Progress towards dijet production in pA scattering within the CGC at NLO

Marcos Guerrero Morales

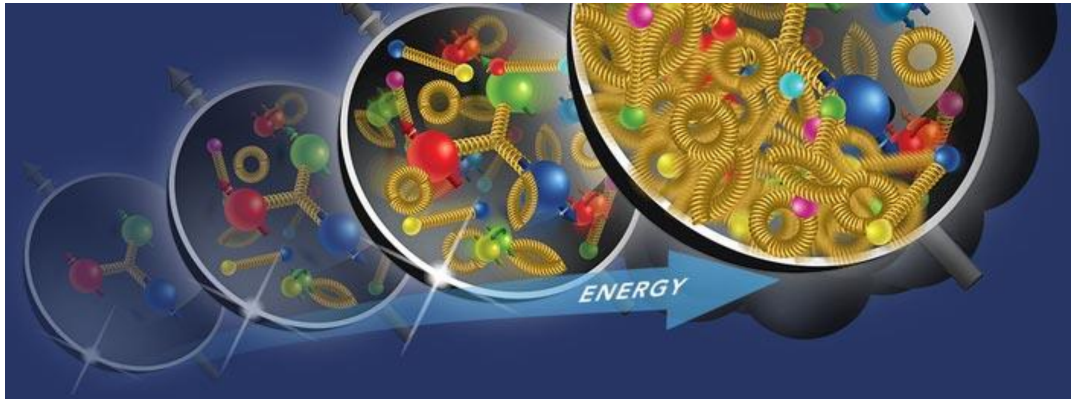
In collaboration with P. Caucal, E. Iancu, F. Salazar, F. Yuan.

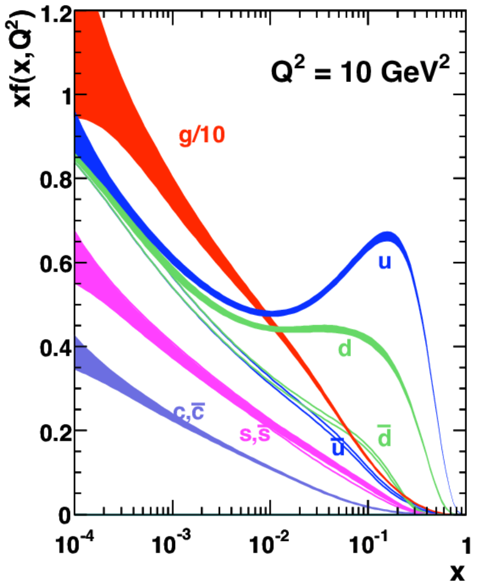
Physics Seminar

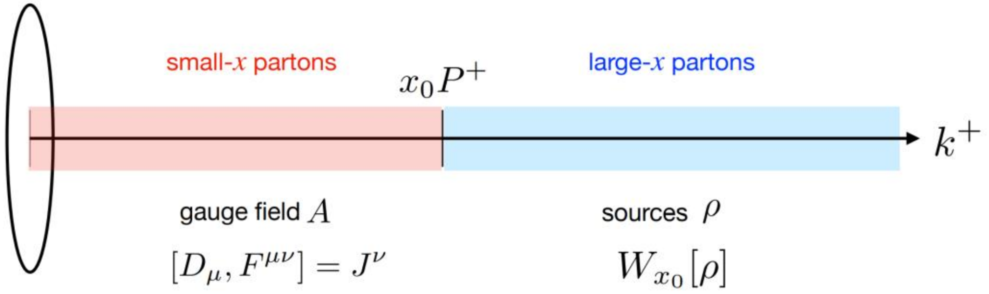
SUBATECH, Nantes, France

08/29/2026

Color Glass Condensate (CGC)







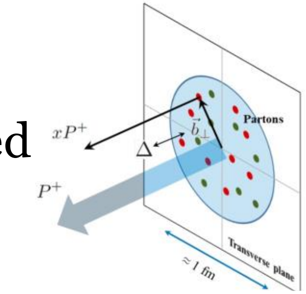
Quantum evolution

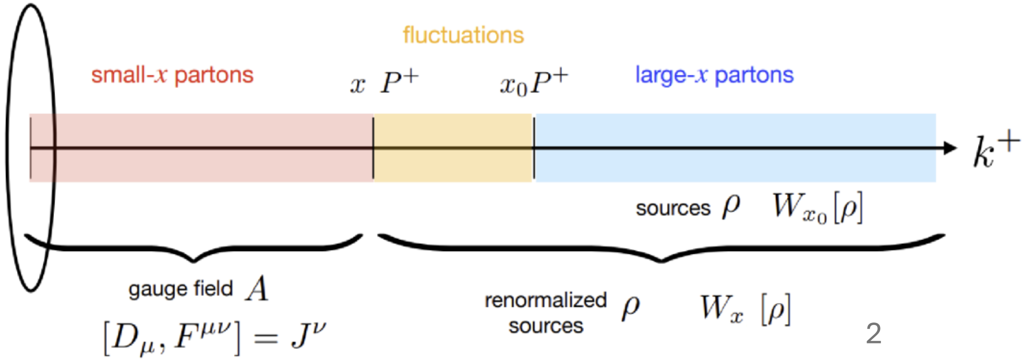
Probing values of x much smaller than factorization scale (going to higher energies) requires renormalization of sources

Evolution is dictated by JIMWLK RGE

Large fraction of momentum partons: **Static, localized** sources of color charge.

Small fraction of momentum partons : Delocalized dynamical **classical field** A^μ.





Effective vertices in CGC

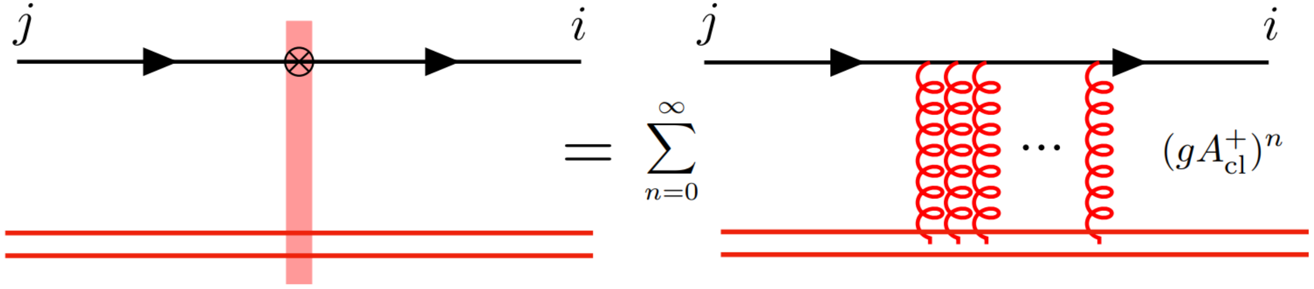
High energy multiple scattering of particles with classical field is described by effective vertices involving Wilson lines. For quark propagator:

$$T^q_{ij}(l,l') = 2\pi\delta(l^- - l'^-)\gamma^- \mathrm{sgn}(l^-)\int \mathrm{d}^2\boldsymbol{x}_\perp e^{-i(\boldsymbol{l}_\perp - \boldsymbol{l}'_\perp)\cdot\boldsymbol{x}_\perp} V_{ij}^{\mathrm{sgn}(l-)}(\boldsymbol{x}_\perp),$$

