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Small-x Weizsäcker-Williams gluon distribution at NLO

Farid Salazar (UCLA/LBL)

California EIC UC Collaboration Meeting
Jan 28th, 2023

Based on

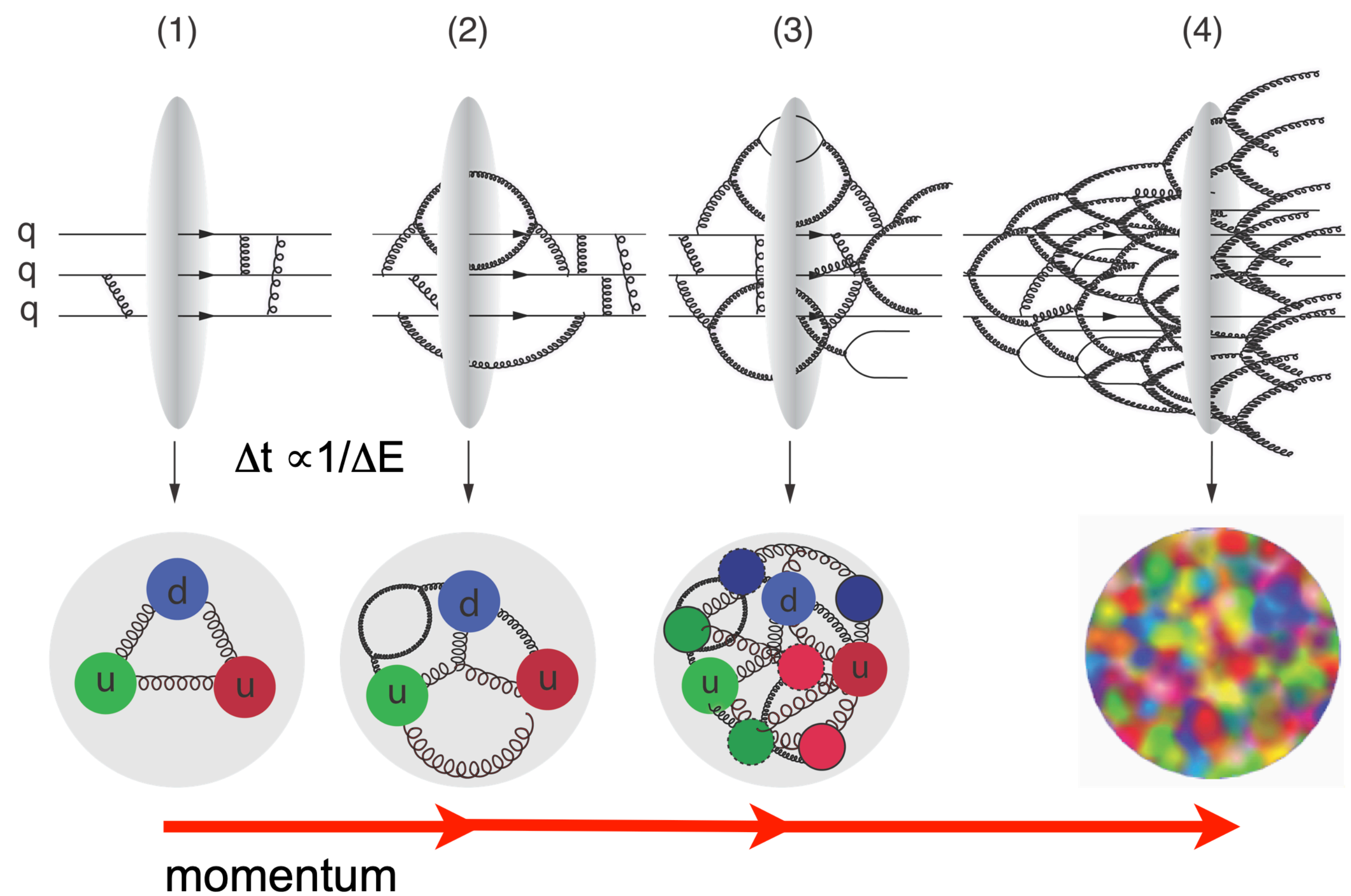
(1) *2108.06347* *[JHEP 11 (2021) 222]*
(2) *2208.13872* *[JHEP 11 (2022) 169]*
(3) *2302.XXXX*

In collaboration with

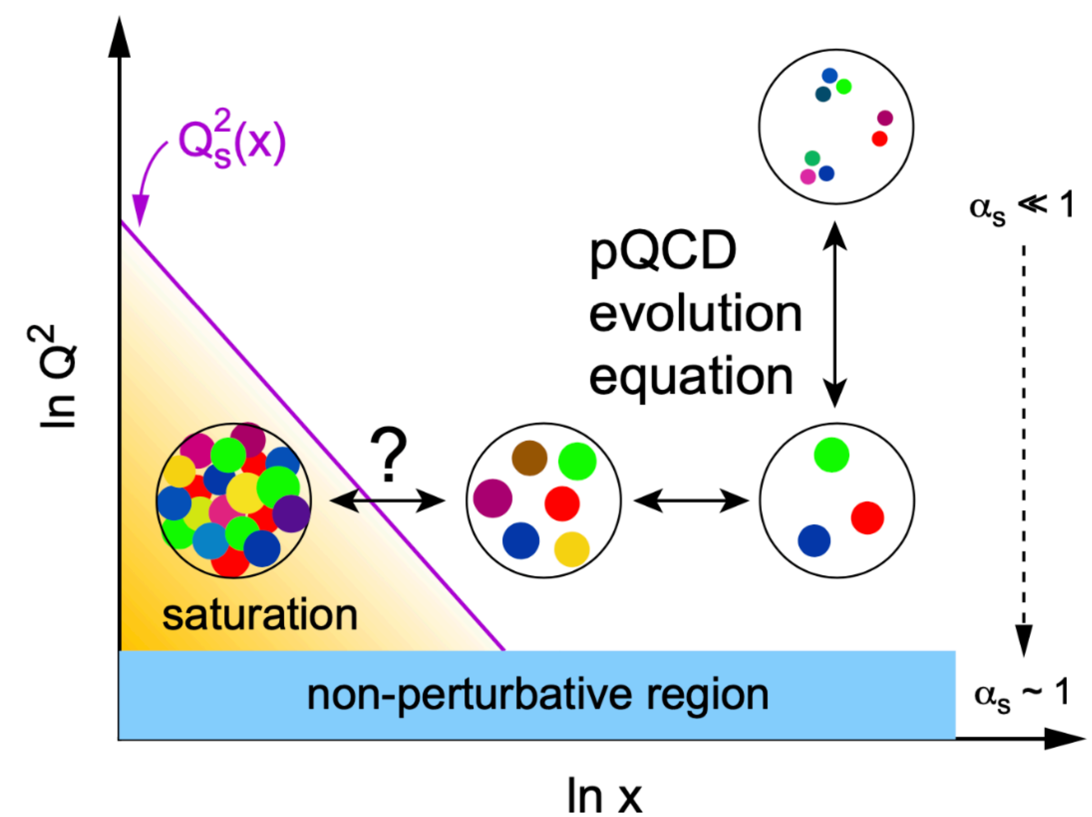
Paul Caucal (Nantes)
Björn Schenke (BNL)
Tomasz Stebel (Jagiellonian)
Raju Venugopalan (BNL)

Gluon saturation

The Color Glass Condensate (CGC) an effective theory for high-energy QCD



Artwork: T. Ullrich



Emergence of an energy and nuclear specie dependent momentum scale (saturation scale)

Multiple scattering (higher twist effects)

Non-linear evolution equations (BK/JIMWLK)

$$Q_s^2 \propto A^{1/3} x^{-\lambda} \qquad x \propto 1/s$$

For a review see Mining gluon saturation at colliders. FS, A. Morreale (Universe 2021)

