Unveiling the Sea

Where are the sea quarks in the CGC?

Farid Salazar
INT

Heavy Ions Physics @ EIC Era

08/21/2024

I) CGC basics:

sources, fields, Wilson lines, dipole, saturation scale, small-x RGE

II) CGC - TMD correspondence (gluon TMDs)

- Momentum space expansion @ LO
- NLO: Sudakov & small-x RGE
- Phenomenology

III) Where are the sea quarks?

- SIDIS
- Two-particle correlations
- Generalized Universality

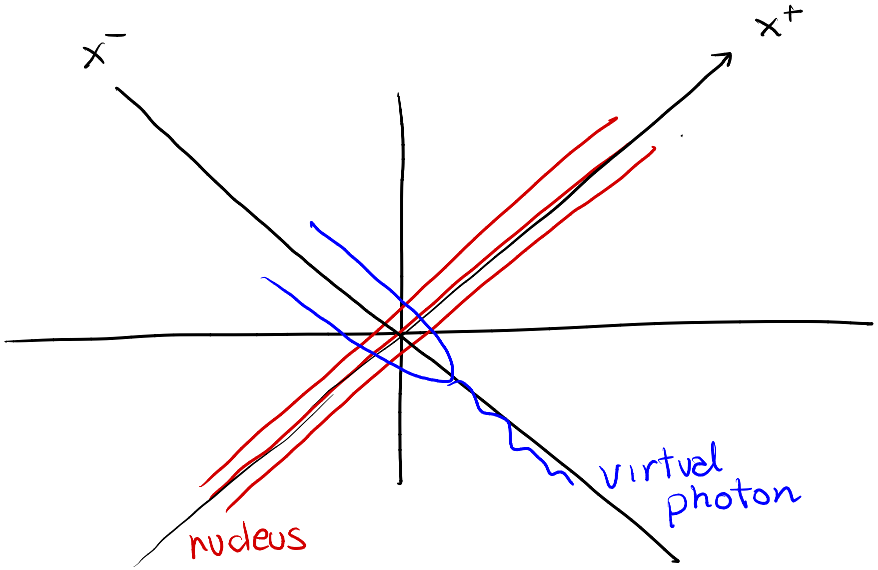
Work in progress with Caucal, Iancu & Yuan

I) CGC basics

A_{cl} bg field generated by fast (large-x) partons

$$[D_\mu, F^{\mu\nu}] = J^\nu$$

eikonal current



$$J^\mu = \delta^{\mu +} \rho(x^-, x_\perp)$$

$\downarrow$ $A^- = 0$ gauge

$$\nabla_\perp^2 A^+(x^-, x_\perp) = -\rho(x^-, x_\perp)$$

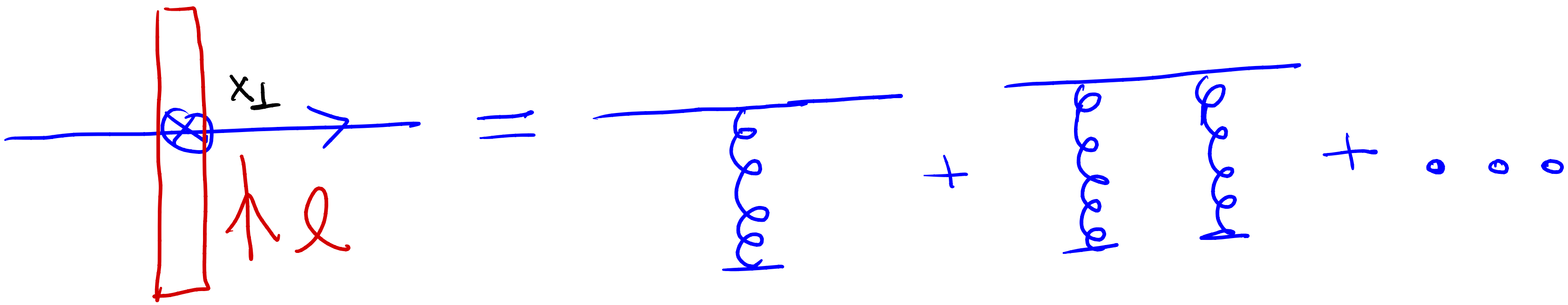
$$A_\perp = 0$$

@ some initial rapidity Y_0 ✓

Non-pert input to describe sources ρ and its correlations

e.g. McLerran–Venugopalan model $\langle \rho^a(x) \rho^b(\bar{x}) \rangle_{Y_0} = \mu^2 \delta^{ab} \delta^{(3)}(x - \bar{x})$

Parton propagating in the background field



Effective quark CGC vertex

$$I_q = 2\pi\,\delta(l^-)\,\gamma^- \int d^2x_\perp\, e^{-i l_\perp \cdot x_\perp} \left[V(x_\perp) - \mathbb{1}\right]$$

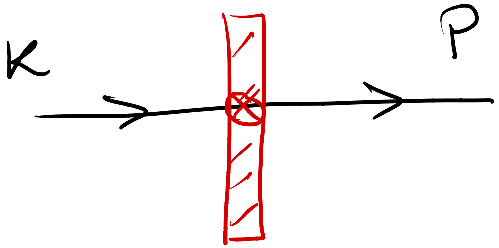
resums all eikonal (coherent) scattering with bg field A^+

Light-like Wilson line

$$V(x_\perp) = P\, e^{ig\int dx^- A^+(x^-, x_\perp)}$$

Similar expression for gluon propagation

Quark-nucleus scattering



$$\mathcal{M} \sim \bar{u}(p)\,\gamma^- u(k) \int d^2x_\perp\, e^{-i p_\perp \cdot x_\perp}\, V(x_\perp)$$