The light-like Wilson lines ***rotate color of partons*** while leaving rest of quantum numbers unchanged

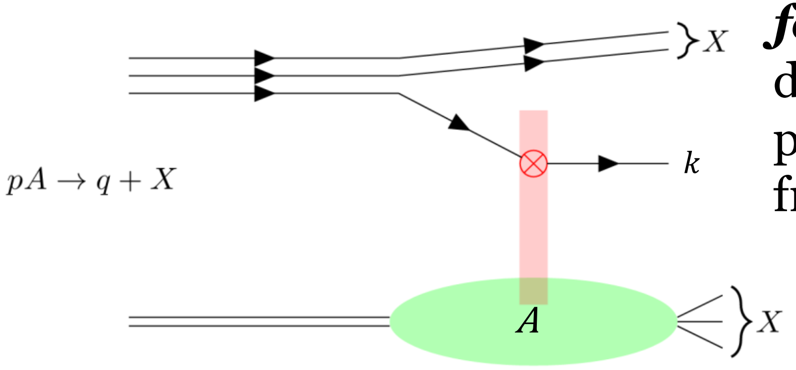
$$V_{ij}(\boldsymbol{x}_\perp) = \mathcal{P}\exp\left(ig\int_{-\infty}^{\infty} dz^- A^{+,c}_{\mathrm{cl}}(z^-,\boldsymbol{x}_\perp)t^c_{ij}\right)$$

SU(3) generators in fundamental representation



For gluons, similar expressions but generators are in adjoint representation

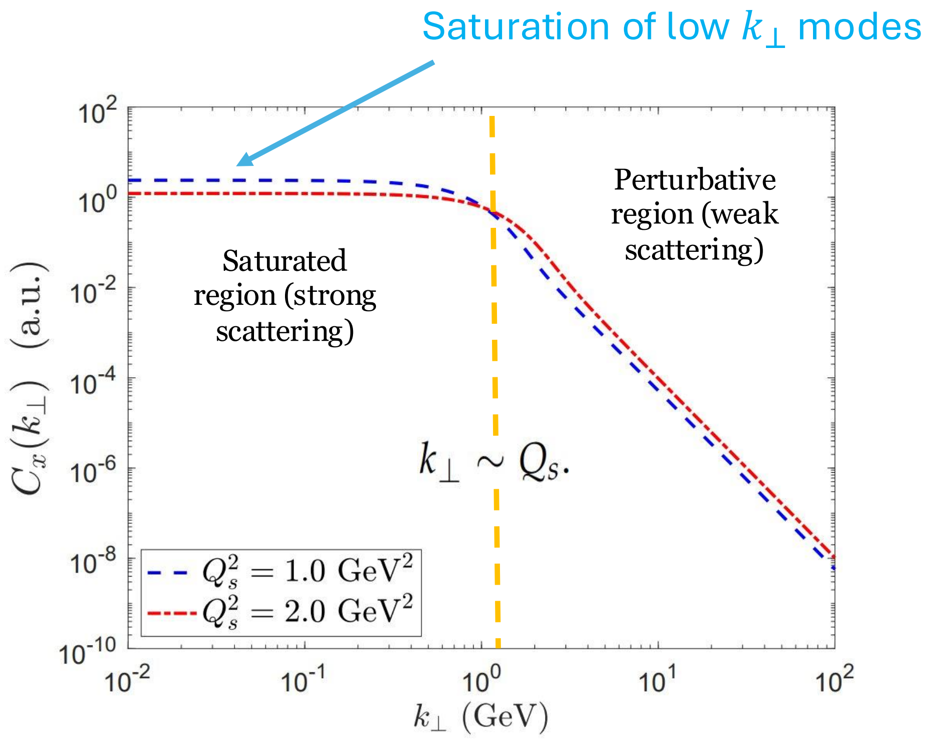
Quark production in pA scattering



<u>Hybrid approximation</u>: At ***forward rapidities*** (jet in the direction of proton), parton from proton has moderate x and parton from nucleus has small x.

$$x_p = \frac{k_\perp}{\sqrt{s}} e^{\eta}, \overset{\eta > 0}{\to} 1$$

$$x_A = \frac{k_\perp}{\sqrt{s}} e^{-\eta} \overset{\eta > 0}{\to} 0$$



Differential cross section:

$$\frac{\mathrm{d}\sigma^{pA\to qX}}{\mathrm{d}\eta\,\mathrm{d}^2\boldsymbol{k}_\perp} = \frac{1}{(2\pi)^2} x_p q(x_p) \tilde{D}_{x_A}(\boldsymbol{k}_\perp)$$

$$\tilde{D}_{x_A}(\boldsymbol{k}_\perp) = \int \mathrm{d}^2\boldsymbol{x}_\perp\,\mathrm{d}^2\boldsymbol{y}_\perp\, D_{x_A}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp)$$

Dipole correlator

$$D_{x_A}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp) = \frac{1}{N_c} \left\langle \mathrm{Tr}(V(\boldsymbol{x}_\perp) V^\dagger(\boldsymbol{y}_\perp)) \right\rangle_{x_A}$$