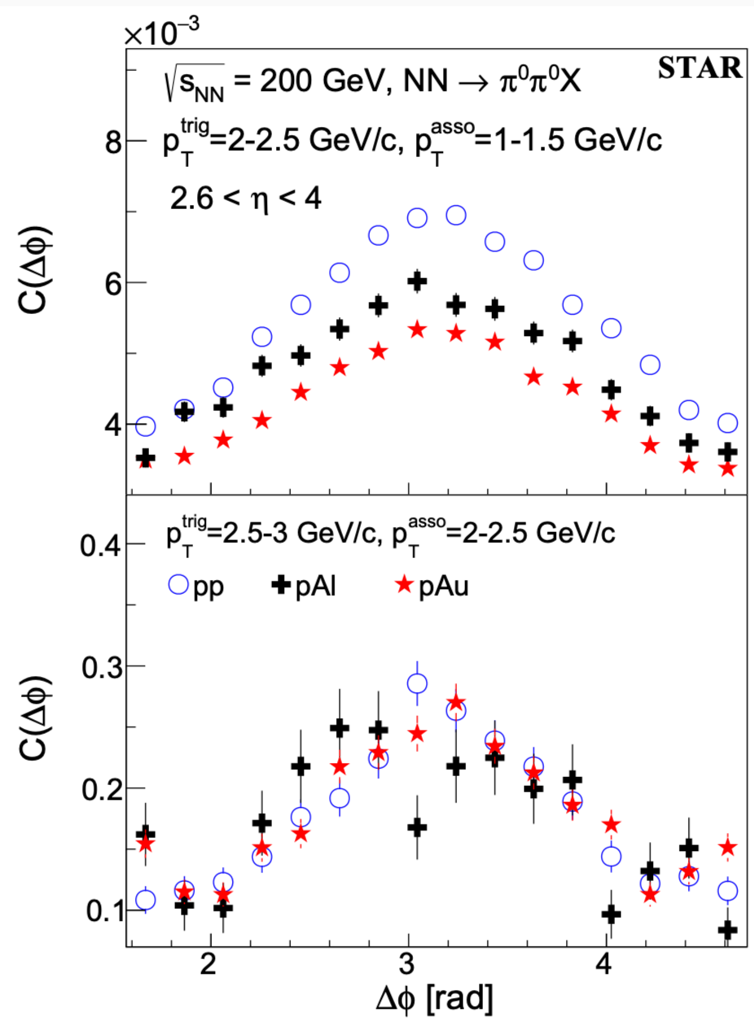
Gluon saturation

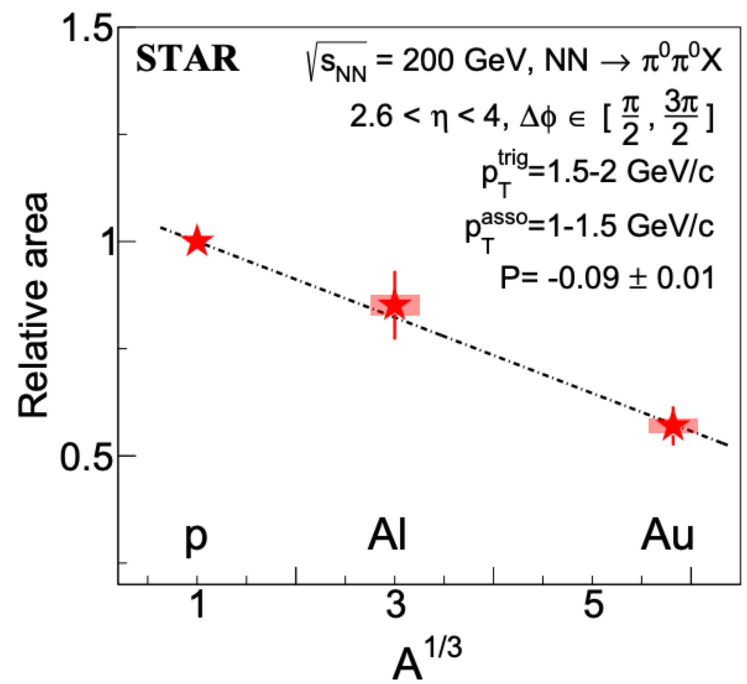
Dihadron azimuthal correlations at RHIC

PHYSICAL REVIEW LETTERS **129**, 092501 (2022)

Evidence for Nonlinear Gluon Effects in QCD and Their Mass Number Dependence at STAR

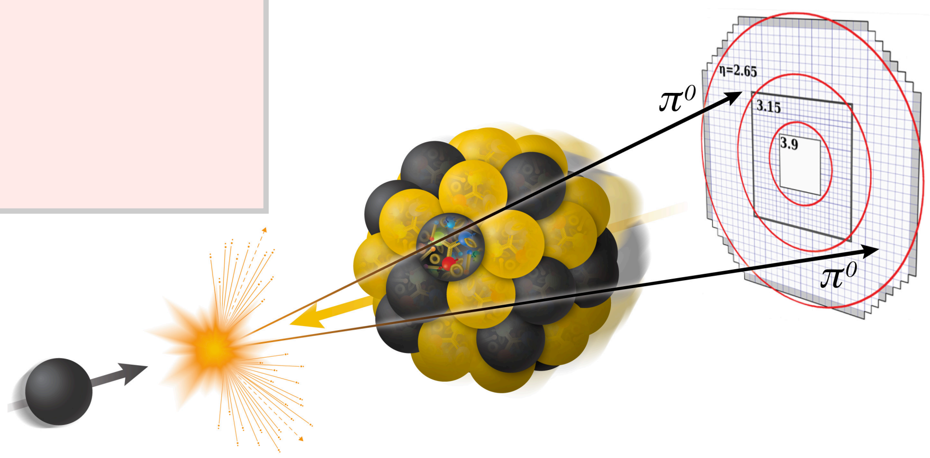
STAR Collaboration





Suppression characteristic of saturation

$$Q_s^2 \propto A^{1/3}$$



Xiaoxuan Chu and Elke Aschenauer

HIT Seminar on Feb 7th!

What about dihadron production at the EIC?

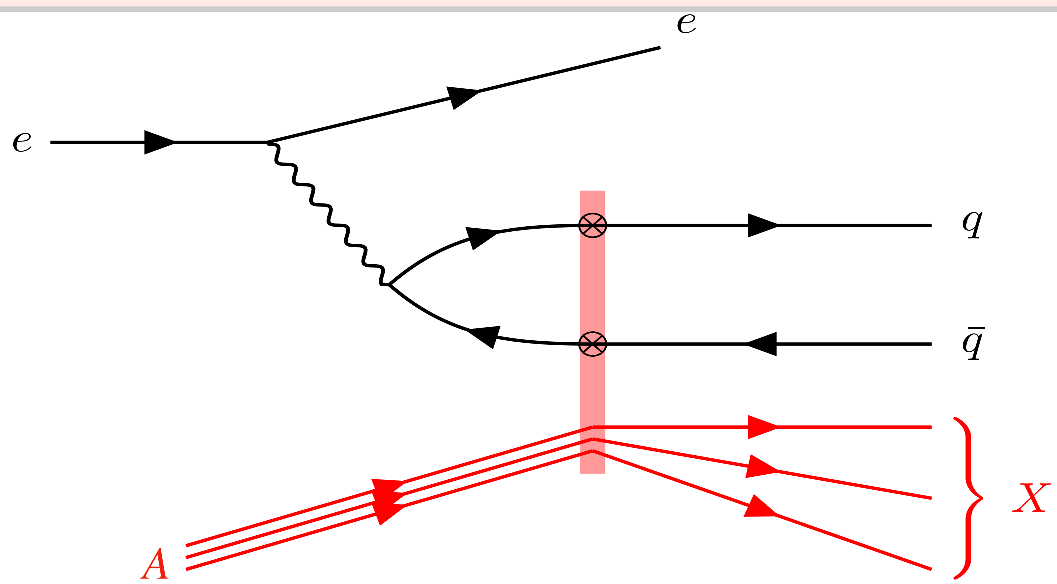
Gluon saturation

Dijet azimuthal correlations in DIS

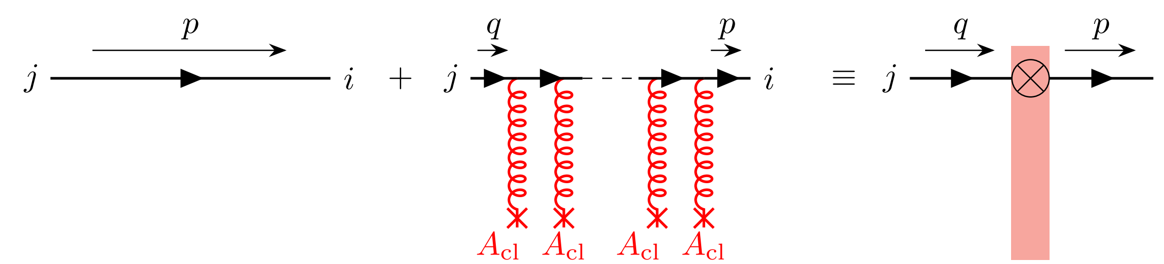
PHYSICAL REVIEW D **67**, 074019 (2003)

From deep inelastic scattering to proton-nucleus collisions in the color glass condensate model

François Gelis   Jamal Jalilian-Marian



Effective interaction of quark with CGC:



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

Unpolarized differential cross-section:

$$\frac{\mathrm{d}\sigma^{\gamma_\lambda^* + A \to q\bar{q} + X}}{\mathrm{d}^2\boldsymbol{k}_{\boldsymbol{1}\perp}\mathrm{d}^2\boldsymbol{k}_{\boldsymbol{2}\perp}\mathrm{d}\eta_1\mathrm{d}\eta_2} \propto \int \mathrm{d}^8\boldsymbol{X}_\perp\; e^{-i\boldsymbol{k}_{\boldsymbol{1}\perp}\cdot(\boldsymbol{x}_\perp - \boldsymbol{x}'_\perp)} e^{-i\boldsymbol{k}_{\boldsymbol{2}\perp}\cdot(\boldsymbol{y}_\perp - \boldsymbol{y}'_\perp)}$$
$$\times \boxed{\langle \Xi_{\rm LO}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp; \boldsymbol{y}'_\perp \boldsymbol{x}'_\perp)\rangle_Y} \boxed{\mathcal{R}^\lambda(\boldsymbol{x}_\perp - \boldsymbol{y}_\perp, \boldsymbol{x}'_\perp - \boldsymbol{y}'_\perp)}$$

Correlators of Wilson lines = multiple scattering + non-linear evolution

$q\bar{q}$ interaction with nucleus

γ^* splitting to $q\bar{q}$

Numerical evaluation is challenging, done for the first time in 2020

PHYSICAL REVIEW LETTERS **124**, 112301 (2020)

Multigluon Correlations and Evidence of Saturation from Dijet Measurements at an Electron-Ion Collider

Heikki Mäntysaari,[1,2,*] Niklas Mueller,[3,†] Farid Salazar,[3,4,‡] and Björn Schenke[3,§]

