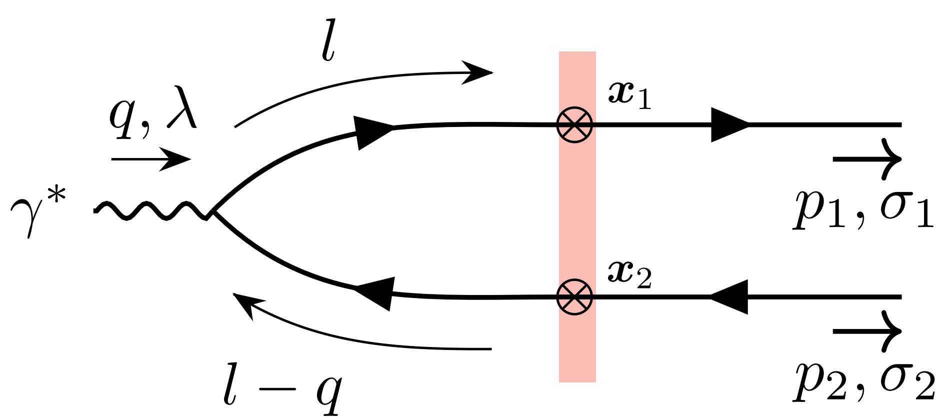
LO diagram in CGC

Inclusive diparton production in DIS

At leading order in the CGC EFT $\gamma_\lambda^* + p \to q\bar{q} + X$



Effective CGC vertex $\mathcal{T}(p,q)$



Scattering amplitude at LO in the CGC

$$\mathcal{S}_\lambda^{\sigma_1,\sigma_2}[\rho_A] = (-ieq_f)\int_l \bar{u}(p_1,\sigma_1)\mathcal{T}(p_1,l)S_0(l)\not\epsilon(q,\lambda) S_0(l-q)\mathcal{T}(l-q,-p_2)v(p_2,\sigma_2)$$

Kinematics in LC coordinates

incoming photon momentum, polarization and virtuality

$$q = \left(-\frac{Q^2}{2q^-}, q^-, \mathbf{0}_\perp\right), \quad \lambda, \quad Q^2 = -q^2$$

Outgoing transverse momenta and longitudinal momentum fraction

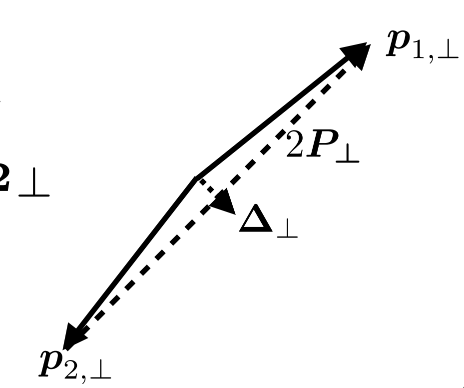
$$\boldsymbol{p_{1,2}}_\perp, \qquad z_{1,2} = \frac{p^-_{1,2}}{q^-}$$

Imbalance and invariant mass

$$\boldsymbol{\Delta}_\perp = \boldsymbol{p_1}_\perp + \boldsymbol{p_2}_\perp$$

$$\boldsymbol{P}_\perp = z_2 \boldsymbol{p_1}_\perp - z_1 \boldsymbol{p_2}_\perp$$