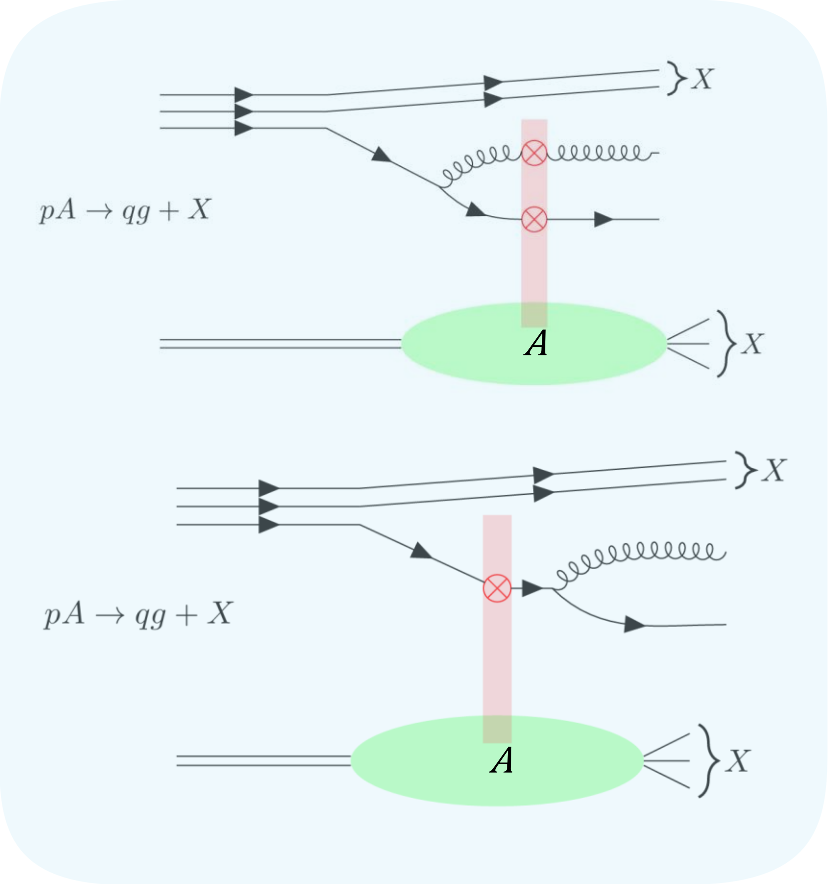
In the MV model

$$D_{x_A}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp) = D_{x_A}(\boldsymbol{r}_\perp) = \exp\left\{-\frac{1}{4}\alpha_s C_F \mu^2 r_\perp^2 \ln\left(\frac{1}{\lambda r_\perp} + e\right)\right\}$$

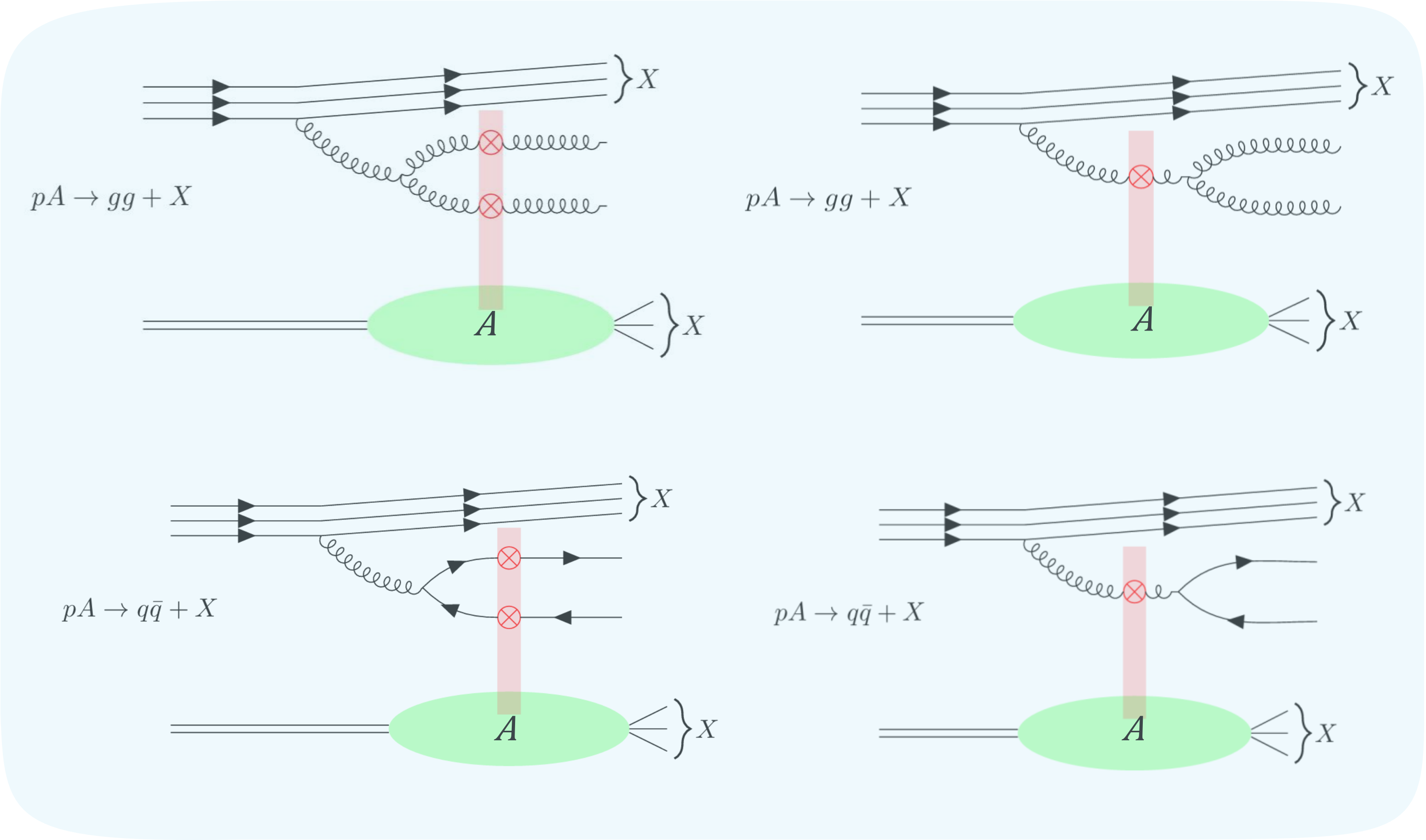
Jalilian-Marian (2005)

Dijet production in pA scattering

Quark initiated channel



Gluon initiated channel



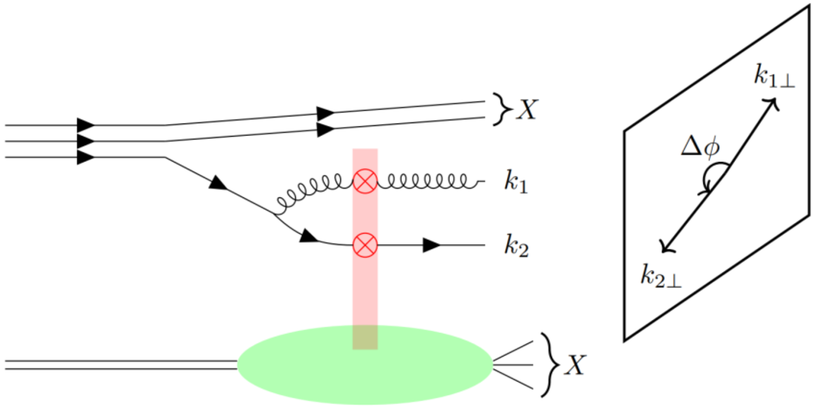
Dominguez, Marquet, Xiao, Yuan (2011)

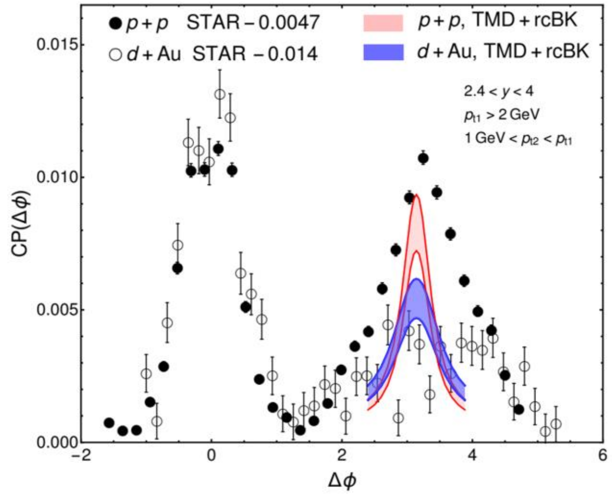
Dijet production in pA scattering

Back-to-back: $k_{1\perp} = -k_{2\perp}$

Azimuthal angle correlations in pA scattering

- Measure number of dihadrons with angle $\Delta\phi$ between transverse momentum of dijets
- Expected **suppression** and **broadening** near the back-to-back region for **larger nuclear sizes**, **higher energies**, and **very forward rapidities**
- Other mechanisms compete with saturation (initial and final state radiation, energy loss,...)