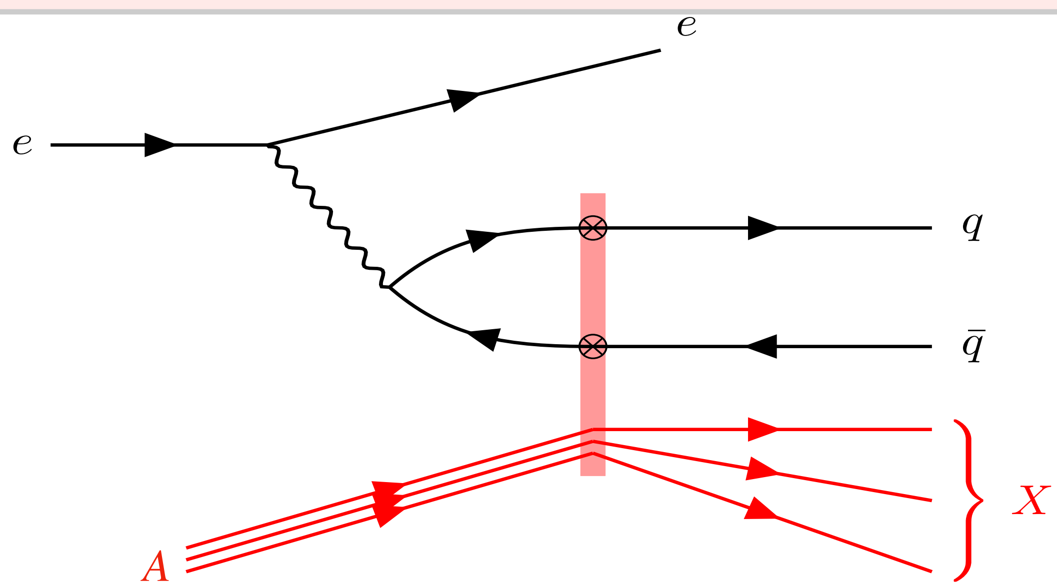
CGC and TMD correspondence

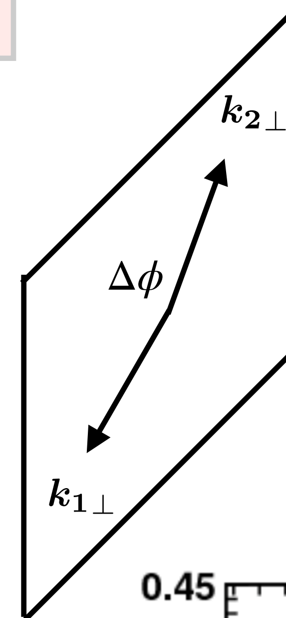
Small-x Weizsäcker-Williams distribution

PHYSICAL REVIEW D **83,** 105005 (2011)

Universality of unintegrated gluon distributions at small *x*

Fabio Dominguez,[1] Cyrille Marquet,[2] Bo-Wen Xiao,[3,4] and Feng Yuan[4,5]





$$\boldsymbol{k}_\perp = \boldsymbol{k}_{1\perp} + \boldsymbol{k}_{2\perp}$$

$$\boldsymbol{P}_\perp = z_2 \boldsymbol{k}_{1\perp} - z_1 \boldsymbol{k}_{2\perp}$$

$\Delta\phi$ distribution sensitive to gluon saturation Q_s via WW

Dijets are produced back-to-back (in transverse place)
CGC cross-section factorizes:

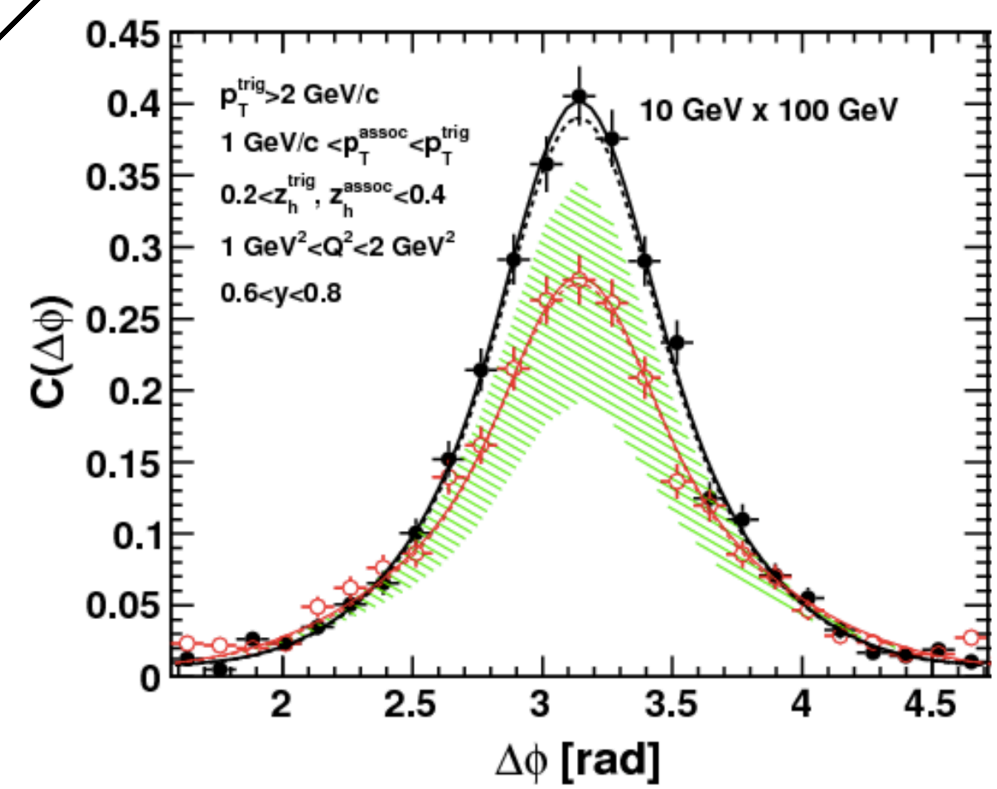
$$\mathrm{d}\sigma^{\gamma^*_\lambda + A \to q\bar{q} + X} \sim \mathcal{H}^{ij}(Q, \boldsymbol{P}_\perp)\, \alpha_s G^{ij}_Y(\boldsymbol{k}_\perp)$$

Perturbatively calculable

WW gluon TMD

Typical momentum of WW $< k_\perp > \sim Q_s$

Nuclear dependence $Q_s^2 \propto A^{1/3}$



Zheng, Aschenauer, Lee, Xiao (2014)

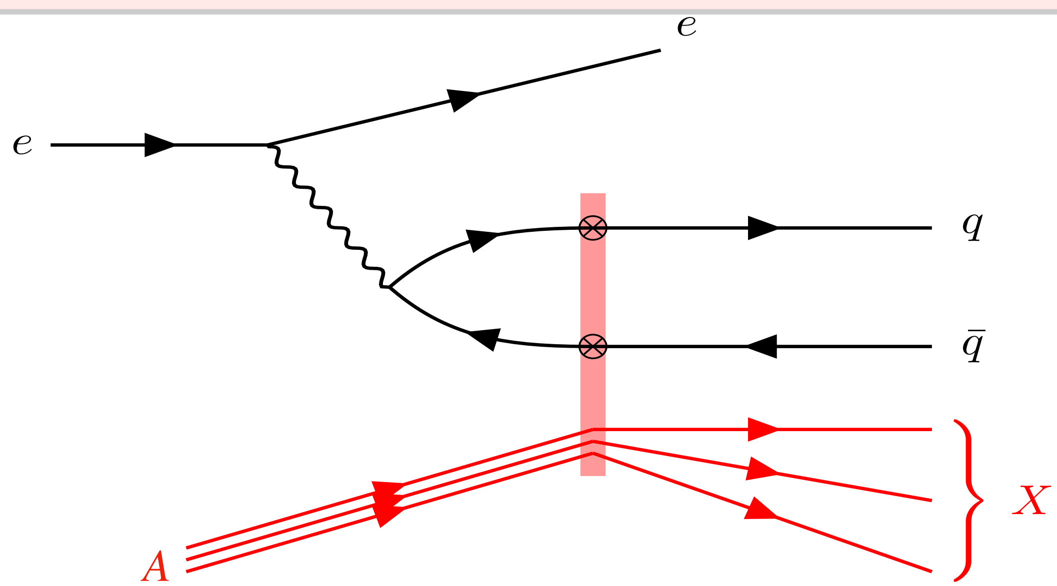
CGC and TMD correspondence

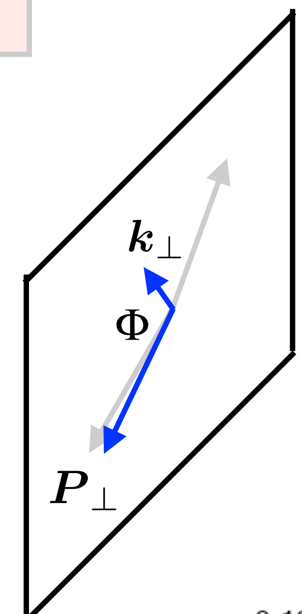
Small-x Weizsäcker-Williams distribution

PHYSICAL REVIEW D **85,** 045003 (2012)

Linearly polarized gluon distributions in the color dipole model

Fabio Dominguez,[1] Jian-Wei Qiu,[2,3] Bo-Wen Xiao,[4] and Feng Yuan[5]





$$\boldsymbol{k}_\perp = \boldsymbol{k_1}_\perp + \boldsymbol{k_2}_\perp$$
$$\boldsymbol{P}_\perp = z_2\boldsymbol{k_1}_\perp - z_1\boldsymbol{k_2}_\perp$$