$$M_{\rm inv}^2 = \frac{\boldsymbol{P}_\perp^2}{z_1 z_2}$$



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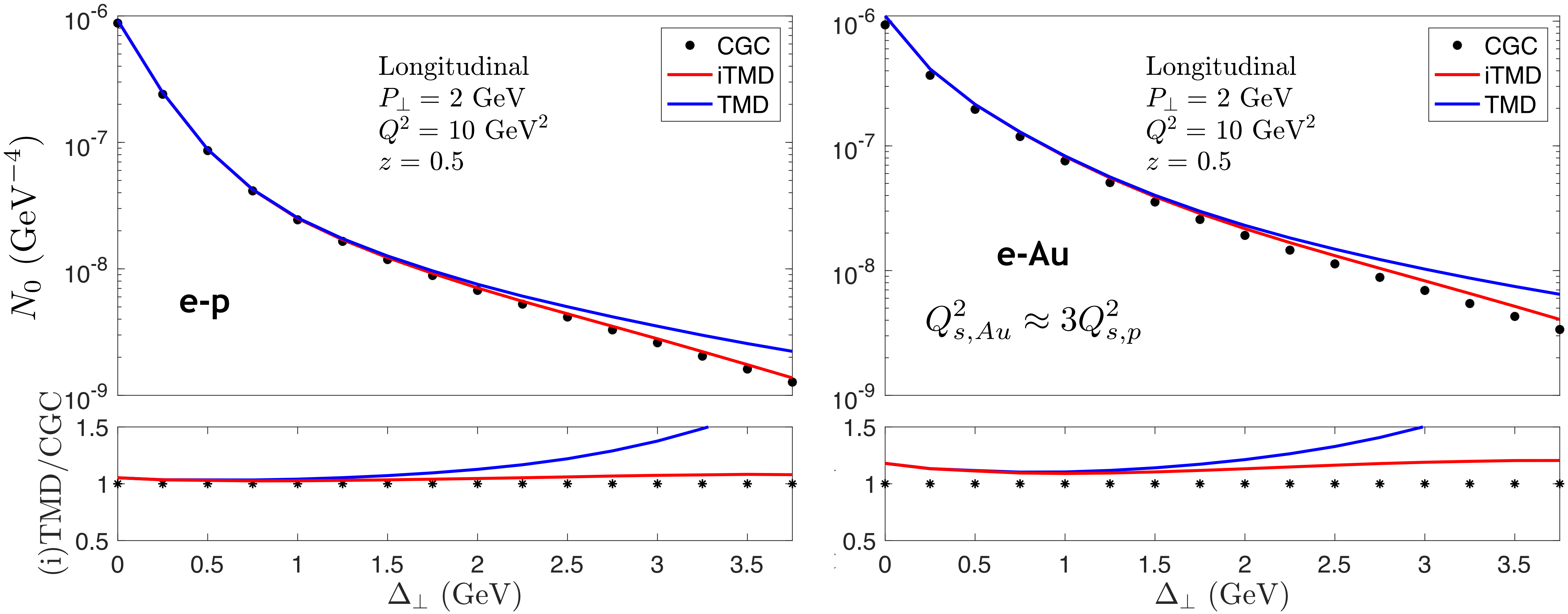