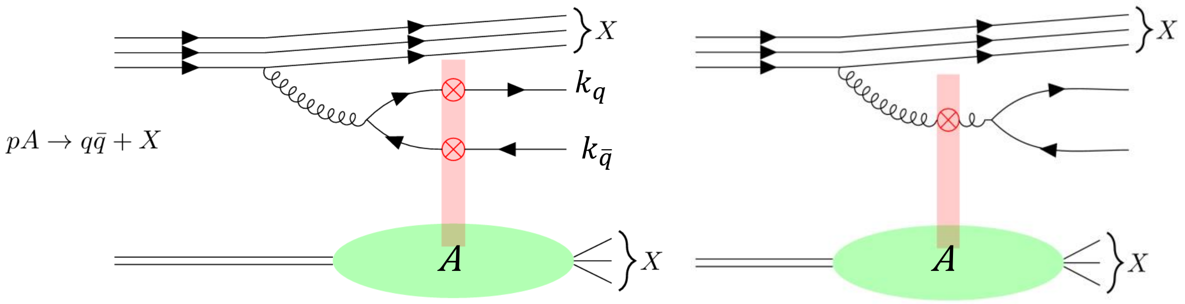




Albacete, Giacalone, Marquet, Matas (2018)

<u>Our ultimate goal is to compute the full next-to-leading order corrections to dijet production in the CGC to improve the precision of these predictions</u>

Gluon TMDs factorization



Dominguez et. al. showed that by taking the back-to-back limit in dijet production in the CGC, we can factorize cross sections in terms of gluon TMDs

As example, take $q\bar{q}$ dijet production in pA scattering:

$$\frac{d\sigma^{gA\to q\bar{q}X}}{\mathrm{d}^2\boldsymbol{k_q}_\perp \mathrm{d}^2\boldsymbol{k_{\bar{q}}}_\perp d\eta_q d\eta_{\bar{q}}} = \frac{\alpha_s}{8(2\pi)^6}\delta(1-z_q-z_{\bar{q}})\int \mathrm{d}^2\boldsymbol{x}_\perp \mathrm{d}^2\boldsymbol{y}_\perp \mathrm{d}^2\boldsymbol{x'}_\perp \mathrm{d}^2\boldsymbol{y'}_\perp e^{-i\boldsymbol{k}_{q_\perp}\cdot(\boldsymbol{x}_\perp-\boldsymbol{x}'_\perp)}e^{-i\boldsymbol{k}_{\bar{q}_\perp}\cdot(\boldsymbol{y}_\perp-\boldsymbol{y}'_\perp)}$$

$$R_{q\bar{q},LO}(\boldsymbol{r}_{xy},\boldsymbol{r}_{x'y'})\Big[S^{q\bar{q}q\bar{q}}(\boldsymbol{x}'_\perp,\boldsymbol{y}'_\perp,\boldsymbol{x}_\perp,\boldsymbol{y}_\perp) - S^{q\bar{q}g}(\boldsymbol{x}'_\perp,\boldsymbol{y}'_\perp,\boldsymbol{w}_\perp) - S^{q\bar{q}g}(\boldsymbol{x}_\perp,\boldsymbol{y}_\perp,\boldsymbol{w}'_\perp) + S^{gg}(\boldsymbol{w}'_\perp,\boldsymbol{w}_\perp)\Big]$$

$$R_{q\bar{q},LO}(\boldsymbol{r}_{xy},\boldsymbol{r}_{x'y'}) = 8z_q z_{\bar{q}}(z_q^2+z_{\bar{q}}^2)\frac{\boldsymbol{r}_{xy}\cdot\boldsymbol{r}_{x'y'}}{r_{xy}^2 r_{x'y'}^2}$$

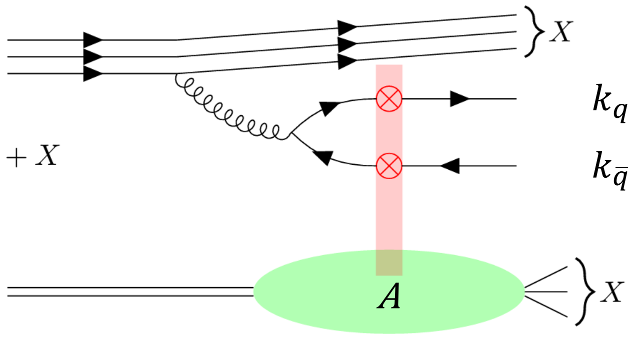
$$S^{q\bar{q}q\bar{q}}(\boldsymbol{x}'_\perp,\boldsymbol{y}'_\perp,\boldsymbol{x}_\perp,\boldsymbol{y}_\perp) = \frac{1}{2C_F N_c}(N_c^2 D_{xx'}D_{yy'} - Q_{xyy'x'}),$$

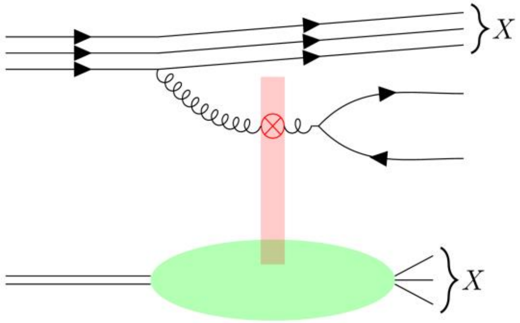
$$S^{q\bar{q}g}(\boldsymbol{x}'_\perp,\boldsymbol{y}'_\perp,\boldsymbol{w}_\perp) = \frac{1}{2C_F N_c}(N_c^2 D_{y'w}D_{wx'} - D_{y'x'}),$$

$$S^{gg}(\boldsymbol{w}'_\perp,\boldsymbol{w}_\perp) = \frac{1}{2C_F N_c}(N_c^2 D_{ww'}D_{w'w} - 1).$$

Dominguez, Marquet, Xiao, Yuan (2011)