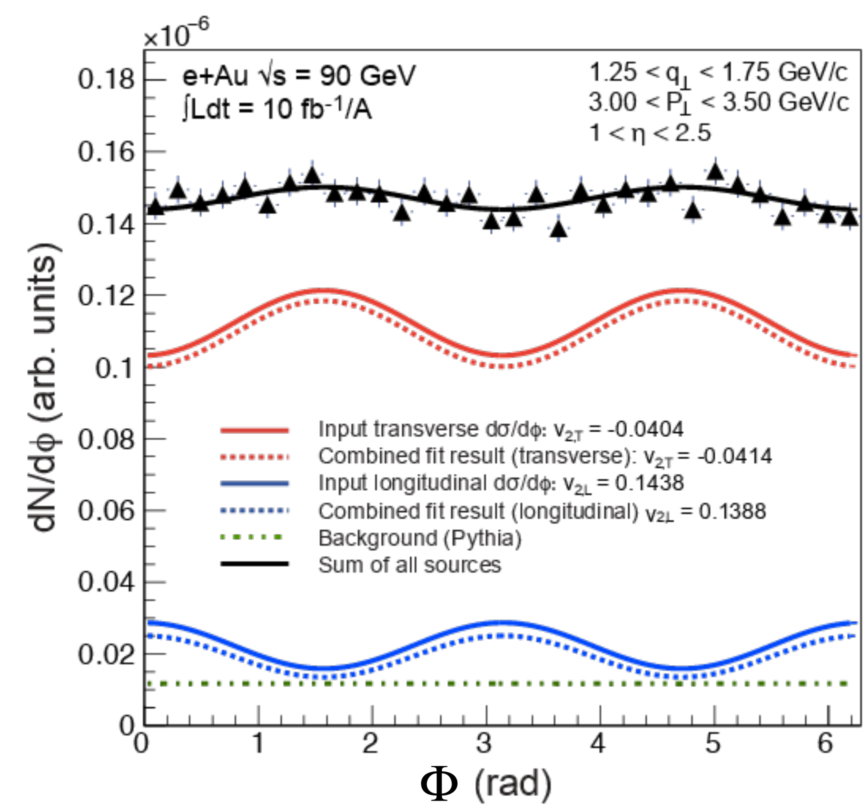
Φ distribution sensitive to linearly polarized WW gluon TMD

Dijets are produced back-to-back (in transverse place)
CGC cross-section factorizes:

$$\mathrm{d}\sigma^{\gamma_\lambda^* + A \to q\bar{q} + X} \sim \underbrace{\mathcal{H}^{ij}(Q, \boldsymbol{P}_\perp)}_{\text{Perturbatively calculable}} \underbrace{\alpha_s G_Y^{ij}(\boldsymbol{k}_\perp)}_{\text{WW gluon TMD}}$$

$$\langle \cos(2\Phi) \rangle \propto h_Y^0(\boldsymbol{k}_\perp)/G_Y^0(\boldsymbol{k}_\perp)$$

Ratio linearly polarized to unpolarized WW



Dumitru, Skokov, Ullrich (2018)

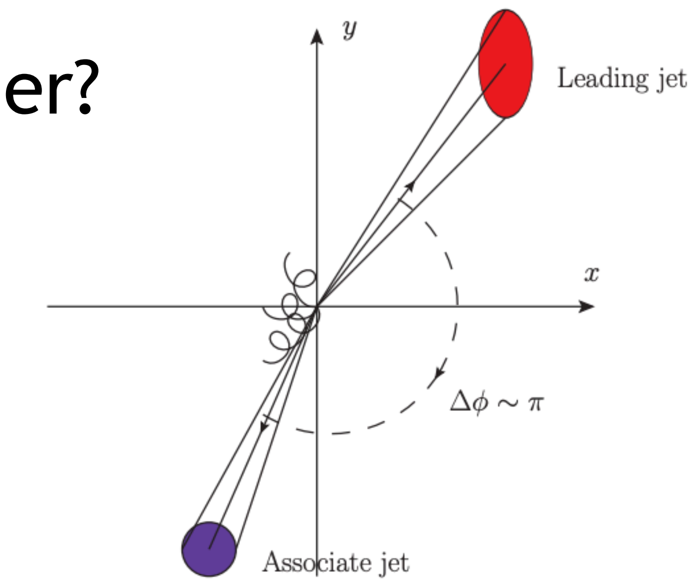
CGC and TMD correspondence

Does correspondence hold at next-to-leading order?

PHYSICAL REVIEW D **88,** 114010 (2013)

Sudakov double logarithms resummation in hard processes in the small-x saturation formalism

A. H. Mueller,[1] Bo-Wen Xiao,[2] and Feng Yuan[3]



Conjecture: joint (soft) Sudakov + small-x resummation

$$\mathrm{d}\sigma^{\gamma^*_\lambda + A \to q\bar{q} + X} \propto \mathcal{H}(Q, \boldsymbol{P}_\perp) \int \frac{\mathrm{d}^2 \boldsymbol{b}_\perp}{(2\pi)^2} e^{-i\boldsymbol{q}_\perp \cdot \boldsymbol{b}_\perp} \alpha_s \widetilde{G}^0_Y(\boldsymbol{b}_\perp) e^{-S_{\mathrm{Sud}}(\boldsymbol{b}_\perp, \boldsymbol{P}_\perp)}$$

Perturbative Sudakov factor:

$$S_{\mathrm{Sud}}(\boldsymbol{b}_\perp, Q) = \int_{\mu_b^2}^{Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2} \left[A \log\left(\frac{Q^2}{\bar{\mu}^2}\right) + B \right]$$

Soft gluon emissions $\longrightarrow$ Change profile of azimuthal correlations

Can we derive these results more rigorously? Can we obtain finite NLO pieces?

CGC and TMD correspondence

Full CGC calculation at NLO

JHEP

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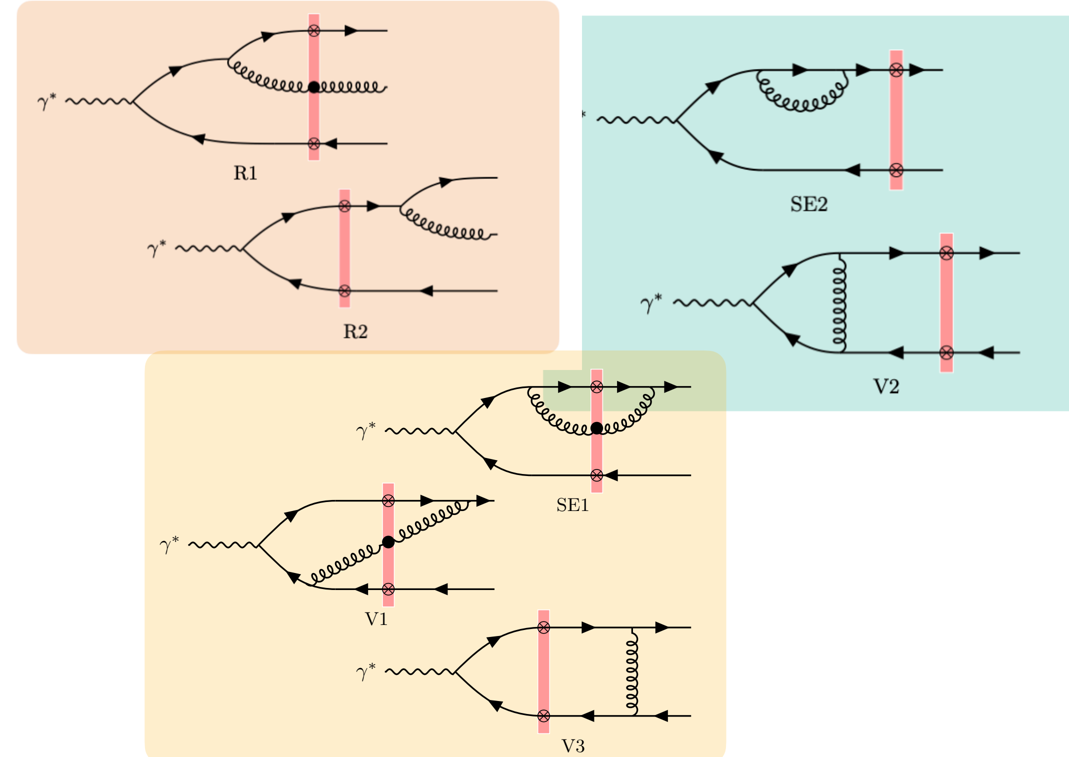
Dijet impact factor in DIS at next-to-leading order in the Color Glass Condensate

Paul Caucal,[a] Farid Salazar[a,b,c] and Raju Venugopalan[a]



$$\mathrm{d}\sigma_{\mathrm{NLO}} = \boxed{\mathrm{d}\widetilde{\sigma}_0 \ln\left(\frac{z_f}{z_0}\right)} + \boxed{\int_0^z \frac{\mathrm{d}z_g}{z_g}\left[\mathrm{d}\widetilde{\sigma}_{\mathrm{NLO}} - \mathrm{d}\widetilde{\sigma}_0 \Theta(z_f - z_g)\right]}$$

Large log at smal−x

impact factor

$$\left.\frac{\mathrm{d}\sigma^{\lambda}_{\mathrm{NLO}}}{\mathrm{d}^2\boldsymbol{k}_{1\perp}\mathrm{d}\eta_1\mathrm{d}^2\boldsymbol{k}_{2\perp}\mathrm{d}\eta_2}\right|_{\mathrm{LLx}} = \frac{\alpha_{\mathrm{em}}e_f^2 N_c}{(2\pi)^6}\delta(1-z_q-z_{\bar{q}})\int \mathrm{d}\boldsymbol{X}_\perp \mathcal{R}^{\lambda}_{\mathrm{LO}}(\boldsymbol{r}_{xy},\boldsymbol{r}_{x'y'})\ln\left(\Lambda_f^-/\Lambda^-\right)$$