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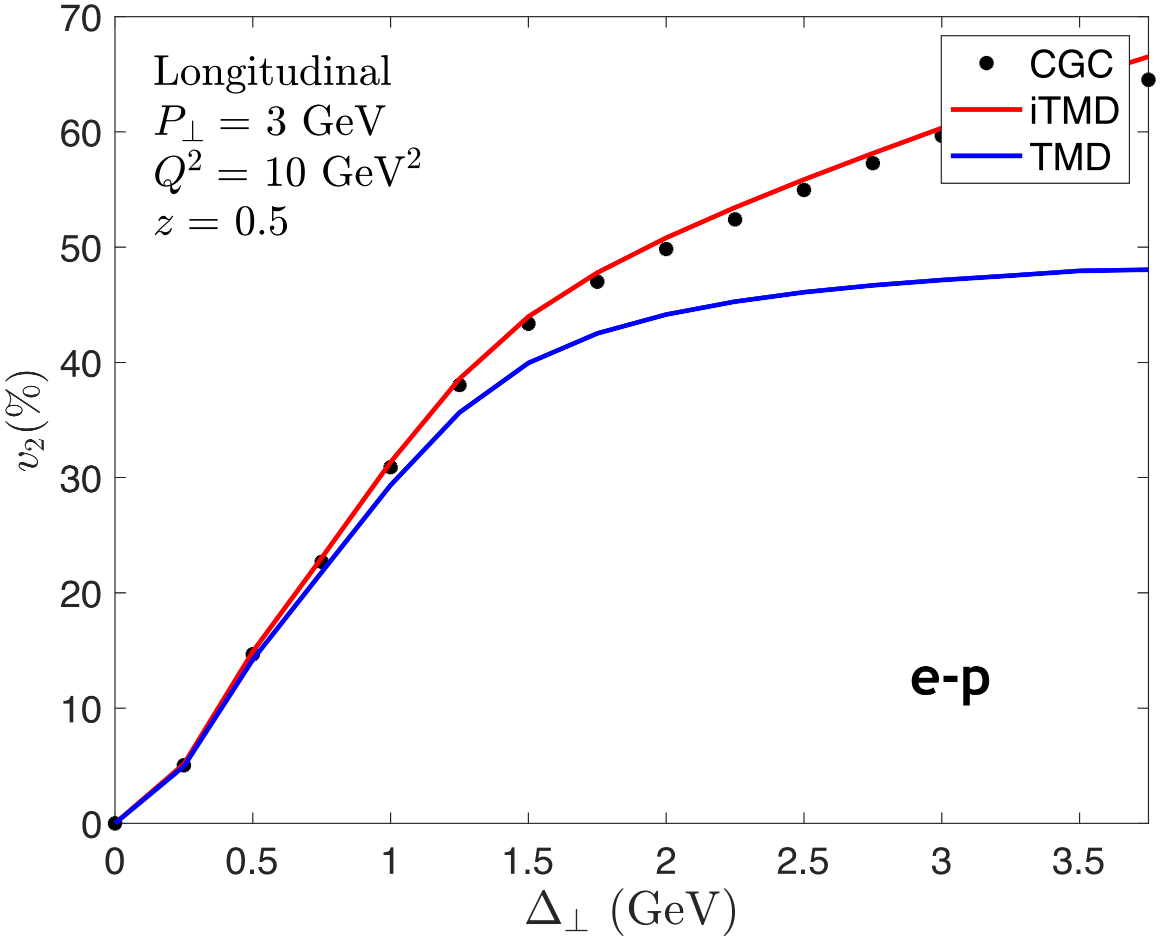