Gluon TMDs factorization





$$\boldsymbol{K}_\perp = \boldsymbol{k}_{q\perp} + \boldsymbol{k}_{\bar{q}\perp}$$

$$\boldsymbol{P}_\perp = \frac{z_{\bar{q}} \boldsymbol{k}_{q\perp} - z_q \boldsymbol{k}_{\bar{q}\perp}}{z_q + z_{\bar{q}}}$$

In the back-to-back limit

$$\frac{d\sigma^{gA \to q\bar{q}X}_{\text{TMD}}}{d^2\boldsymbol{P}_\perp \, d^2\boldsymbol{K}_\perp \, d\eta_1 \, d\eta_2} = \sum_f x_p g(x_p) \frac{\alpha_s^2}{\hat{s}^2} \left[\mathcal{F}_{gg}^{(1)} H^{(1)}_{gg \to q\bar{q}} + \mathcal{F}_{gg}^{(2)} H^{(2)}_{gg \to q\bar{q}} \right]$$

Gluon TMD distributions

$$H^{(1)}_{gg \to q\bar{q}} = \frac{1}{4N_c} \frac{2\left(\hat{t}^2 + \hat{u}^2\right)^2}{\hat{s}^2 \hat{u}\hat{t}},$$

$$H^{(2)}_{gg \to q\bar{q}} = \frac{1}{4N_c} \frac{4\left(\hat{t}^2 + \hat{u}^2\right)}{\hat{s}^2},$$

$$\mathcal{F}_{gg}^{(1)} = 2 \int \frac{d\xi^- d^2\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - iq_\perp \cdot \xi_\perp} \left\langle \text{Tr}\left[F(\xi) \frac{\text{Tr}\left[\mathcal{U}^{[\square]}\right]}{N_c} \mathcal{U}^{[-]\dagger} F(0) \mathcal{U}^{[+]} \right] \right\rangle,$$

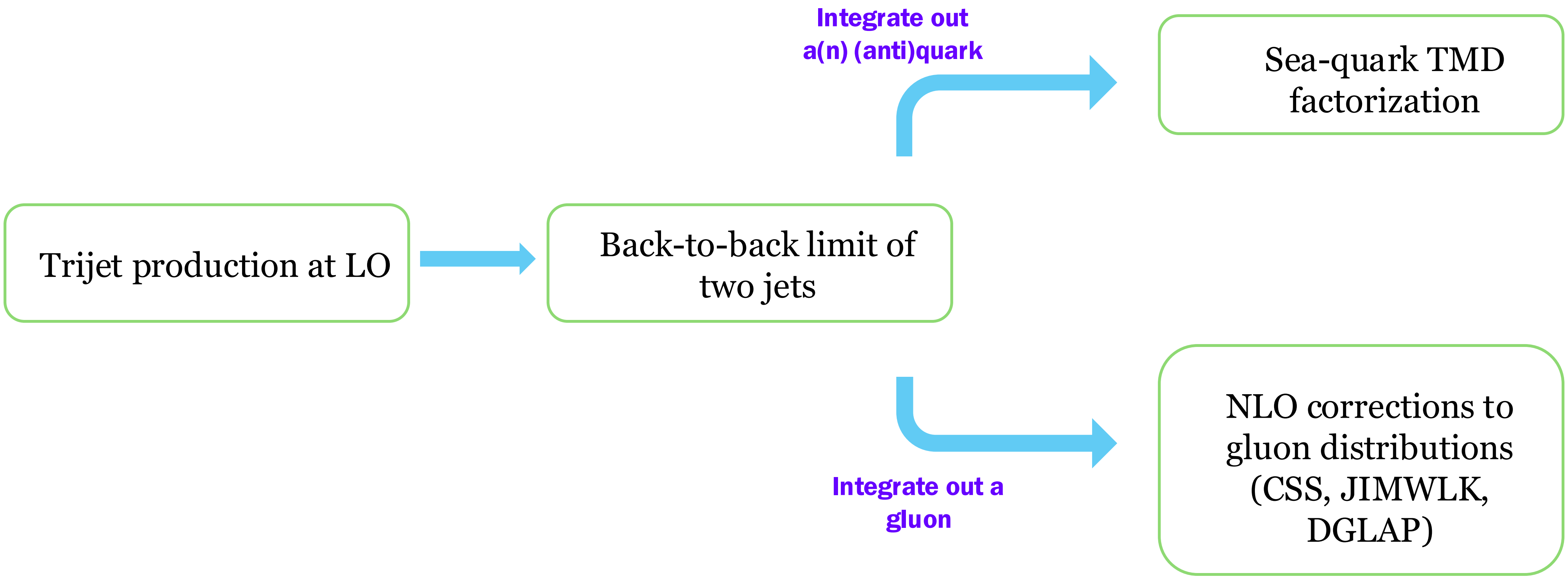
$$\mathcal{F}_{gg}^{(2)} = 2 \int \frac{d\xi^- d^2\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - iq_\perp \cdot \xi_\perp} \frac{1}{N_c} \left\langle \text{Tr}\left[F(\xi) \mathcal{U}^{[\square]\dagger} \right] \text{Tr}\left[F(0) \mathcal{U}^{[\square]} \right] \right\rangle,$$

But what about the sea-quarks?...

Real corrections to dijet production in pA scattering

Real corrections to dijet production in pA scattering

They are obtained by computing LO trijet production and integrating out a final state parton.



Real corrections to dijet production in pA scattering

Trijet production and real corrections for quark initiated channel addressed in: Iancu, Mulian (2019), Iancu, Mulian (2021)

In gluon initiated channel, two final states involved: The ***$q\bar{q}g$ final state*** and the ***ggg final state***

We use spinor helicity methods (Ayala, Hentschinski, Jalilian-Marian, Tejeda, (2017)) and techniques from NLO calculations in DIS (Roy, Venugopalan (2019), Caucal, Salazar, Venugopalan, (2022))

Idea: Decompose fermion and gluon propagators into regular and instantaneous pieces

$$\not{k} = \not{\bar{k}} + \frac{k^2}{2k^-}\not{n},$$

Propagators interacting with shockwave have vanishing instantaneous part

Amplitudes for each diagram will have the form

Color factors

Perturbative factors

$$\int d^2\boldsymbol{x}_\perp d^2\boldsymbol{y}_\perp d^2\boldsymbol{z}_\perp e^{-i\boldsymbol{k}_{1\perp}\cdot\boldsymbol{x}_\perp} e^{-i\boldsymbol{k}_{2\perp}\cdot\boldsymbol{y}_\perp} e^{-i\boldsymbol{k}_{3\perp}\cdot\boldsymbol{z}_\perp} C_{Rn}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp, \boldsymbol{z}_\perp) N_{Rn}^{\bar{\lambda}\sigma\lambda\sigma'}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp, \boldsymbol{z}_\perp)$$