$\mathcal{H}_{\mathrm{LL}}\left\langle \Xi_{\mathrm{LO}}(\boldsymbol{x}_\perp,\boldsymbol{y}_\perp;\boldsymbol{x}'_\perp\boldsymbol{y}'_\perp)\right\rangle_Y$

$$\begin{aligned}\times\frac{\alpha_s N_c}{4\pi^2}\Big\langle\int \mathrm{d}^2\boldsymbol{z}_\perp\Big\{&\frac{\boldsymbol{r}^2_{xy}}{\boldsymbol{r}^2_{zx}\boldsymbol{r}^2_{zy}}(2D_{xy}-2D_{xz}D_{zy}+D_{zy}Q_{y'x',xz}+D_{xz}Q_{y'x',zy}-Q_{xy,y'x'}-D_{xy}D_{y'x'})\\ &+\frac{\boldsymbol{r}^2_{x'y'}}{\boldsymbol{r}^2_{zx'}\boldsymbol{r}^2_{zy'}}(2D_{y'x'}-2D_{y'z}D_{zx'}+D_{zx'}Q_{xy,y'z}+D_{y'z}Q_{xy,zx'}-Q_{xy,y'x'}-D_{xy}D_{y'x'})\\ &+\frac{\boldsymbol{r}^2_{xx'}}{\boldsymbol{r}^2_{zx}\boldsymbol{r}^2_{zx'}}(D_{zx'}Q_{xy,y'z}+D_{xz}Q_{y'x',zy}-Q_{xy,y'x'}-D_{xx'}D_{y'y})\\ &+\frac{\boldsymbol{r}^2_{yy'}}{\boldsymbol{r}^2_{zy}\boldsymbol{r}^2_{zy'}}(D_{y'z}Q_{xy,zx'}+D_{zy}Q_{y'x',xz}-Q_{xy,y'x'}-D_{xx'}D_{y'y})\\ &+\frac{\boldsymbol{r}^2_{xy'}}{\boldsymbol{r}^2_{zx}\boldsymbol{r}^2_{zy'}}(D_{xx'}D_{y'y}+D_{xy}D_{y'x'}-D_{zx'}Q_{xy,y'z}-D_{zy}Q_{y'x',xz})\\ &+\frac{\boldsymbol{r}^2_{x'y}}{\boldsymbol{r}^2_{zx'}\boldsymbol{r}^2_{zy}}(D_{xx'}D_{y'y}+D_{xy}D_{y'x'}-D_{y'z}Q_{xy,zx'}-D_{xz}Q_{y'x',zy})\Big\}\Big\rangle_Y\end{aligned}$$

Small-x evolution of dipole and quadrupole!

JIMWLK LL Hamiltonian acting on LO cross-section → Renormalization of Wilson line operators

CGC and TMD correspondence

Full CGC calculation at NLO

Published for SISSA by Springer

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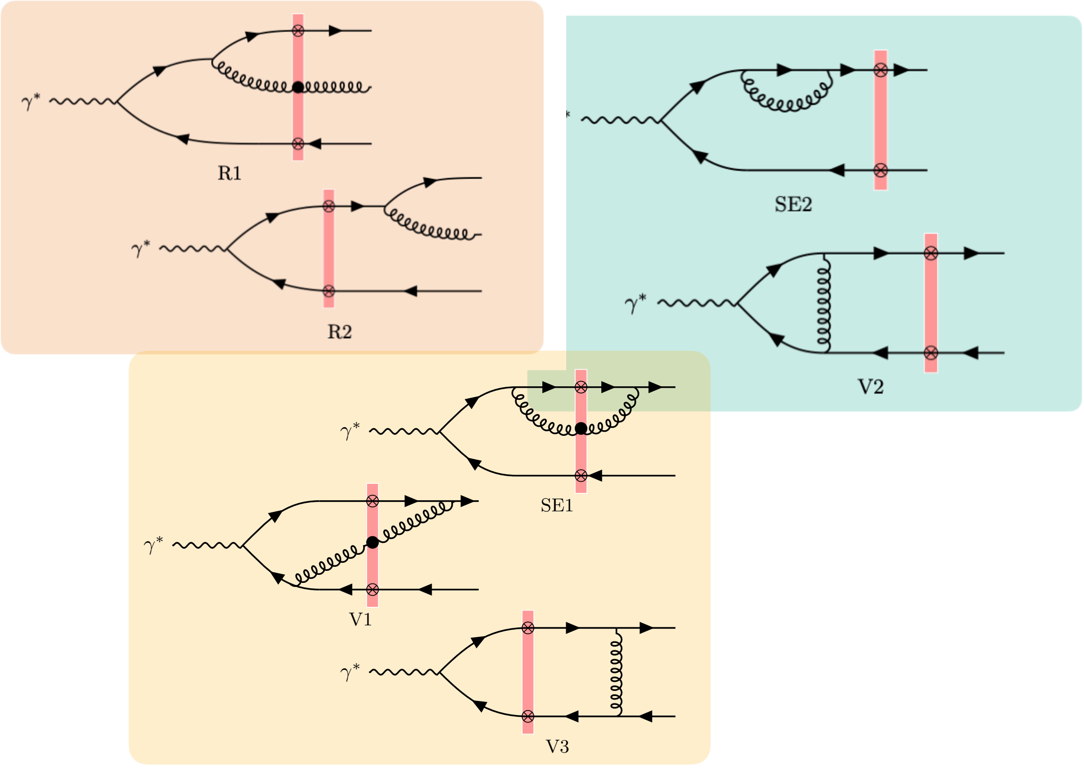
Dijet impact factor in DIS at next-to-leading order in the Color Glass Condensate

Paul Caucal,[a] Farid Salazar[a,b,c] and Raju Venugopalan[a]

$$\mathrm{d}\sigma_{\mathrm{NLO}} = \boxed{\mathrm{d}\widetilde{\sigma}_0 \ln\left(\frac{z_f}{z_0}\right)} + \boxed{\int_0^z \frac{\mathrm{d}z_g}{z_g}\left[\mathrm{d}\widetilde{\sigma}_{\mathrm{NLO}} - \mathrm{d}\widetilde{\sigma}_0 \Theta(z_f - z_g)\right]}$$

Large log at smal−x

impact factor



$$\mathrm{d}\sigma_{\mathrm{R_2\times R_2,sud2}} = \frac{\alpha_{\mathrm{em}} e_f^2 N_c \delta_z^{(2)}}{(2\pi)^6} \int \mathrm{d}^8\boldsymbol{X}_\perp e^{-i\boldsymbol{k_{1\perp}}\cdot\boldsymbol{r}_{xx'} - i\boldsymbol{k_{2\perp}}\cdot\boldsymbol{r}_{yy'}} \mathcal{R}^\lambda_{\mathrm{LO}}(\boldsymbol{r}_{xy}, \boldsymbol{r}_{x'y'})$$
$$\times C_F \Xi_{\mathrm{LO}}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp; \boldsymbol{x}'_\perp, \boldsymbol{y}'_\perp) \times \frac{\alpha_s}{\pi}\int_0^1 \frac{\mathrm{d}\xi}{\xi}\left[1 - e^{-i\xi\boldsymbol{k_{1\perp}}\cdot\boldsymbol{r}_{xx'}}\right] \ln\left(\frac{\boldsymbol{k_{1\perp}}^2 \boldsymbol{r}^2_{xx'} R^2 \xi^2}{c_0^2}\right)$$

$$\mathrm{d}\sigma_{\mathrm{sud1}} = \frac{\alpha_{\mathrm{em}} e_f^2 N_c \delta_z^{(2)}}{(2\pi)^6} \int \mathrm{d}^8\boldsymbol{X}_\perp e^{-i\boldsymbol{k_{1\perp}}\cdot\boldsymbol{r}_{xx'} - i\boldsymbol{k_{2\perp}}\cdot\boldsymbol{r}_{yy'}} \mathcal{R}^\lambda_{\mathrm{LO}}(\boldsymbol{r}_{xy}, \boldsymbol{r}_{x'y'}) \times \frac{\alpha_s}{\pi}$$
$$\times \left\{ C_F \Xi_{\mathrm{LO}}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp; \boldsymbol{x}'_\perp, \boldsymbol{y}'_\perp) \left[\ln\left(\frac{z_f}{z_1}\right) \ln\left(\frac{\boldsymbol{r}^2_{xx'}}{|\boldsymbol{r}_{xy}||\boldsymbol{r}_{x'y'}|}\right) + \ln\left(\frac{z_f}{z_2}\right)\ln\left(\frac{\boldsymbol{r}^2_{yy'}}{|\boldsymbol{r}_{xy}||\boldsymbol{r}_{x'y'}|}\right)\right]\right.$$