$$k = (0, k^-, 0_\perp)$$

$$p = \left(\frac{p_\perp^2}{2p^-}, p^-, p_\perp\right)$$

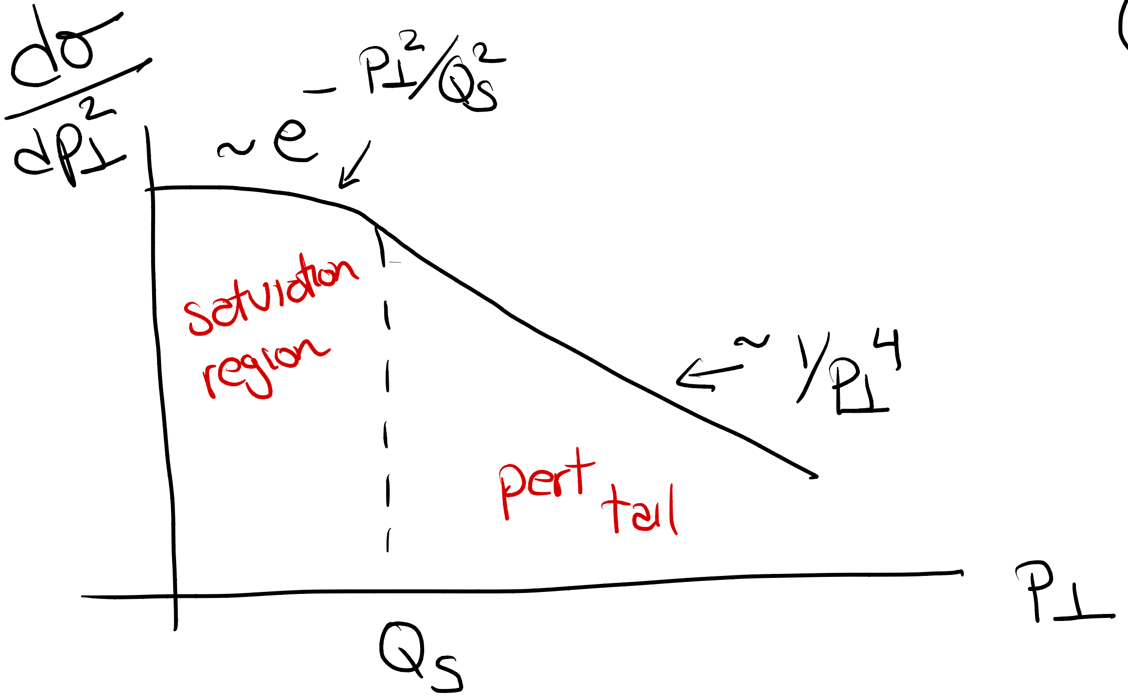
$$\frac{d\sigma}{dp_\perp^2} \sim \int d^2x_\perp\, d^2\bar{x}_\perp\, e^{-i p_\perp \cdot (x_\perp - \bar{x}_\perp)}\, S_Y^{(2)}(x_\perp, \bar{x}_\perp)$$

$$S_Y^{(2)}(x_\perp, \bar{x}_\perp) \equiv \frac{1}{N_c} \left\langle \mathrm{Tr}\left[V(x_\perp)\, V^\dagger(\bar{x}_\perp)\right] \right\rangle_Y$$

dipole

2pt correlator of Wilson lines

In the MV model:



Q_s^2 saturation scale

implicit in dipole $S^{(2)}$

$Q_s^2 \sim \mu^2 \leftarrow$ MV model transverse color charge density

Q_s^2 increases with energy (RGE): $Q_s^2 \sim x^{-\lambda}$

$\lambda \sim 0.3$

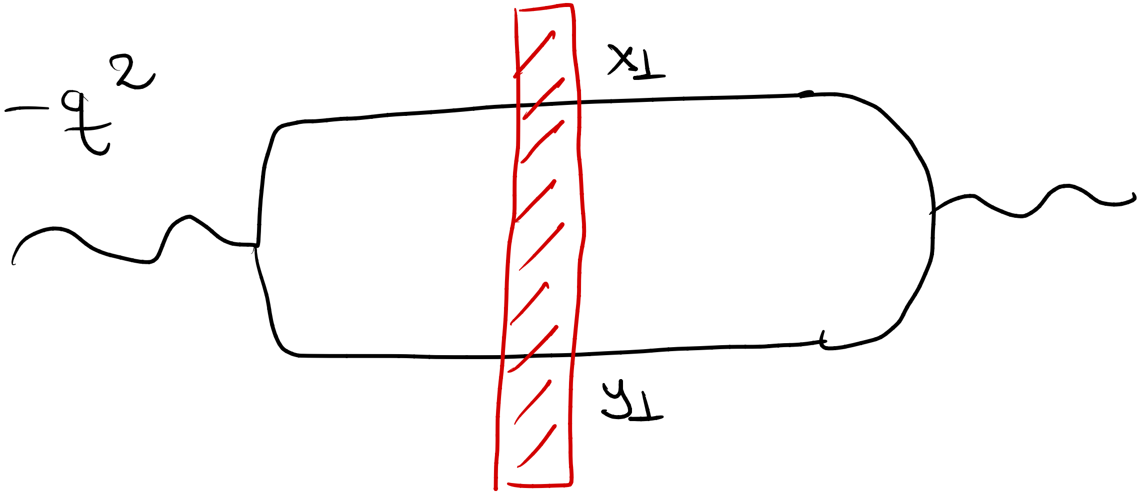
Q_s^2 increases with nuclear size: $Q_s^2 \sim A^{1/3}$

Deep inelastic scattering

$$\sigma_{DIS}(x, Q^2) \sim 2\,\mathrm{Im}\left[\mathcal{M}^{\gamma^* A \to \gamma^* A}\right] \leftarrow \text{optical thm}$$