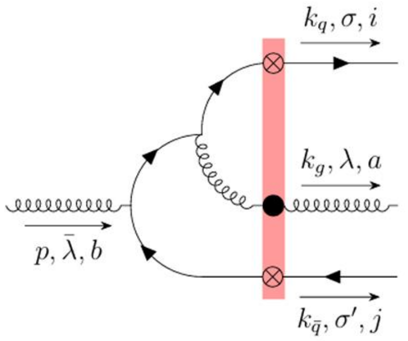
JHEP08(2026)134

$$N_{Rn}^{\bar{\lambda}\sigma\lambda\sigma'} = N_{Rn,reg}^{\bar{\lambda}\sigma\lambda\sigma'} + N_{Rn,inst1}^{\bar{\lambda}\sigma\lambda\sigma'} + \cdots + N_{Rn,instk}^{\bar{\lambda}\sigma\lambda\sigma'}$$

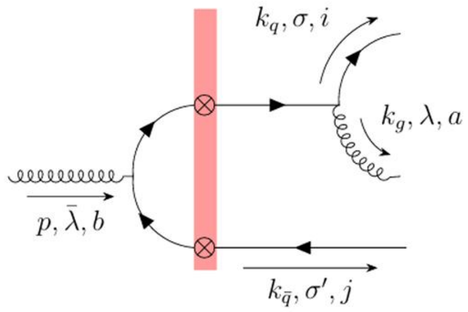
Real corrections to dijet production in pA scattering

I will mainly focus on the $\boldsymbol{q\bar{q}g}$ ***final state***

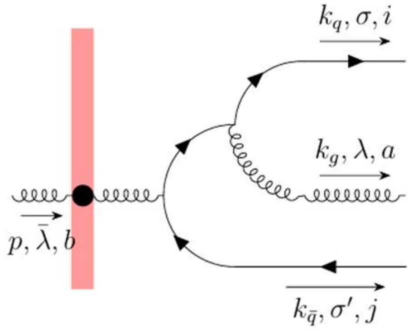
Gluon emission by quark



(R1)

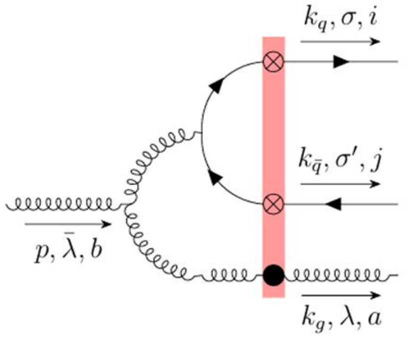


(R2)

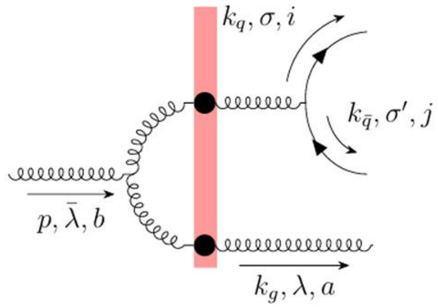


(R3)

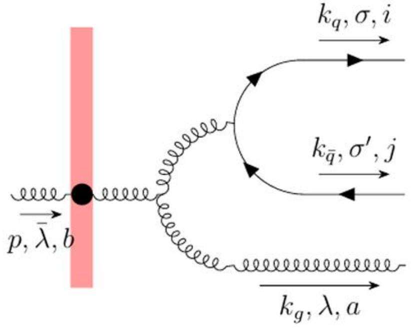
Gluon emission by gluon



(R4)



(R5)



(R6)

Diagrams with emission from antiquark obtained from reversing current flow of quark diagrams

Real corrections to dijet production in pA scattering

For *gluon emission by a quark*, the amplitude reads

Color factors

$$\mathcal{M}_{q,ij}^{\bar\lambda\lambda\sigma\sigma',ab} = \int \mathrm{d}^6\mathbf{\Pi} \left\{ \mathcal{N}_{q,\mathrm{reg}}^{\bar\lambda\lambda\sigma\sigma'} \left[\Theta_{q,1}\left(C_{R1,ij}^{ab} - C_{R3,ij}^{ab}\right) - \left(C_{R2,ij}^{ab} - C_{R3,ij}^{ab}\right)\right] + \left(C_{R1,ij}^{ab} - C_{R3,ij}^{ab}\right)\mathcal{N}_{q,\mathrm{inst}}^{\bar\lambda\lambda\sigma\sigma'} \right\},$$

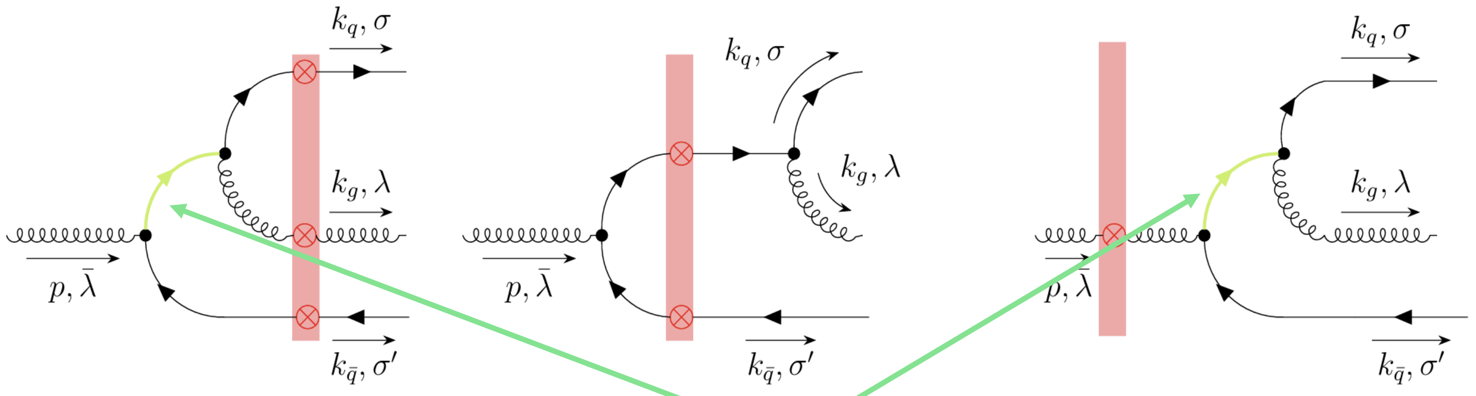
Perturbative factors

$$\mathrm{d}^6\mathbf{\Pi} = \mathrm{d}^2\boldsymbol{x}_\perp \mathrm{d}^2\boldsymbol{y}_\perp \mathrm{d}^2\boldsymbol{z}_\perp e^{-i\boldsymbol{k}_{q\perp}\cdot\boldsymbol{x}_\perp} e^{-i\boldsymbol{k}_{\bar q\perp}\cdot\boldsymbol{y}_\perp} e^{-i\boldsymbol{k}_{g\perp}\cdot\boldsymbol{z}_\perp}$$

$$\Theta_{q,1} = \frac{r_{wy}^2}{r_{wy}^2 + \frac{z_q z_g}{z_{\bar q}(z_q+z_g)^2} r_{zx}^2}$$

$$\Theta_{q,2} = \frac{r_{zx}^2}{r_{zx}^2 + \frac{z_{\bar q}(z_q+z_g)^2}{z_q z_g} r_{wy}^2}$$

$$\boldsymbol{w}_\perp = \frac{z_q \boldsymbol{x}_\perp + z_{\bar q}\boldsymbol{y}_\perp}{z_q + z_{\bar q}}$$