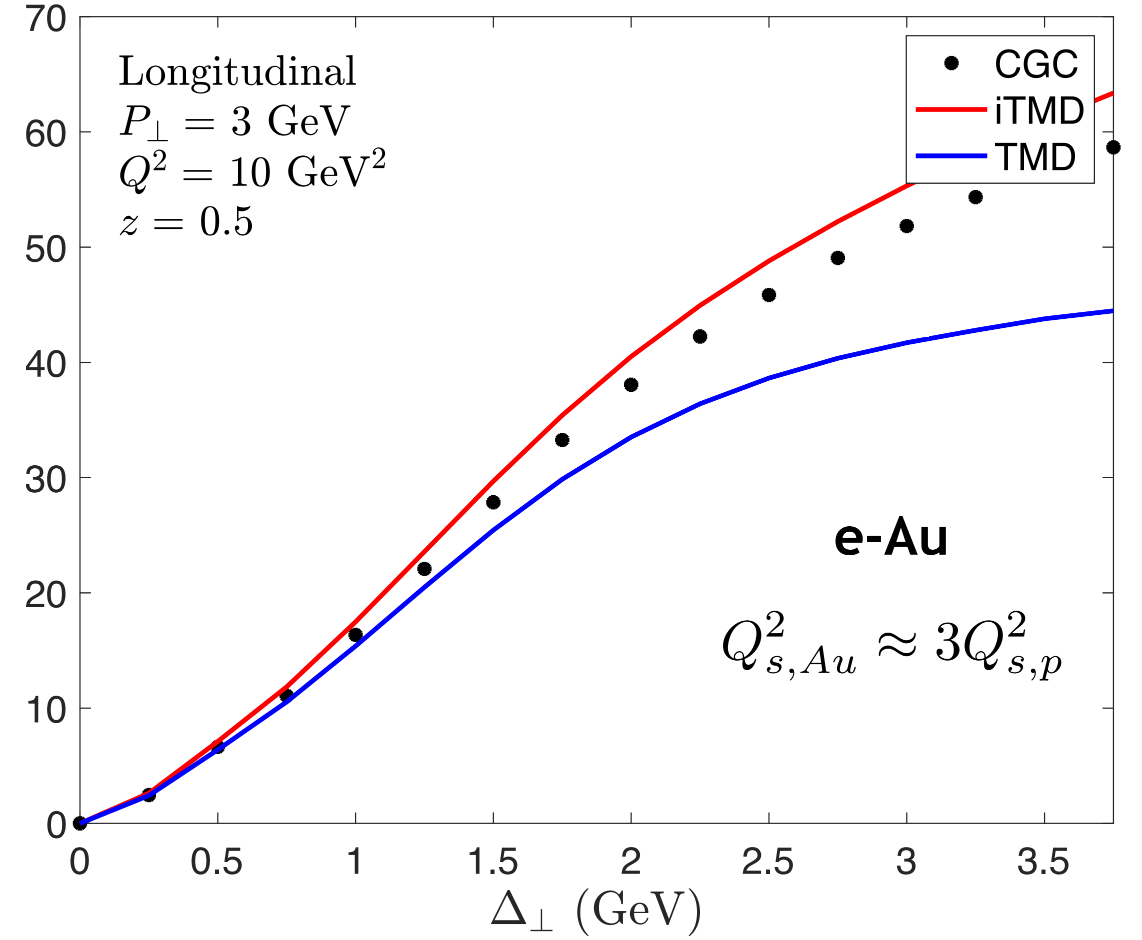

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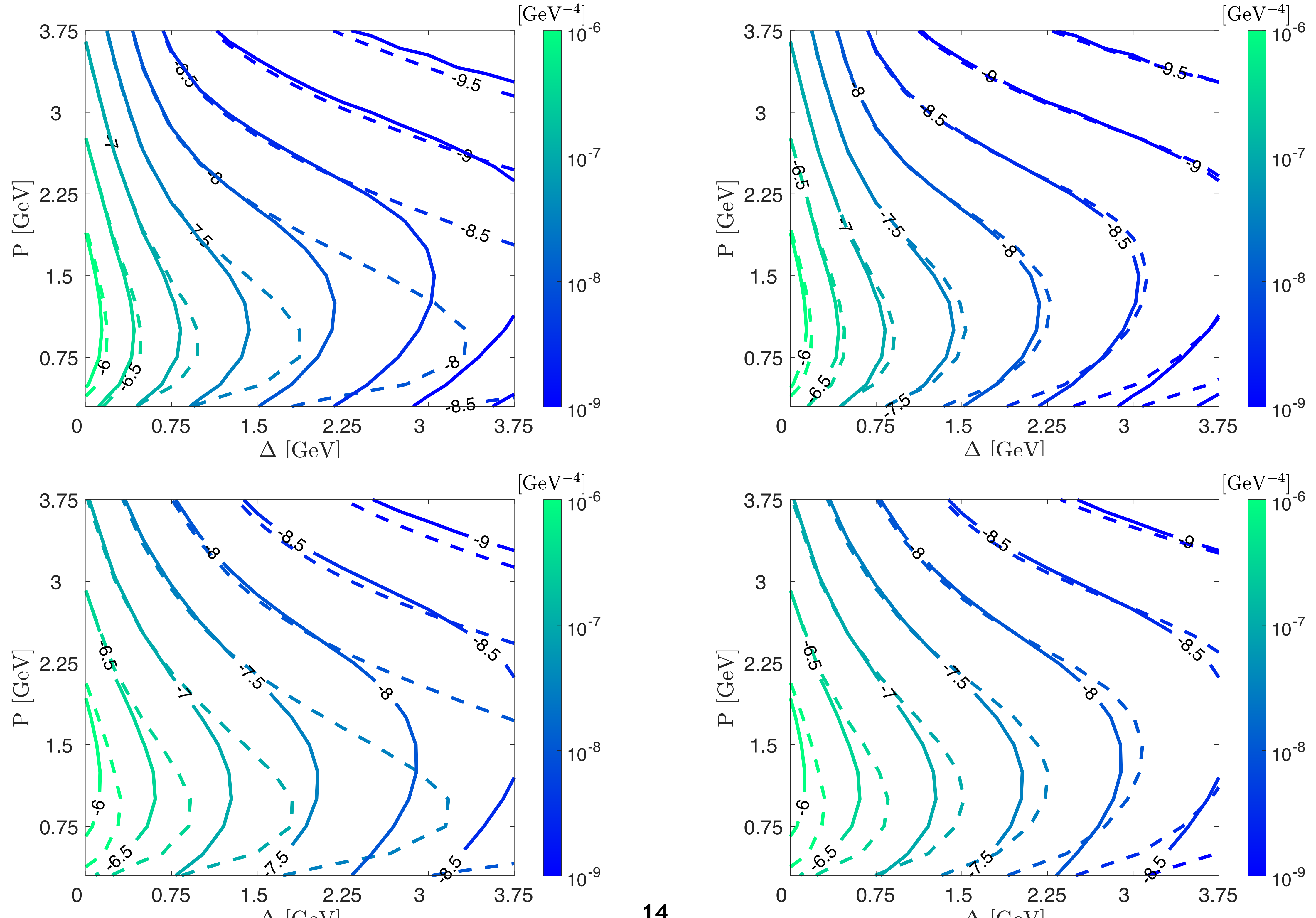
Back-up: $P_\perp$ and $\Delta_\perp$ phase space