$\uparrow$ forward scatt amplitude

$Q^2 \equiv -q^2$



$r_\perp = x_\perp - y_\perp$

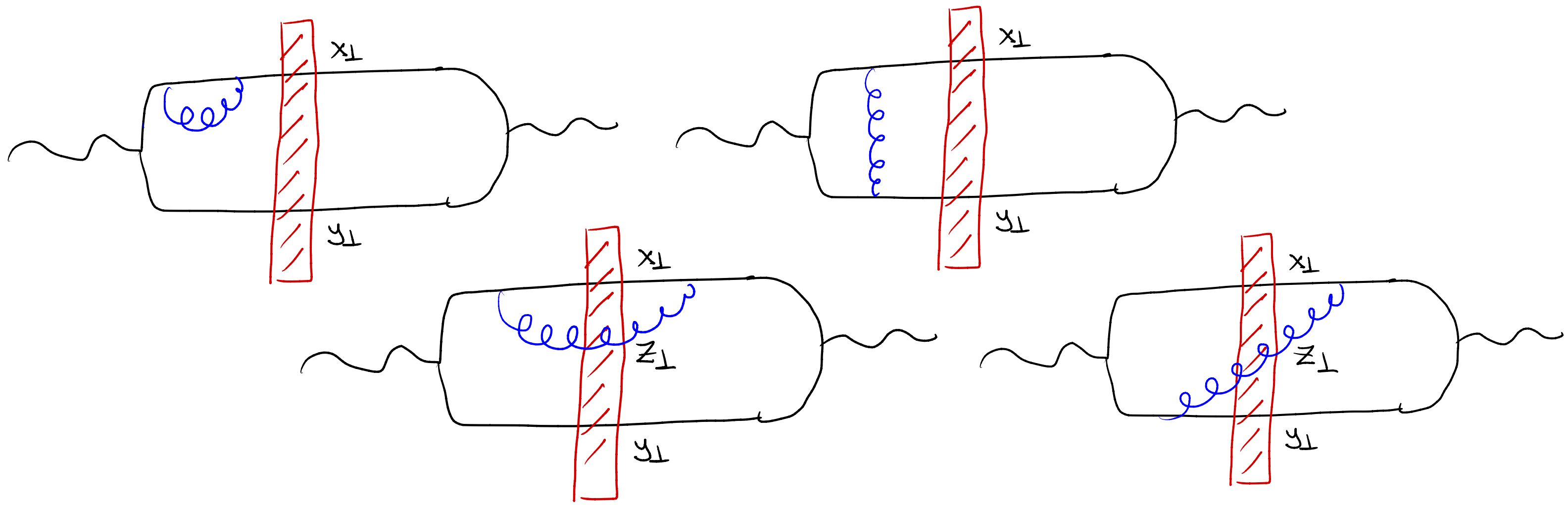
dipole

$$\mathrm{Im}(\mathcal{M}) = \int d^2x_\perp d^2y_\perp \left|\Psi^{\gamma^* \to q\bar{q}}(Q, z, r_\perp)\right|^2 \underbrace{\left[1 - S_Y^{(2)}(x_\perp, y_\perp)\right]}_{\equiv T_Y(x_\perp, y_\perp)}$$

QED

RG evolution: gluons with momentum $\Lambda_0^+ < k_g^+ \Longleftrightarrow k_g^- < \Lambda_0^-$ are accounted by sources, but large corrections of type $\alpha_s \ln(q^-/\Lambda_0^-)$ in high energy limit $q^- \gg \Lambda_0^-$

$$\int_{\Lambda_0^-}^{q^-} \frac{dk_g^-}{k_g^-}$$



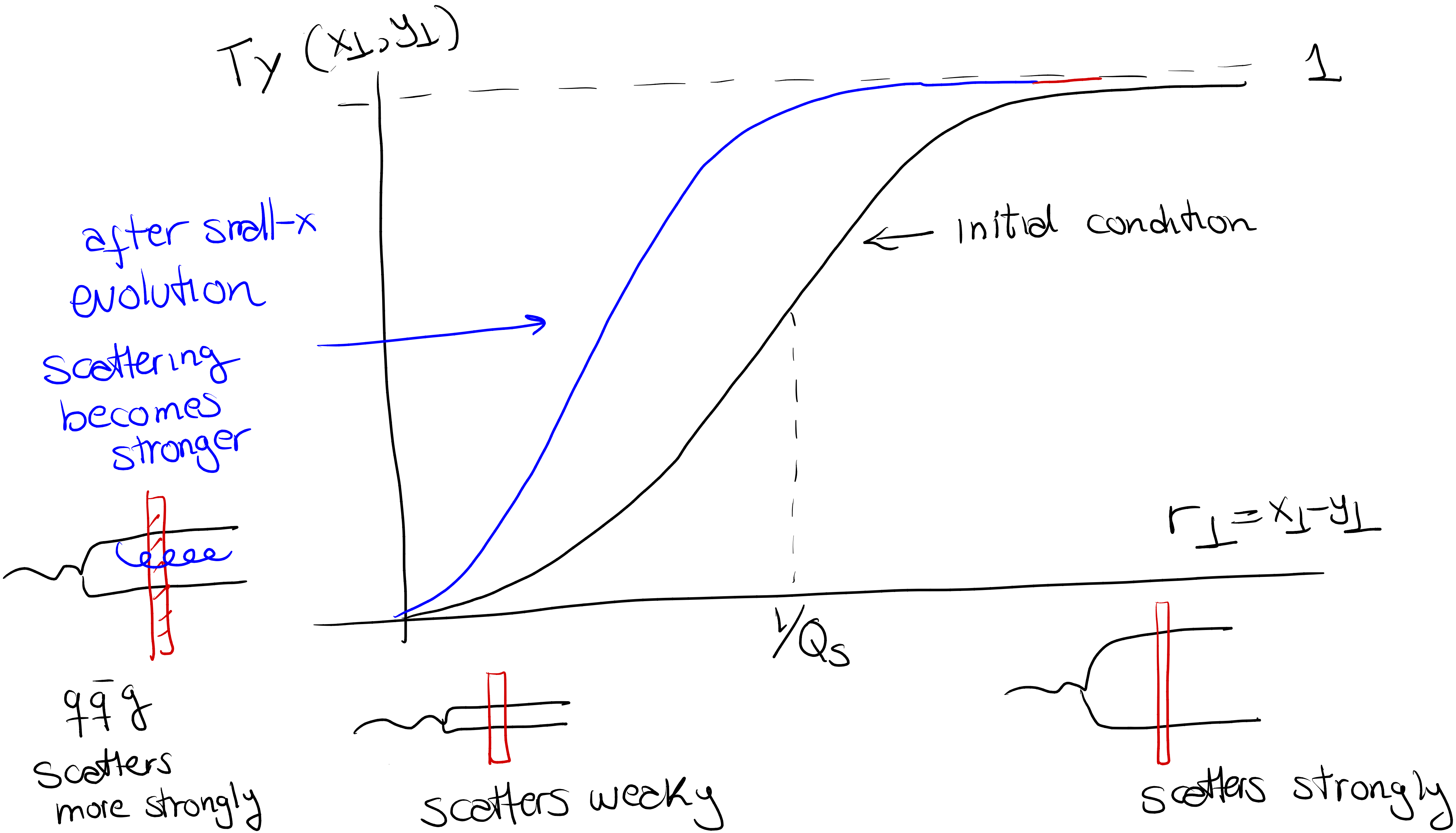
$$\frac{\partial S_Y(x_\perp, y_\perp)}{\partial Y} = \frac{\alpha_s N_c}{2\pi^2} \int d^2 z_\perp \frac{(x_\perp - y_\perp)^2}{(x_\perp - z_\perp)^2 (y_\perp - z_\perp)^2} \left[S_Y(x_\perp, z_\perp) S_Y(y_\perp, z_\perp) - S_Y(x_\perp, y_\perp) \right]$$