Contains a regular and instantaneous term

Real corrections to dijet production in pA scattering

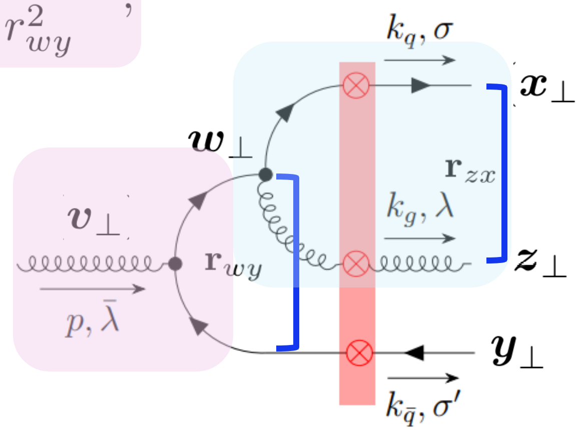
For *gluon emission by quark*

Perturbative factors:

$$N_{q,reg}^{\bar{\lambda}\lambda\sigma\sigma'} = -\frac{8p^-}{(z_q+z_g)}\sqrt{z_q z_{\bar{q}}}\delta^{\sigma,-\sigma'}\Gamma_{q\to qg}^{\sigma\lambda}(z_q+z_g,z_q)\Gamma_{g\to q\bar{q}}^{\sigma\bar{\lambda}}(z_q+z_g,z_{\bar{q}})\frac{\epsilon_\perp^{*\lambda}\cdot\mathbf{r}_{zx}}{r_{zx}^2}\frac{\epsilon_\perp^{\bar{\lambda}}\cdot\mathbf{r}_{wy}}{r_{wy}^2},$$

$$N_{q,inst}^{\bar{\lambda}\lambda\sigma\sigma'} = -\frac{4p^- z_g (z_q z_{\bar{q}})^{3/2}}{(z_q+z_g)}\frac{\delta^{\sigma,-\sigma'}\delta^{\sigma,\lambda}\delta^{\lambda,\bar{\lambda}}}{X_R^2},$$

$$X_R^2 = z_q z_{\bar{q}} r_{xy}^2 + z_g z_q r_{zx}^2 + +z_g z_{\bar{q}} r_{yz}^2$$



Color factors:

a: color of incoming gluon
b: color of outgoing gluon
i: color of final state quark
j: color of final state antiquark

$$C_{R1,ij}^{ab}(\boldsymbol{x}_\perp,\boldsymbol{y}_\perp,\boldsymbol{z}_\perp) = \left[V(\boldsymbol{x}_\perp)t^c t^a V^\dagger(\boldsymbol{y}_\perp)U_{bc}(\boldsymbol{z}_\perp)\right]_{ij},$$

$$C_{R2,ij}^{ab}(\boldsymbol{w}_\perp,\boldsymbol{z}_\perp) = \left[t^b V(\boldsymbol{w}_\perp)t^a V^\dagger(\boldsymbol{y}_\perp)\right]_{ij},$$

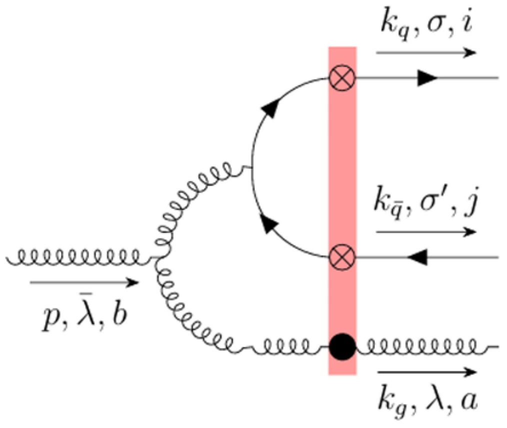
$$C_{R3,ij}^{ab}(\boldsymbol{v}_\perp) = \left[t^a t^c U_{cb}(\boldsymbol{v}_\perp)\right]_{ij}.$$

Real corrections to dijet production in pA scattering

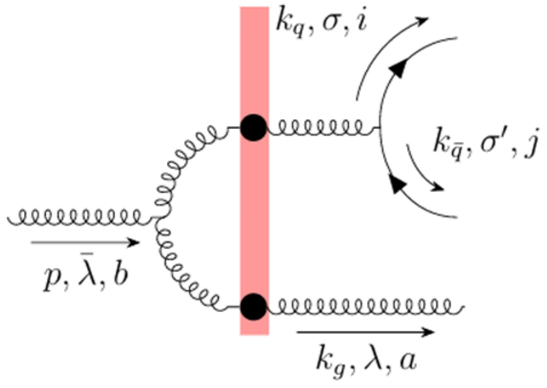
The $q\bar{q}g$ final state

For *gluon emission by a gluon*, the amplitude reads

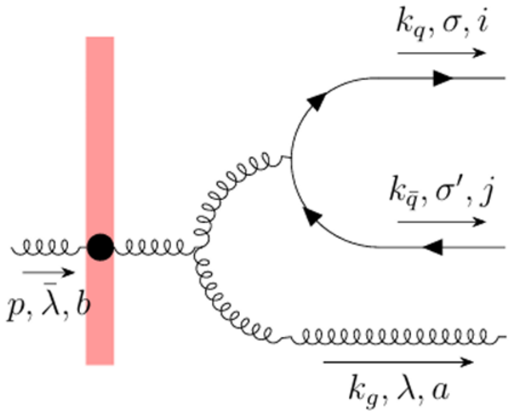
$$\mathcal{M}_{g,ij}^{\bar{\lambda}\lambda\sigma\sigma',ab} = \int \mathrm{d}^6\mathbf{\Pi}\Big\{\mathcal{N}_{g,\mathrm{reg}}^{\bar{\lambda}\lambda\sigma\sigma'}\left[\Theta_{g,1}(C_{R4,ij}^{ab} - C_{R6,ij}^{ab}) - (C_{R5,ij}^{ab} - C_{R6,ij}^{ab})\right] + (C_{R4,ij}^{ab} - C_{R6,ij}^{ab})\mathcal{N}_{g,\mathrm{inst}}^{\bar{\lambda}\lambda\sigma\sigma'}\Big\}\,,$$



(R4)