$$\mathrm{d}\sigma^{\lambda=\mathrm{L}}_{\mathrm{V,no-sud,NLO_3}} = \frac{\alpha_{\mathrm{em}} e_f^2 N_c \delta_z^{(2)}}{(2\pi)^6} \int \mathrm{d}^3\boldsymbol{X}_\perp e^{-i\boldsymbol{k_{1\perp}}\cdot\boldsymbol{r}_{xx'} - i\boldsymbol{k_{2\perp}}\boldsymbol{r}_{yy'}} 8 z_1^3 z_2^3 Q^2 K_0(\bar{Q} r_{x'y'})$$
$$\times \frac{\alpha_s}{\pi}\int_0^{z_1}\frac{\mathrm{d}z_g}{z_g}\left\{K_0(\bar{Q}_{\mathrm{V3}} r_{xy})\left[\left(1-\frac{z_g}{z_1}\right)^2\left(1+\frac{z_g}{z_2}\right)(1+z_g) e^{i(\boldsymbol{P}_\perp + z_g \boldsymbol{q}_\perp)\cdot\boldsymbol{r}_{xy}} K_0(-i\Delta_{\mathrm{V3}} r_{xy})\right.\right.$$
$$\left. - \left(1 - \frac{z_g}{2z_1} + \frac{z_g}{2z_2} - \frac{z_g^2}{2z_1z_2}\right) e^{i\frac{z_g}{z_1}\boldsymbol{k_{1\perp}}\cdot\boldsymbol{r}_{xy}} \mathcal{J}_\odot\left(\boldsymbol{r}_{xy}, \left(1-\frac{z_g}{z_1}\right)\boldsymbol{P}_\perp, \Delta_{\mathrm{V3}}\right)\right]$$
$$\left. + K_0(\bar{Q} r_{xy}) \ln\left(\frac{z_g P_\perp r_{xy}}{c_0 z_1 z_2}\right) + (1\leftrightarrow 2)\right\} \Xi_{\mathrm{NLO},3}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp; \boldsymbol{x}'_\perp, \boldsymbol{y}'_\perp) + c.c.$$

$$\mathrm{d}\sigma_{\mathrm{V,no-sud,LO}} = \frac{\alpha_{\mathrm{em}} e_f^2 N_c \delta_z^{(2)}}{(2\pi)^6} \int \mathrm{d}^8\boldsymbol{X}_\perp e^{-i\boldsymbol{k_{1\perp}}\cdot\boldsymbol{r}_{xx'} - i\boldsymbol{k_{2\perp}}\cdot\boldsymbol{r}_{yy'}} \mathcal{R}^\lambda_{\mathrm{LO}}(\boldsymbol{r}_{xy}, \boldsymbol{r}_{x'y'}) \Xi_{\mathrm{LO}}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp; \boldsymbol{x}'_\perp, \boldsymbol{y}'_\perp)$$
$$\times \frac{\alpha_s C_F}{\pi}\left\{-\frac{3}{4}\ln\left(\frac{\boldsymbol{k_{1\perp}}^2 \boldsymbol{k_{2\perp}}^2 \boldsymbol{r}^2_{xy}\boldsymbol{r}^2_{x'y'}}{c_0^4}\right) - 3\ln(R) + \frac{1}{2}\ln^2\left(\frac{z_1}{z_2}\right) + \frac{11}{2} + 3\ln(2) - \frac{\pi^2}{2}\right\}$$

$$\mathrm{d}\sigma^{\lambda=\mathrm{L}}_{\mathrm{V,no-sud,other}} = \frac{\alpha_{\mathrm{em}} e_f^2 N_c \delta_z^{(2)}}{(2\pi)^6} \int \mathrm{d}^8\boldsymbol{X}_\perp e^{-i\boldsymbol{k_{1\perp}}\cdot\boldsymbol{r}_{xx'} - i\boldsymbol{k_{2\perp}}\boldsymbol{r}_{yy'}} 8 z_1^3 z_2^3 Q^2 K_0(\bar{Q} r_{x'y'}) \int_0^{z_1}\frac{\mathrm{d}z_g}{z_g}$$
$$\times \frac{\alpha_s}{\pi}\int\frac{\mathrm{d}^2\boldsymbol{z}_\perp}{\pi}\left\{\frac{1}{\boldsymbol{r}^2_{zx}}\left[\left(1-\frac{z_g}{z_1}+\frac{z_g^2}{2z_1^2}\right)e^{-i\frac{z_g}{z_1}\boldsymbol{k_{1\perp}}\cdot\boldsymbol{r}_{zx}} K_0(QX_V) - \Theta(z_f - z_g)K_0(\bar{Q} r_{xy})\right]\Xi_{\mathrm{NLO},1}\right.$$
$$- \frac{1}{\boldsymbol{r}^2_{zx}}\left[\left(1-\frac{z_g}{z_1}+\frac{z_g^2}{2z_1^2}\right)e^{-\frac{\boldsymbol{r}^2_{zx}}{\boldsymbol{r}^2_{xy}e^{\gamma_E}}} K_0(\bar{Q} r_{xy}) - \Theta(z_f - z_g) e^{-\frac{\boldsymbol{r}^2_{zx}}{\boldsymbol{r}^2_{xy}e^{\gamma_E}}} K_0(\bar{Q} r_{xy})\right] C_F \Xi_{\mathrm{LO}}$$
$$- \frac{\boldsymbol{r}_{zx}\cdot\boldsymbol{r}_{zy}}{\boldsymbol{r}^2_{zx}\boldsymbol{r}^2_{zy}}\left[\left(1-\frac{z_g}{z_1}\right)\left(1+\frac{z_g}{z_2}\right)\left(1-\frac{z_g}{2z_1}-\frac{z_g}{2(z_2+z_g)}\right)e^{-i\frac{z_g}{z_1}\boldsymbol{k_{1\perp}}\cdot\boldsymbol{r}_{zx}} K_0(QX_V)\right.$$
$$\left.\left. - \Theta(z_f - z_g) K_0(\bar{Q} r_{xy})\right] \Xi_{\mathrm{NLO},1} + (1\leftrightarrow 2)\right\} + c.c..$$

$$\mathrm{d}\sigma_{\mathrm{R_2\times R_2',sud2}} = \frac{\alpha_{\mathrm{em}} e_f^2 N_c \delta_z^{(2)}}{(2\pi)^6} \int \mathrm{d}^8\boldsymbol{X}_\perp e^{-i\boldsymbol{k_{1\perp}}\cdot\boldsymbol{r}_{xx'} - i\boldsymbol{k_{2\perp}}\cdot\boldsymbol{r}_{yy'}} \mathcal{R}^\lambda_{\mathrm{LO}}(\boldsymbol{r}_{xy}, \boldsymbol{r}_{x'y'})$$
$$\times \Xi_{\mathrm{NLO},3}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp; \boldsymbol{x}'_\perp, \boldsymbol{y}'_\perp) \times \frac{(-\alpha_s)}{\pi}\int_0^1\frac{\mathrm{d}\xi}{\xi}\left[1 - e^{-i\xi\boldsymbol{k_{1\perp}}\cdot\boldsymbol{r}_{xy'}}\right]\ln\left(\frac{\boldsymbol{P}^2_\perp \boldsymbol{r}^2_{xy'}\xi^2}{z_2^2 c_0^2}\right)$$
$$\left. + \Xi_{\mathrm{NLO},3}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp; \boldsymbol{x}'_\perp, \boldsymbol{y}'_\perp)\left[\ln\left(\frac{z_1}{z_f}\right)\ln\left(\frac{\boldsymbol{r}^2_{xy'}}{|\boldsymbol{r}_{xy}||\boldsymbol{r}_{x'y'}|}\right) + \ln\left(\frac{z_2}{z_f}\right)\ln\left(\frac{\boldsymbol{r}^2_{yx'}}{|\boldsymbol{r}_{xy}||\boldsymbol{r}_{x'y'}|}\right)\right]\right\}$$

$$\mathrm{d}\sigma^{\gamma^\star_{\mathrm{L}}+A\to q\bar{q}g+X}_{\mathrm{R,no-sud,LO}} = \frac{\alpha_{\mathrm{em}} e_f^2 N_c}{(2\pi)^8} \int \mathrm{d}^8\boldsymbol{X}_\perp e^{-i\boldsymbol{k_{1\perp}}\cdot\boldsymbol{r}_{xx'} - i\boldsymbol{k_{2\perp}}\cdot\boldsymbol{r}_{yy'}} (4\alpha_s C_F) \Xi_{\mathrm{LO}}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp; \boldsymbol{x}'_\perp, \boldsymbol{y}'_\perp)$$
$$\times \frac{e^{-i\boldsymbol{k_{g\perp}}\cdot\boldsymbol{r}_{xx'}}}{(\boldsymbol{k_{g\perp}} - \frac{z_g}{z_1}\boldsymbol{k_{1\perp}})^2}\left\{8 z_1 z_2^3 (1-z_2)^2 Q^2\left(1+\frac{z_g}{z_1}+\frac{z_g^2}{2z_1^2}\right) K_0(\bar{Q}_{\mathrm{R2}} r_{xy}) K_0(\bar{Q}_{\mathrm{R2}} r_{x'y'})\delta_z^{(3)}\right.$$
$$\left. - \mathcal{R}^{\mathrm{L}}_{\mathrm{LO}}(\boldsymbol{r}_{xy}, \boldsymbol{r}_{x'y'})\Theta(z_1 - z_g)\delta_z^{(2)}\right\} + (1\leftrightarrow 2)$$

$$\mathrm{d}\sigma^{\gamma^\star_{\mathrm{L}}+A\to q\bar{q}g+X}_{\mathrm{R,no-sud,NLO_3}} = \frac{\alpha_{\mathrm{em}} e_f^2 N_c}{(2\pi)^8} \int \mathrm{d}^2\boldsymbol{X}_\perp e^{-i\boldsymbol{k_{1\perp}}\cdot\boldsymbol{r}_{xx'} - i\boldsymbol{k_{2\perp}}\cdot\boldsymbol{r}_{yy'}} (-4\alpha_s) \Xi_{\mathrm{NLO},3}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp; \boldsymbol{x}'_\perp, \boldsymbol{y}'_\perp)$$
$$\times \frac{e^{-i\frac{z_g}{z_1}\boldsymbol{k_{1\perp}}\cdot\boldsymbol{r}_{xy'}}}{\boldsymbol{l}^2_\perp}\left\{8 z_1^2 z_2^2 (1-z_2)(1-z_1) Q^2 K_0(\bar{Q}_{\mathrm{R2}} r_{xy}) K_0(\bar{Q}_{\mathrm{R2'}} r_{x'y'})\left[1 + \frac{z_g}{2z_1} + \frac{z_g}{2z_2}\right]\right.$$
$$\left. \times e^{-i\boldsymbol{l}_\perp\cdot\boldsymbol{r}_{xy'}} \frac{\boldsymbol{l}_\perp\cdot(\boldsymbol{l}_\perp + \boldsymbol{K}_\perp)}{(\boldsymbol{l}_\perp + \boldsymbol{K}_\perp)^2}\delta_z^{(3)} - \mathcal{R}^{\mathrm{L}}_{\mathrm{LO}}(\boldsymbol{r}_{xy}, \boldsymbol{r}_{x'y'})\Theta\left(\frac{c_0^2}{\boldsymbol{r}^2_{xy'}} \geq \boldsymbol{l}^2_\perp \geq \boldsymbol{K}^2_\perp\right)\Theta(z_1 - z_g)\delta_z^{(2)}\right\}$$
$$+ (1\leftrightarrow 2)$$