BK-equation

$Y = \ln(k_g^-/\Lambda_0^-)$

Recover BFKL $S \to 1 - T$ & $T \ll 1$

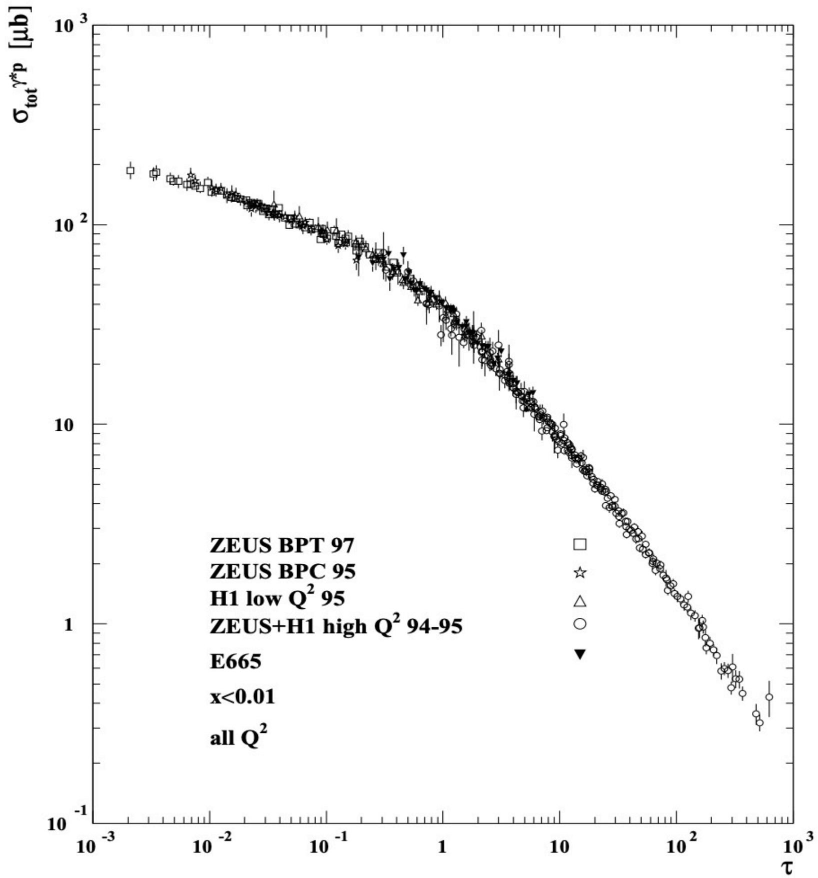
Dipole amplitude

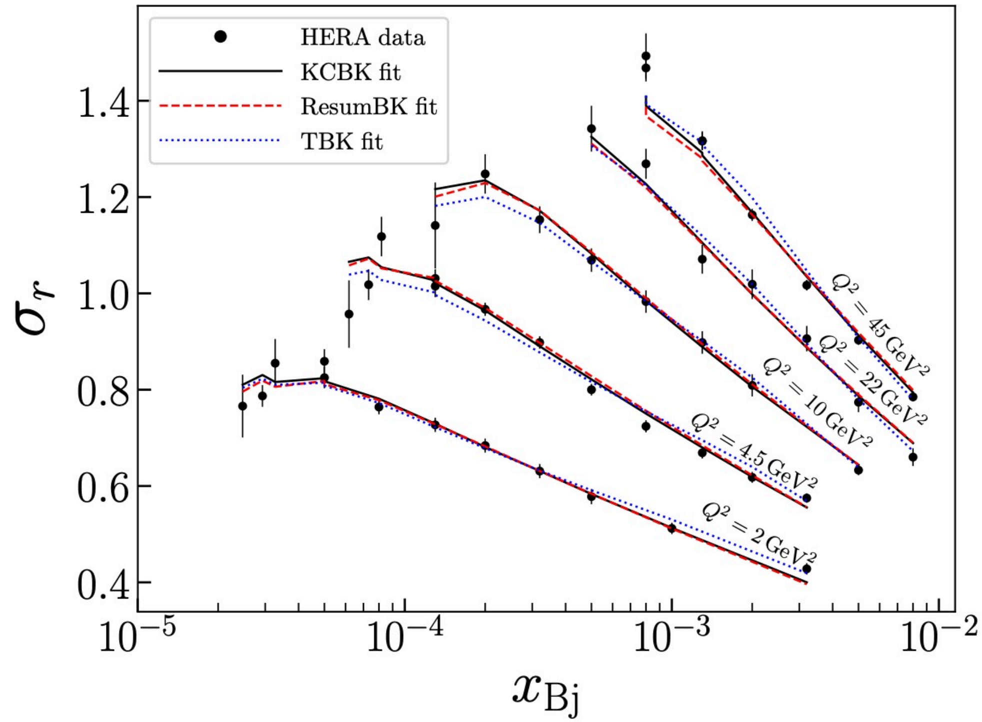


Confronting DIS with HERA

geometric scaling

Reduced structure function





Hänninen et al (2020)

$$\tau = Q^2/Q_s^2(x)$$

Staśto et al (2000)

II) CGC-TMD correspondence
(gluon TMDs)

Semi-inclusive dijet production in DIS

$$\gamma^*(q) + A(P_A) \longrightarrow q(P_1) + \bar{q}(P_2)$$

$$s = (P_A + q)^2$$

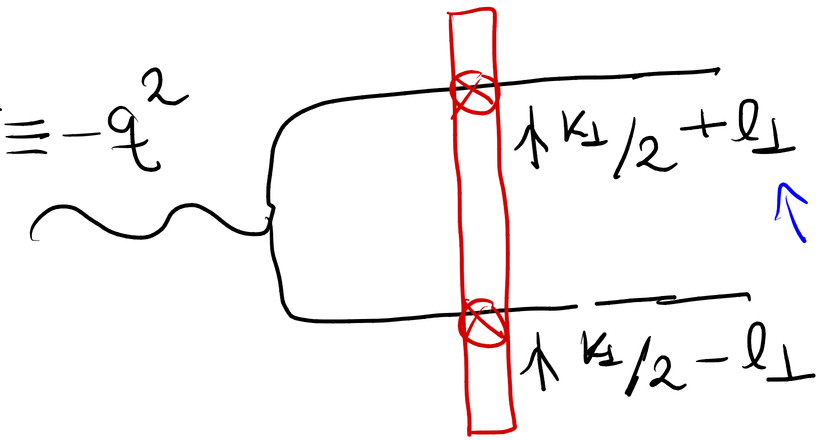
$$\boxed{k_\perp, P_\perp, Q \ll \sqrt{s}}$$

high energy limit kinematics

$$k_\perp \equiv P_{1\perp} + P_{2\perp}$$

$$P_\perp = \frac{1}{2}(P_{1\perp} - P_{2\perp})$$

$$Q^2 \equiv -q^2$$



loop momentum due to multiple scatt

c.c. amplitude

$$d\sigma \sim \int d^2 l_\perp d^2 \tilde{l}_\perp \underbrace{H(P_\perp, Q; l_\perp, l_\perp')}_{\text{pert computable}} \underbrace{\mathcal{G}_Y(k_\perp; l_\perp, l_\perp')}_{\text{correlator of Wilson lines}}$$