The differential yield TMD, iTMD and CGC (longitudinal photon pol)

$Q^2 = 10\ \mathrm{GeV}^2$ TMD vs CGC Improved TMD vs CGC

e-p

e-Au



Solid line CGC, dashed line TMD

Solid line CGC, dashed line iTMD

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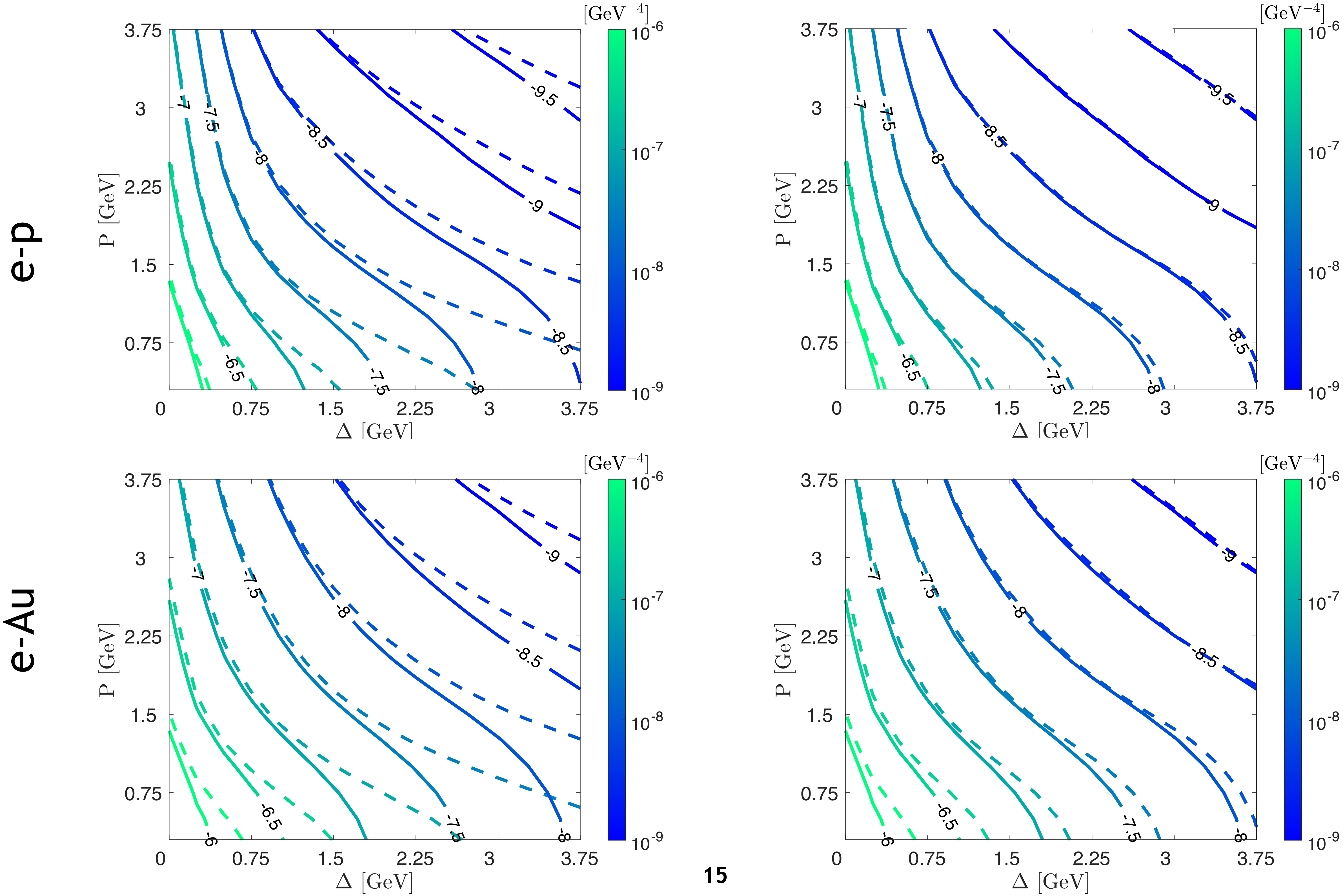