$$\mathrm{d}\sigma^{\gamma^\star_{\mathrm{L}}+A\to q\bar{q}g+X}_{\mathrm{R,no-sud,other}} = \frac{\alpha_{\mathrm{em}} e_f^2 N_c \delta_z^{(3)}}{(2\pi)^8} \int \mathrm{d}^8\boldsymbol{X}_\perp e^{-i\boldsymbol{k_{1\perp}}\cdot\boldsymbol{r}_{xx'} - i\boldsymbol{k_{2\perp}}\cdot\boldsymbol{r}_{yy'}} 8 z_1^3 z_2^3 Q^2 \int \frac{\mathrm{d}^2\boldsymbol{z}_\perp}{\pi}\frac{\mathrm{d}^2\boldsymbol{z}'_\perp}{\pi} e^{-i\boldsymbol{k_{g\perp}}\cdot\boldsymbol{r}_{zz'}}$$
$$\alpha_s\left\{-\frac{\boldsymbol{r}_{zx}\cdot\boldsymbol{r}_{z'x'}}{\boldsymbol{r}^2_{zx}\boldsymbol{r}^2_{z'x'}} K_0(QX_{\mathrm{R}}) K_0(\bar{Q}_{\mathrm{R2}} r_{w'y'})\left(1+\frac{z_g}{z_1}+\frac{z_g^2}{2z_1^2}\right)\Xi_{\mathrm{NLO},1}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp, \boldsymbol{z}_\perp; \boldsymbol{w}'_\perp, \boldsymbol{y}'_\perp)\right.$$
$$+ \frac{\boldsymbol{r}_{zy}\cdot\boldsymbol{r}_{z'x'}}{\boldsymbol{r}^2_{zy}\boldsymbol{r}^2_{z'x'}} K_0(QX_{\mathrm{R}}) K_0(\bar{Q}_{\mathrm{R2'}} r_{w'y'})\left(1+\frac{z_g}{2z_1}+\frac{z_g}{2z_2}\right)\Xi_{\mathrm{NLO},1}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp, \boldsymbol{z}_\perp; \boldsymbol{w}'_\perp, \boldsymbol{y}'_\perp)$$
$$+ \frac{1}{2}\frac{\boldsymbol{r}_{zx}\cdot\boldsymbol{r}_{z'x'}}{\boldsymbol{r}^2_{zx}\boldsymbol{r}^2_{z'x'}} K_0(QX_{\mathrm{R}}) K_0(QX'_{\mathrm{R}})\left(1+\frac{z_g}{z_1}+\frac{z_g^2}{2z_1^2}\right)\Xi_{\mathrm{NLO},4}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp, \boldsymbol{z}_\perp; \boldsymbol{x}'_\perp, \boldsymbol{y}'_\perp, \boldsymbol{z}'_\perp)$$
$$- \frac{1}{2}\frac{\boldsymbol{r}_{zy}\cdot\boldsymbol{r}_{z'x'}}{\boldsymbol{r}^2_{zy}\boldsymbol{r}^2_{z'x'}} K_0(QX_{\mathrm{R}}) K_0(QX'_{\mathrm{R}})\left(1+\frac{z_g}{2z_1}+\frac{z_g}{2z_2}\right)\Xi_{\mathrm{NLO},4}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp, \boldsymbol{z}_\perp; \boldsymbol{x}'_\perp, \boldsymbol{y}'_\perp, \boldsymbol{z}'_\perp)$$
$$\left. + (1\leftrightarrow 2) + c.c.\right\} - \frac{\alpha_{\mathrm{em}} e_f^2 N_c \delta_z^{(2)}}{(2\pi)^8}\alpha_s\Theta(z_f - z_g) \times \text{“slow”}$$

Only longitudinally polarized photon shown, lengthier expressions for transversely polarized photon

CGC and TMD correspondence

Back-to-back limit of CGC calculation at NLO

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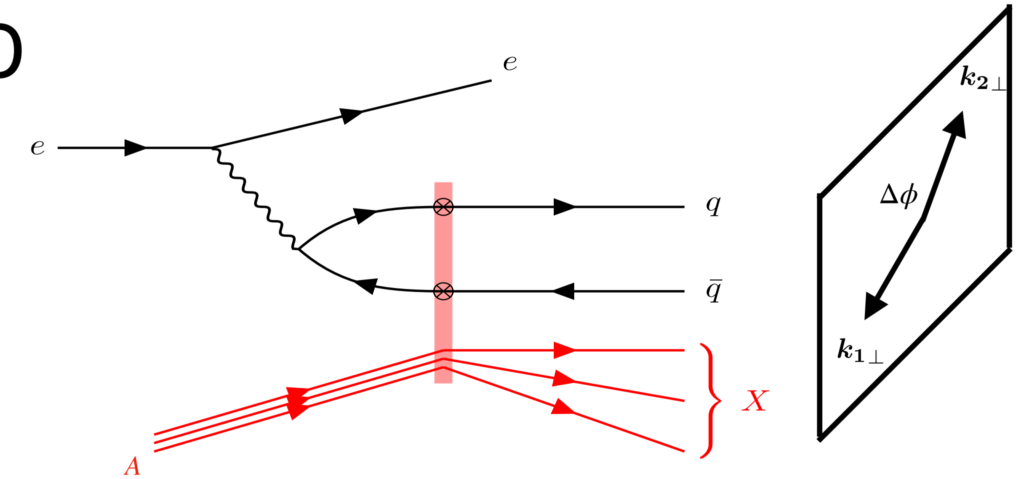
Back-to-back inclusive dijets in DIS at small x: Sudakov suppression and gluon saturation at NLO

Paul Caucal,[a] Farid Salazar,[b,c,d,e] Björn Schenke[a] and Raju Venugopalan[a]



$$d\sigma^{\gamma^*_\lambda + A \to q\bar{q} + X} = \mathcal{H}(Q, \boldsymbol{P}_\perp) \int \frac{d^2\boldsymbol{b}_\perp}{(2\pi)^2} e^{-i\boldsymbol{k}_\perp \cdot \boldsymbol{b}_\perp} \alpha_s \widetilde{G}^0_Y(\boldsymbol{b}_\perp) e^{-S_{\mathrm{Sud}}(\boldsymbol{b}_\perp, \boldsymbol{P}_\perp)} + \mathcal{O}(\alpha_s^2)$$

Joint resummation of small-x and soft gluons at finite Nc and to single log accuracy

Small-x evolution for WW follows well-known BK-JIMWLK equations **amended with a kinematic constrain** to separate small-x and soft gluons

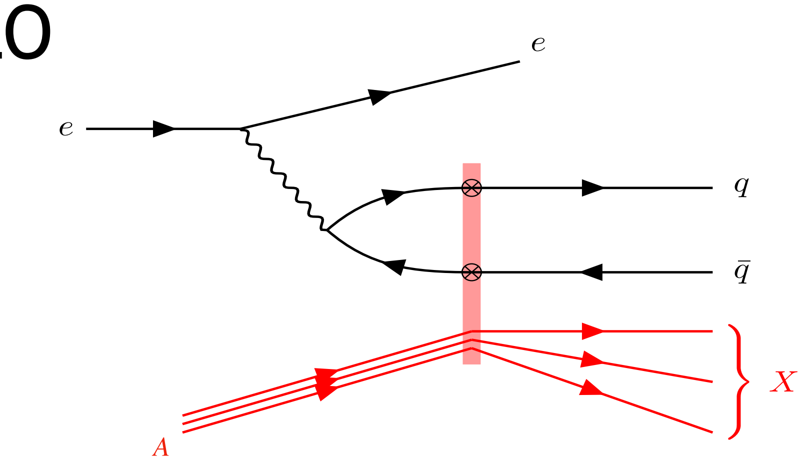
Pure $\mathcal{O}(\alpha_s^2)$ Explicit results, yet *apparently* involve complicated convolution including operators beyond WW, but **needed for precision!**

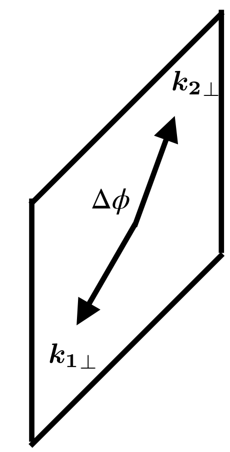
CGC and TMD correspondence

Back-to-back limit of CGC calculation at NLO

Work in progress (2203.XXXX)

In collaboration with Paul Caucal, Björn Schenke,
Tomasz Stebel, and Raju Venugopalan