Momentum space expansion

For kinematics $\quad k_\perp, Q_s \ll P_\perp, Q \ll \sqrt{s}$

$\hookrightarrow \quad l_\perp \sim l'_\perp \sim k_\perp, Q_s \ll P_\perp, Q$

Taylor expansion around $l_\perp, l'_\perp$

$$d\sigma \sim H_{\alpha\alpha'}(P_\perp, Q) \underbrace{\int d^2 l_\perp d^2 \tilde{l}_\perp \, l_\perp^{\alpha} l_\perp'^{\alpha'} G_y(k_\perp; l_\perp, l'_\perp)}_{G_y^{\alpha\alpha'}(k_\perp)}$$

$\gamma^* g \to q\bar{q}$ hard factor

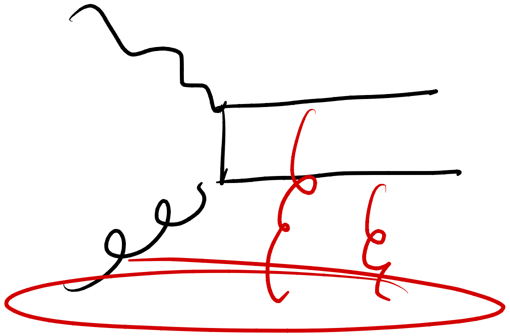
$G_y^{\alpha\alpha'}(k_\perp) \leftarrow$ Weizsacker Williams gluon TMD

$$d\sigma \sim H(P_\perp, Q)\, \underbrace{G_y(k_\perp)}$$

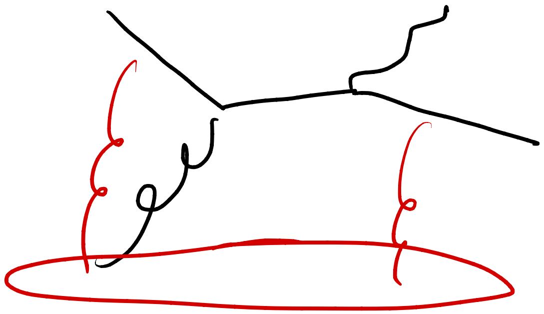
Knows about the physics of saturation Q_s

A tale of two gluon distributions

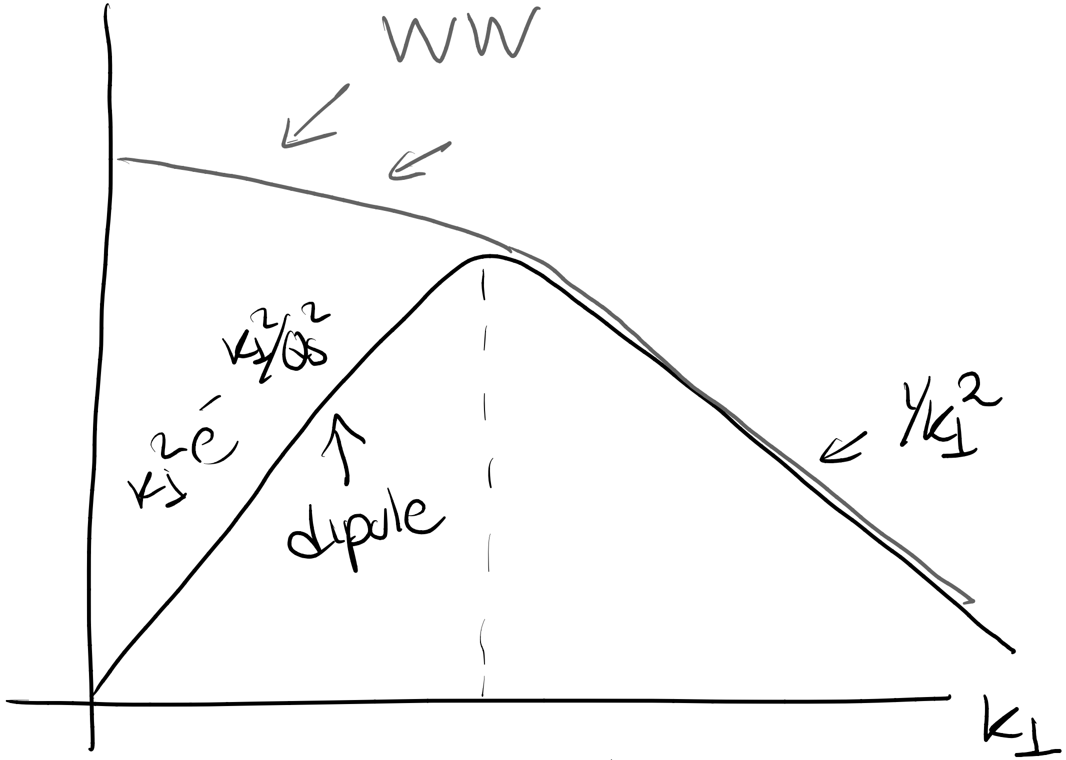
Correspondence can be shown for other process e.g.
photon + jet/hadron in pA
but another TMD distribution emerges: dipole-type



only final state interactions



both initial & final state



differ when
$k_\perp \lesssim Q_s$

Dijet production @ NLO

One-loop correction will generate large logs

$\alpha_s \ln(s/P_\perp^2) \leftarrow$ small-x log

$\alpha_s \ln^2(P_\perp^2/k_\perp^2) \leftarrow$ Sudakov log

resums Sudakov

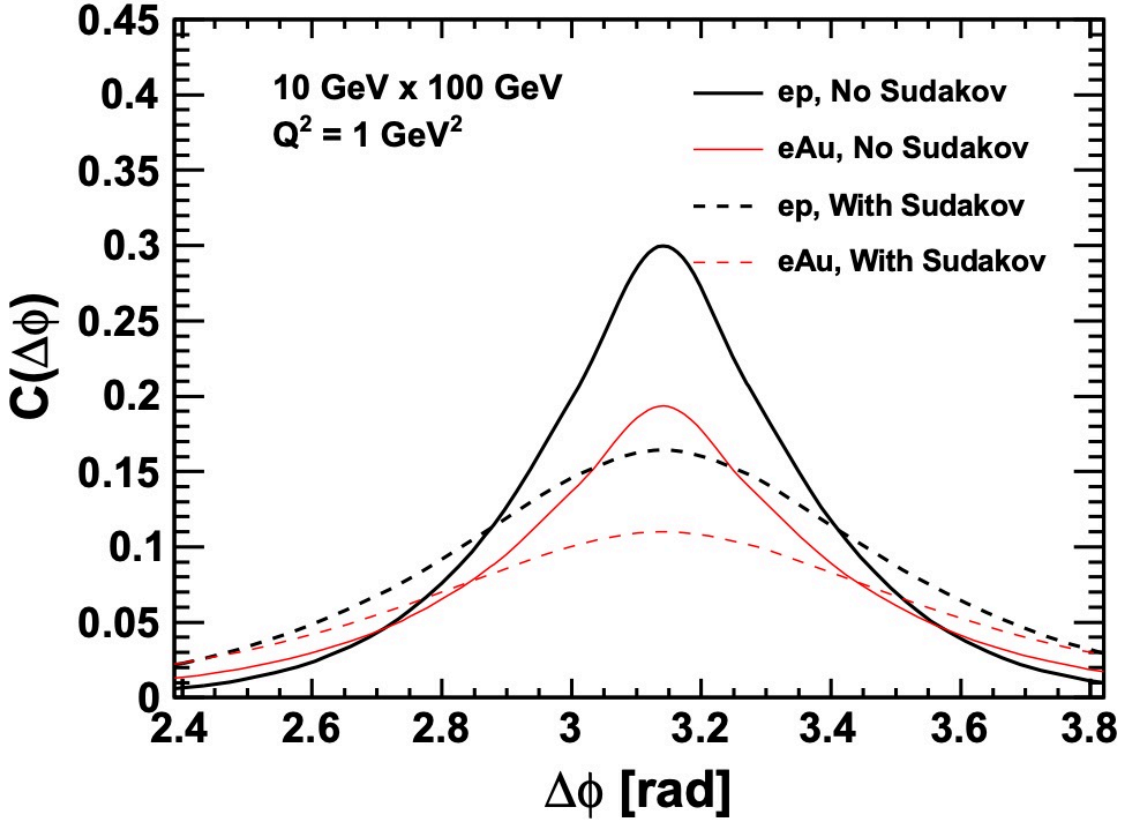
$$d\sigma \sim H(P_\perp, Q)\, G_Y(k_\perp) \otimes e^{-\frac{\alpha_s N_c}{2\pi}\ln^2(P_\perp^2/k_\perp^2)}$$