Back-up: TMD factorization

Dominguez, Marquet, Xiao, Yuan. 1101.0715

In coordinate space the diparton production amplitude in the CGC is given by

$$\mathcal{M}_{ij}^{\gamma^* A\to q\bar{q}X} \sim \int_{\boldsymbol{r}_\perp,\boldsymbol{b}_\perp} e^{-i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp} e^{-i\boldsymbol{P}_\perp\cdot\boldsymbol{r}_\perp} \Psi^{\gamma^*\to q\bar{q}}(\boldsymbol{r}_\perp) \left[\mathcal{I} - V\left(\boldsymbol{b}_\perp + z_1\boldsymbol{r}_\perp\right) V^\dagger\left(\boldsymbol{b}_\perp - z_2\boldsymbol{r}_\perp\right)\right]$$

Small dipole size expansion $r_\perp \ll b_\perp$

$$\left[\mathcal{I} - V^\dagger\left(\boldsymbol{b}_\perp + \bar{z}\boldsymbol{r}_\perp\right) V\left(\boldsymbol{b}_\perp - z\boldsymbol{r}_\perp\right)\right] \approx \boldsymbol{r}_\perp^i \left[V^\dagger(\boldsymbol{b}_\perp)\partial^i V(\boldsymbol{b}_\perp)\right]$$

Thus cross-section can be written as

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

Hard-factor:

$$\mathcal{H}^{ij}_{\mathrm{TMD}}(\boldsymbol{P}_\perp) = \mathcal{I}^i(\boldsymbol{P}_\perp)\mathcal{I}^{j,*}(\boldsymbol{P}_\perp)$$

$$\mathcal{I}^i(\boldsymbol{P}_\perp) = \int_{\boldsymbol{r}_\perp} e^{-i\boldsymbol{P}_\perp\cdot\boldsymbol{r}_\perp} \boldsymbol{r}_\perp^i \Psi^{\gamma\to q\bar{q}}(\boldsymbol{r}_\perp)$$

Weizsäcker-Williams gluon TMD at small-x:

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

Back-up: improved TMD factorization

Kotko, Kutak, Marquet, Petreska, Sapeta, van Hameren 1503.03421
Altinoluk, Boussarie, Kotko. 1901.01175 1902.07930
See also Boussarie, Mehtar-Tani. 2001-06449