Pure $\mathcal{O}(\alpha_s^2)$ contributions can be absorbed into NLO impact factor

$$\mathrm{d}\sigma^{\gamma_\lambda^*+A\to\mathrm{dijet}+X} \propto \mathcal{H}^{\lambda}_{\mathrm{NLO}}(Q,\boldsymbol{P}_\perp;\mu_F;R)\int\frac{\mathrm{d}^2\boldsymbol{b}_\perp}{(2\pi)^2}e^{-i\boldsymbol{q}_\perp\cdot\boldsymbol{b}_\perp}\alpha_s\widetilde{G}^0_Y(\boldsymbol{b}_\perp)e^{-S_{\mathrm{Sud}}(\boldsymbol{b}_\perp,\mu_F)} + \mathcal{O}(\alpha_s^3)$$

fully analytic result

- The first proof of TMD factorization at NLO in small-x kinematics (modulo the non-linear evolution of the WW)?
- Fully analytic NLO impact factor (contains $\ln(Q/P_\perp)$ and dilogarithms…) in back-to-back kinematics, suitable for numerical implementation

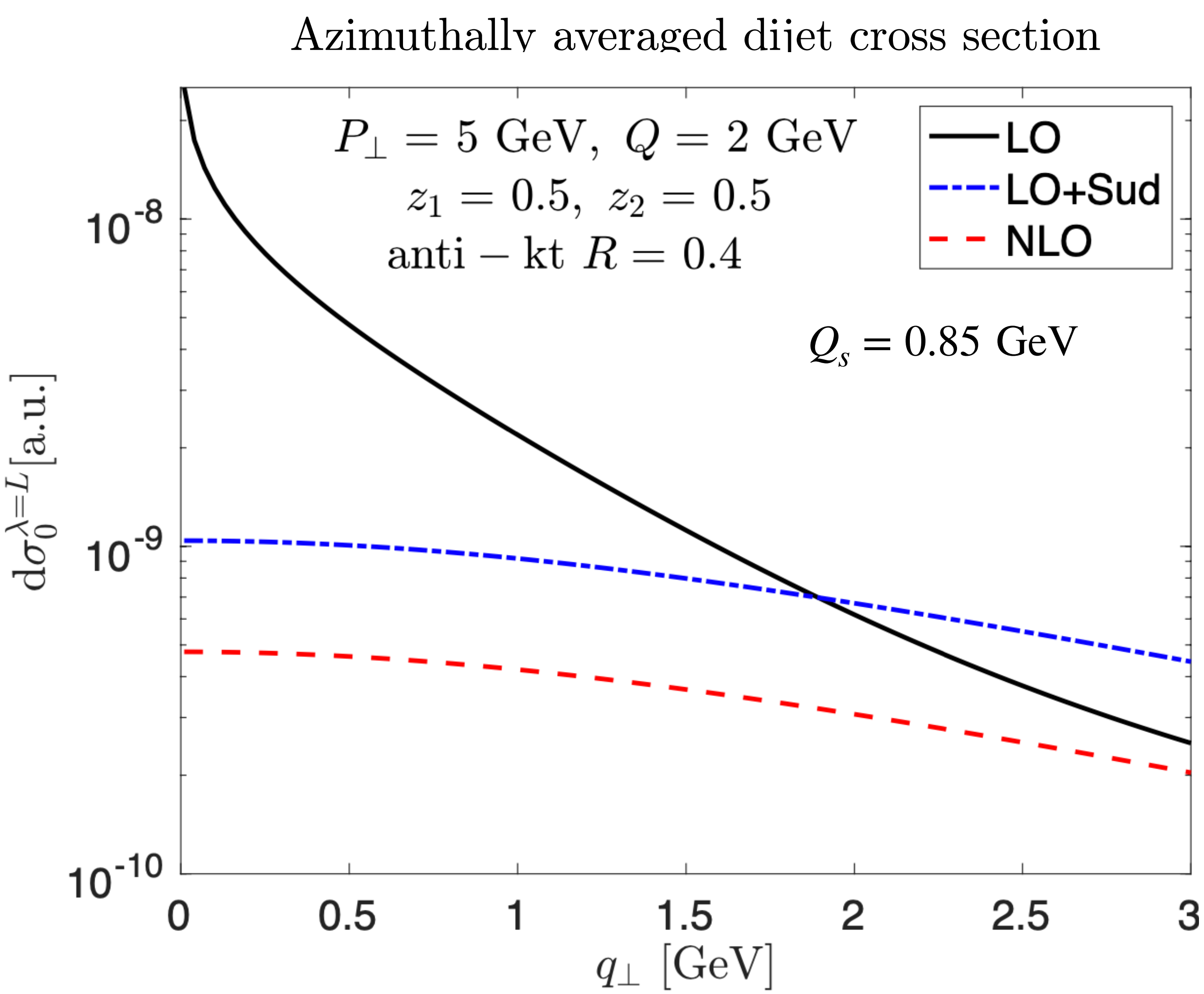
Back-to-back inclusive dijets in DIS at NLO

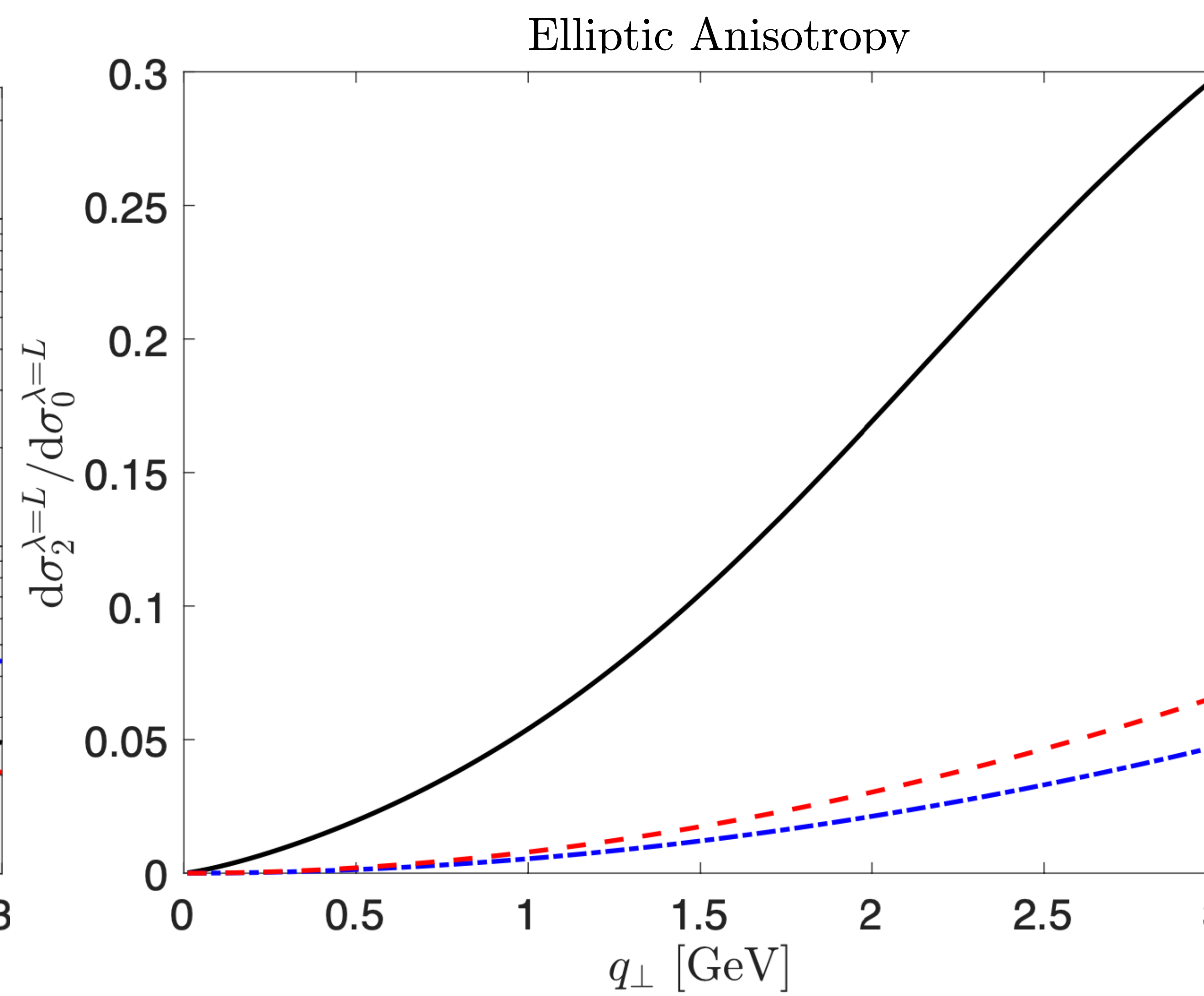
Numerical results teaser (only $\gamma_L^* + A \rightarrow dijet + X$)

Work in progress (2203.XXXX)

In collaboration with Paul Caucal, Björn Schenke, Tomasz Stebel, and Raju Venugopalan

- NLO* Include:
  Sudakov double and single logs at finite Nc + NLO impact factor
- NLO* does not include:
  Proper small-x evolution.





More coming soon!

Summary

Motivation:

2-particle azimuthal correlations → powerful observables to search for saturation

Results:

full NLO calculation dijets in DIS $\xrightarrow{\text{back-to-back limit}}$

- small-x and soft gluon resummation
- NLO impact (hard) factor
- preliminary numerical results

Outlook:

Include kinematically constrained small-x evolution in numerical result

Other observables: Dihadrons, UPCs

Could SCET-like techniques help us promote results beyond NLO/ more complex observables?

We choose to do these things not because they are easy, but because ~~they are hard~~ we thought they would be easy

On a more serious note:

Extraordinary discoveries require extraordinary evidence [a lot of hard work and collective effort]