resums small-x log

For full NLO see Caucal, FS, Schenke, Stebel, Venugopalan (2023)

needed to impose kinematic constraint in small-x evolution

Pheno : dihadron production @ EIC



Aschenauer et (2014)

$\Delta\phi$ azimuthal angle between hadrons

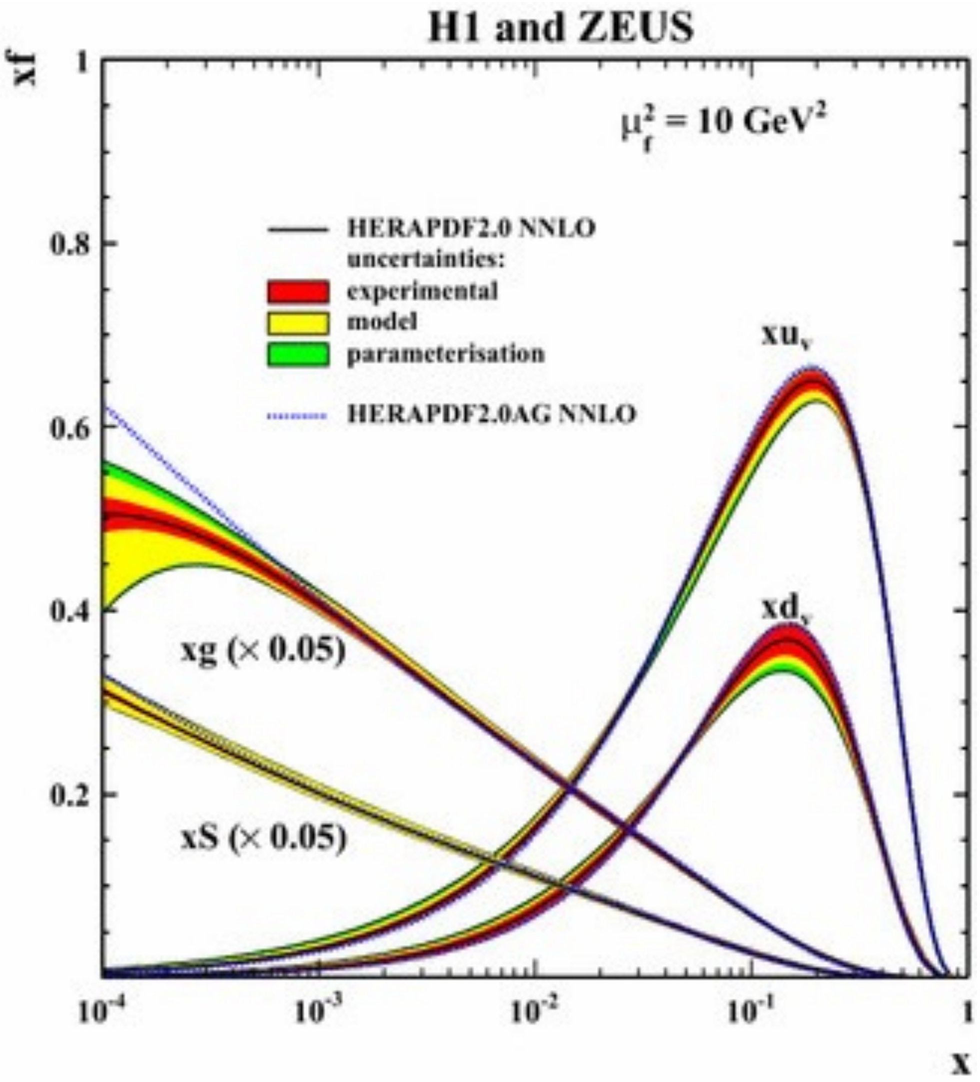
$$C(\Delta\phi) = \frac{\text{two-part-corr}}{\text{trigger}}$$

decorrelation due to saturation

we expect further decorrelation @ lower-x / higher energies

Focal ?

III) Where are sea quarks?



Sea quarks are numerous too @ low-x

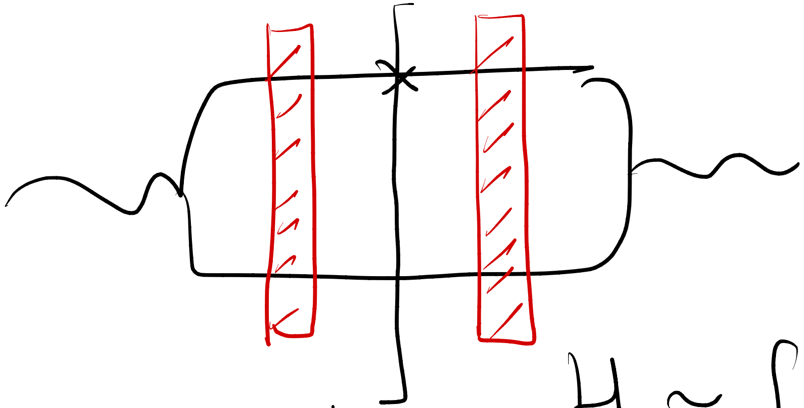
they come from splitting of low-x gluons

$$g \to q\bar{q}$$

So where are they in the shockwave?