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

$$\mathcal{H}^{ij}_{\mathrm{iTMD}}(\boldsymbol{P}_\perp, \boldsymbol{\Delta}_\perp) = \mathcal{J}^i(\boldsymbol{P}_\perp, \boldsymbol{\Delta}_\perp)\mathcal{J}^{j,*}(\boldsymbol{P}_\perp, \boldsymbol{\Delta}_\perp)$$

$$\mathcal{J}^i(\boldsymbol{P}_\perp, \boldsymbol{\Delta}_\perp) = \int_{\boldsymbol{r}_\perp} e^{-i\boldsymbol{P}_\perp\cdot\boldsymbol{r}_\perp}\boldsymbol{r}^i_\perp \Psi^{\gamma\to q\bar{q}}(\boldsymbol{r}_\perp)\left[\frac{e^{i\alpha z_2\boldsymbol{\Delta}_\perp\cdot\boldsymbol{r}_\perp} - e^{-i\alpha z_1\boldsymbol{\Delta}_\perp\cdot\boldsymbol{r}_\perp}}{i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{r}_\perp}\right]$$

resums kinematic power corrections

In the limit $\Delta_\perp \to 0$, phase $\to 1$ and $\mathcal{J}^i(\boldsymbol{P}_\perp, \boldsymbol{\Delta}_\perp) \to \mathcal{I}^i(\boldsymbol{P}_\perp)$

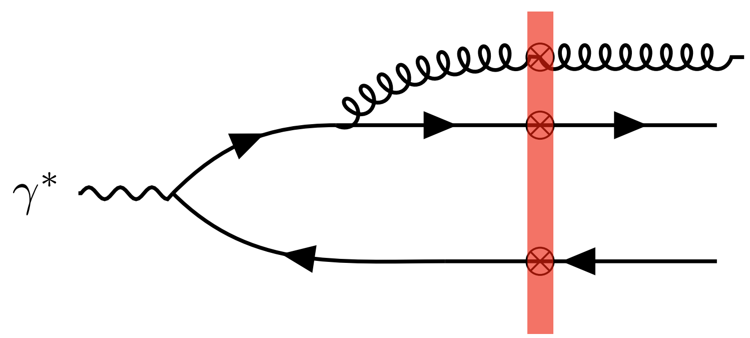
recovering the TMD factorization

Hard factor includes correlations between $\boldsymbol{P}_\perp$ and $\boldsymbol{\Delta}_\perp$

Back-up: diparton production in DIS at NLO in the CGC

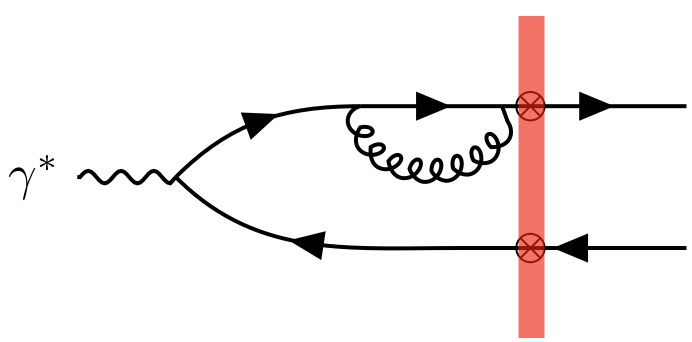
Evolution and impact factor

Real diagrams



+3 others

Virtual diagrams



+ 8 others

Cross section at NLO has
$32\ (= 4 \times 4 + 8 \times 2)$ contributions

$$d\sigma = d\sigma^{(0)} + \alpha_s d\sigma^{(1)} + \mathcal{O}(\alpha_s^2)$$

LO NLO

$$d\sigma = d\sigma^{(0)} + \alpha_s \ln(1/x) \mathcal{H}_{LO} d\sigma^{(0)} + \alpha_s d\sigma^{(1,\mathrm{IF})} + \mathcal{O}(\alpha_s^2)$$

log enhanced
(part of LLx JIMWLK)

impact factor
(not log enhanced)

Dijet studies include LLx JIMWLK/
BK+Gaussian, but miss the **impact factor**

Computing impact factor for diparton production
will provide more theoretical predictive power