Do we need to introduce a quark background field?

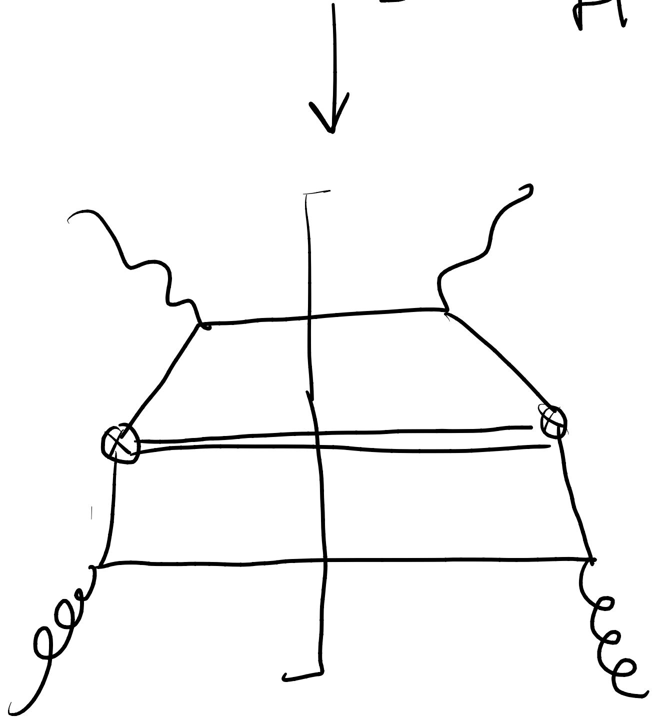
SIDIS



$$\frac{d^2\sigma}{d^2k_\perp} \sim \int d^2\ell_\perp \, F_y(\ell_\perp)\, H(k_\perp, \ell_\perp, Q)$$

fourier transform of dipole

$$H \sim \int_0^1 dz \left[z^2 + (1-z)^2\right] \left| \frac{\vec{k}_\perp}{k_\perp^2 + z(1-z)Q^2} - \frac{\vec{k} - \vec{\ell}_\perp}{(k_\perp - \ell_\perp)^2 + z(1-z)Q^2} \right|^2$$



Study limit $k_\perp, Q_s \ll Q \ll \sqrt{s}$

Controlled by end point $1-z \sim k_\perp/Q \ll 1$

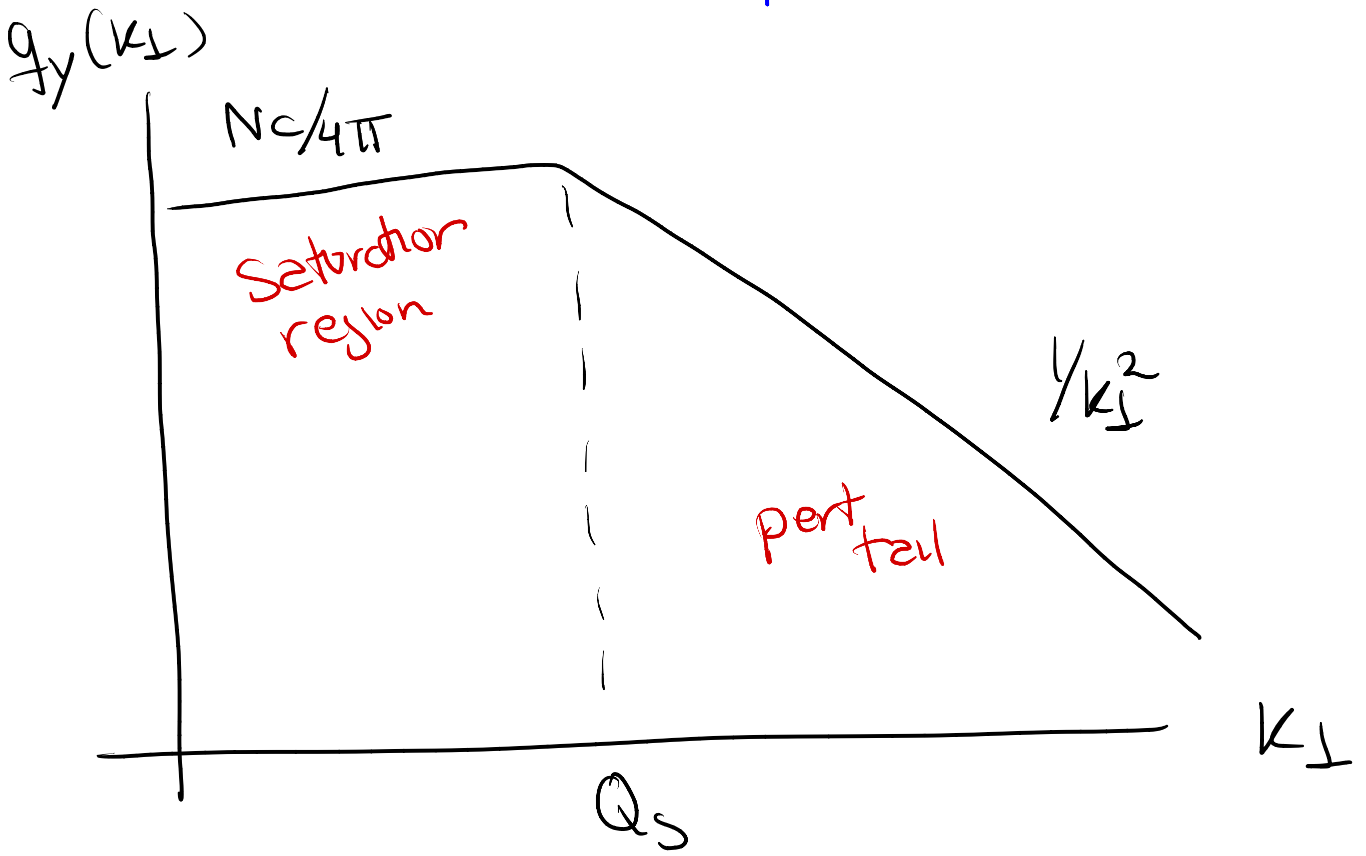
$$\frac{d\sigma}{dk_\perp^2} = H^{\gamma^* q \to q}(Q)\; q_y(k_\perp)$$

sea quark TMD

Sea quark TMD from small-x gluons

$$q_y(k_\perp) \sim \int d^2 l_\perp \, F_y(l_\perp) \left[1 - \frac{k_\perp \cdot (k_\perp - l_\perp)}{(k_\perp^2 - (k_\perp - l_\perp)^2} \ln \left(\frac{k_\perp^2}{(k_\perp - l_\perp)^2} \right) \right]$$

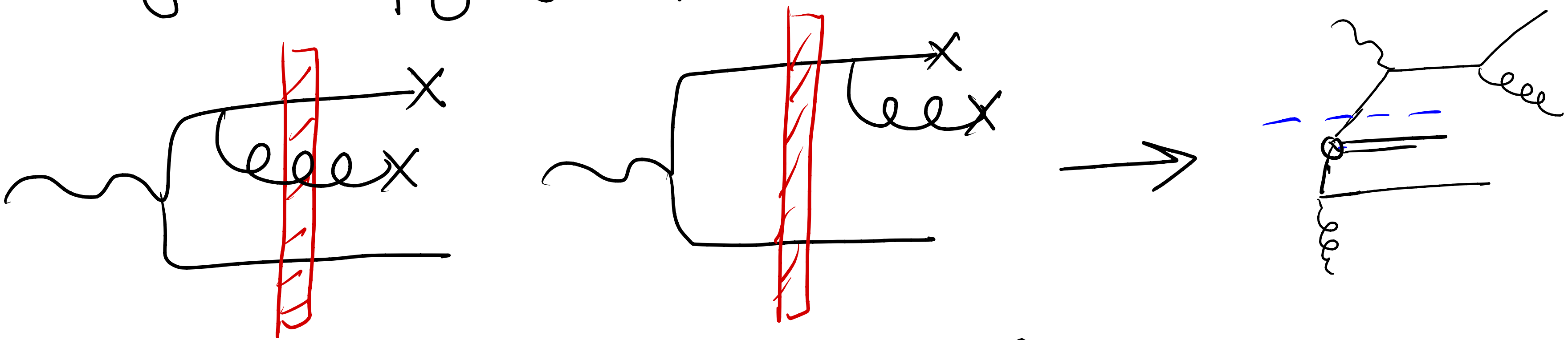
dipole

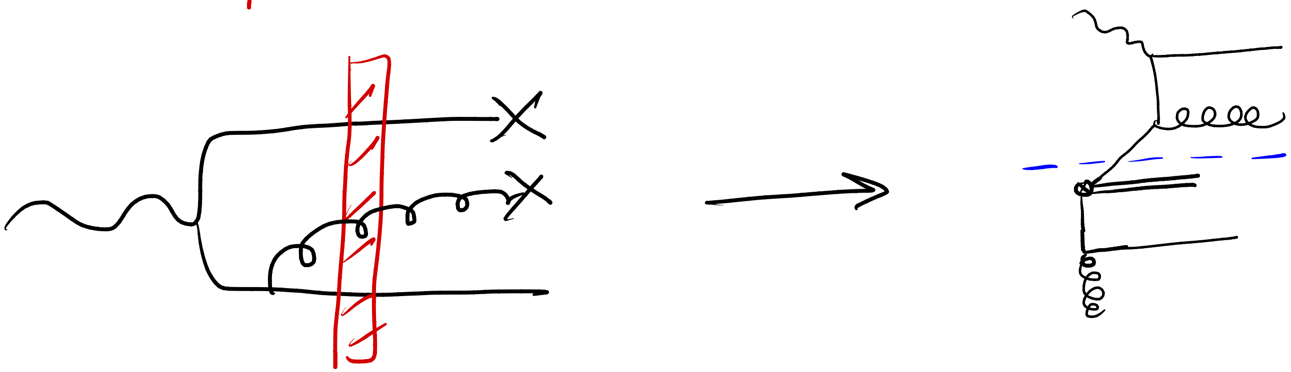


Two-particle correlations

We proved these correspondence for all two-particle correlation involving one photon

E.g. qg jet production in DIS when qg are back-to-back



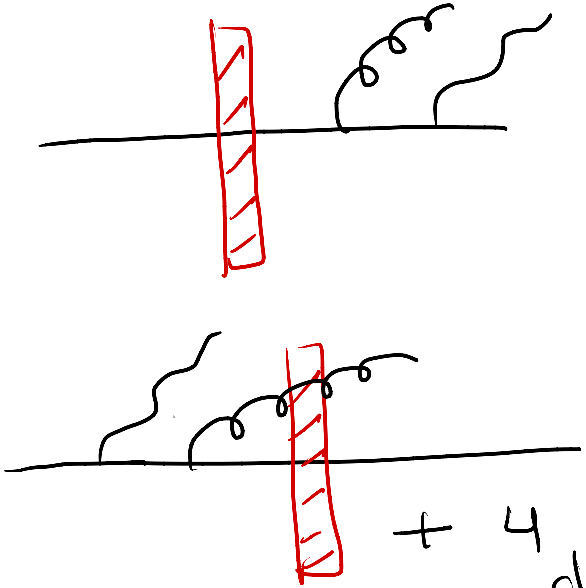


Same sea-quark TMD as SIDIS

$$d\sigma \sim H^{\gamma^* q \to qg}(P_\perp, Q)\; q_y(k_\perp)$$

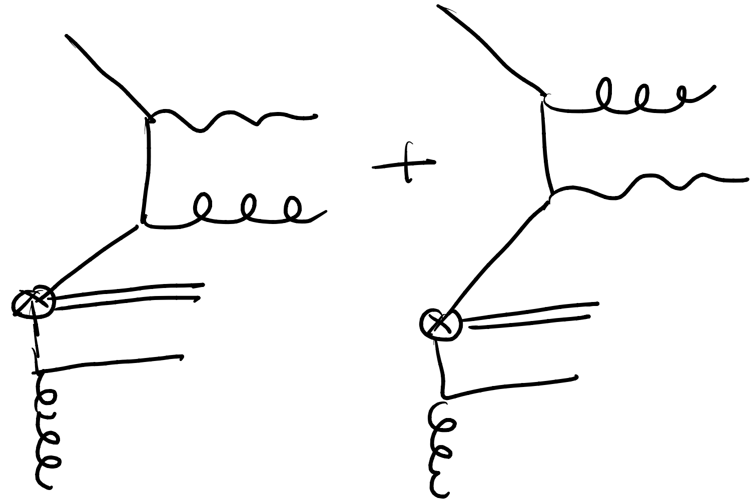
Process dependence

gluon jet + photon production in pA



+ 4 other diagrams

when $g\,\gamma$ are back-to-back $\longrightarrow$



$$d\sigma \sim H^{q\bar{q}\to\gamma g}(P_\perp)\, f_g^{(2)}(k_\perp)$$

both initial & final state interactions

$$f_g^{(2)}(k_\perp) = f_g(k_\perp) \otimes F(k_\perp)$$

gauge link structure consistent with Bomhof et al (2006)

Summary

I Rich correspondence between CGC–TMD

II Two-particle azimuthal decorrelation a consequence of saturation. Need to study energy, rapidity, nuclear size dependence : RHIC, LHC, EIC

III Extend CGC–TMD correspondence to sea-quark initiated channels