(R5)



(R6)

$$\Theta_{g,1} = \frac{r_{w_2z}^2}{r_{w_2z}^2 + \frac{z_q z_{\bar{q}}}{z_g(z_q+z_{\bar{q}})^2}r_{yx}^2}$$

$$\Theta_{g,2} = \frac{r_{yx}^2}{r_{yx}^2 + \frac{z_g(z_q+z_{\bar{q}})^2}{z_q z_{\bar{q}}}r_{w_2z}^2}$$

Real corrections to dijet production in pA scattering

The $q\bar{q}g$ final state

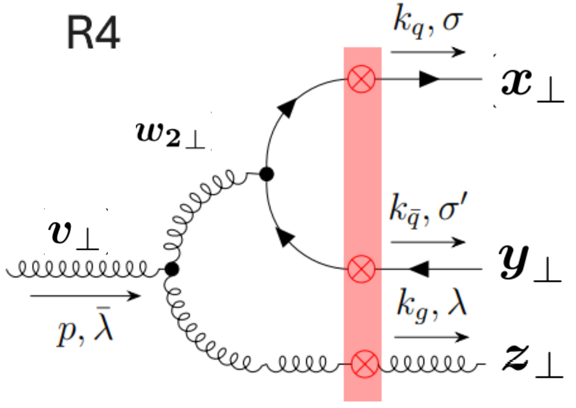
$g \to gg$ splitting vertex function

$$G_{\perp}^{\bar{\lambda}\lambda\eta}(z_1, z_2) = \frac{1}{z_1}\delta^{\lambda\bar{\lambda}}\epsilon_{\perp}^{\eta*} + \frac{1}{z_2}\delta^{\bar{\lambda}\eta}\epsilon_{\perp}^{\lambda*} - \delta^{\lambda,-\eta}\epsilon_{\perp}^{\bar{\lambda}}$$

Perturbative factors:

$$N_{g,reg}^{\bar{\lambda}\lambda\sigma\sigma'}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp, \boldsymbol{z}_\perp) = \frac{8p^- z_g\sqrt{z_q z_{\bar{q}}}}{(z_q + z_{\bar{q}})}\delta^{\sigma,-\sigma'}\Gamma_{g\to q\bar{q}}^{\sigma\eta}(z_q, z_{\bar{q}})\frac{\epsilon_{\perp}^{\eta}\cdot\boldsymbol{r}_{yx}}{r_{yx}^2}\frac{G_{\perp}^{\bar{\lambda}\lambda\eta}(z_q + z_{\bar{q}}, z_g)\cdot\boldsymbol{r}_{w_2 z}}{r_{w_2 z}^2},$$

$$N_{g,\text{inst}}^{\bar{\lambda}\lambda\sigma\sigma'}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp, \boldsymbol{z}_\perp) = -\frac{4p^- z_g(1+z_g)(z_q z_{\bar{q}})^{3/2}}{(z_q + z_{\bar{q}})^2}\frac{\delta^{\sigma,-\sigma'}\delta^{\lambda,\bar{\lambda}}}{X_R^2}.$$



Color factors:

$$C_{R4,ij}^{ab}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp, \boldsymbol{z}_\perp) = \left[V(\boldsymbol{x}_\perp)t^d V^\dagger(\boldsymbol{y}_\perp)U_{bc}(\boldsymbol{z}_\perp)if^{acd}\right]_{ij},$$

$$C_{R5,ij}^{ab}(\boldsymbol{w_2}_\perp, \boldsymbol{z}_\perp) = \left[if^{cdb}U_{de}^\dagger(\boldsymbol{w_2}_\perp)t^e U_{ac}(\boldsymbol{z}_\perp)\right]_{ij},$$

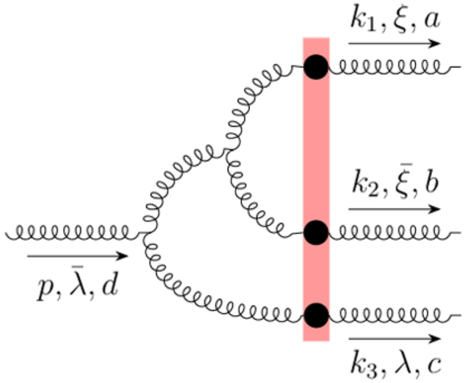
$$C_{R6,ij}^{ab}(\boldsymbol{v}_\perp) = \left[it^c f^{dac}U_{bd}^\dagger(\boldsymbol{v}_\perp)\right]_{ij}.$$

a: color of incoming gluon
b: color of outgoing gluon
i: color of final state quark
j: color of final state antiquark

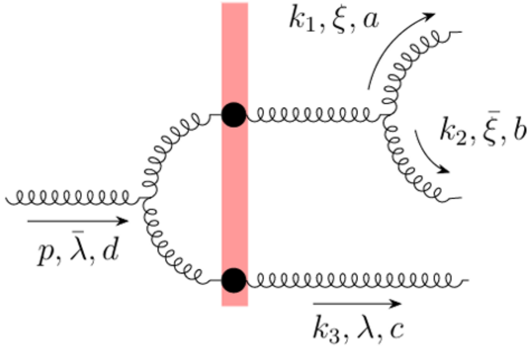
Real corrections to dijet production in pA scattering

Diagrams for ggg trijet production in pA scattering

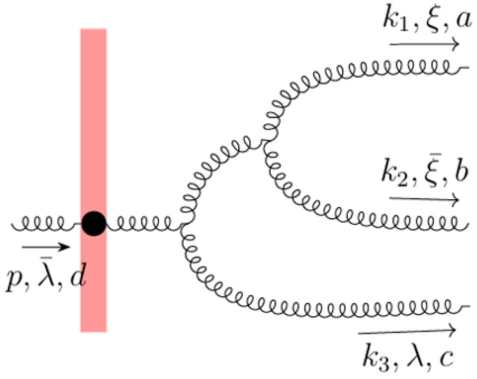
Double gluon splitting



(R7)

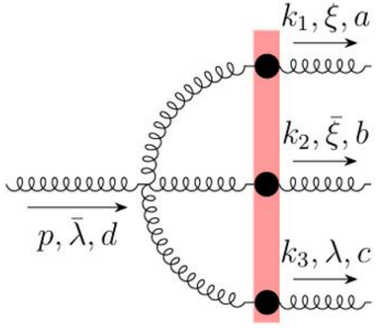


(R8)

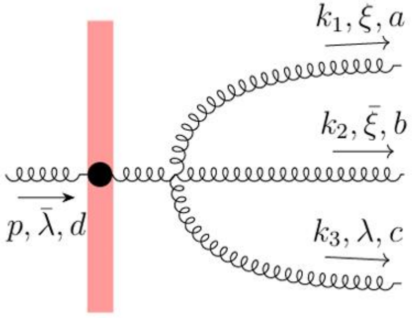


(R9)

Four gluon vertex



(R10)

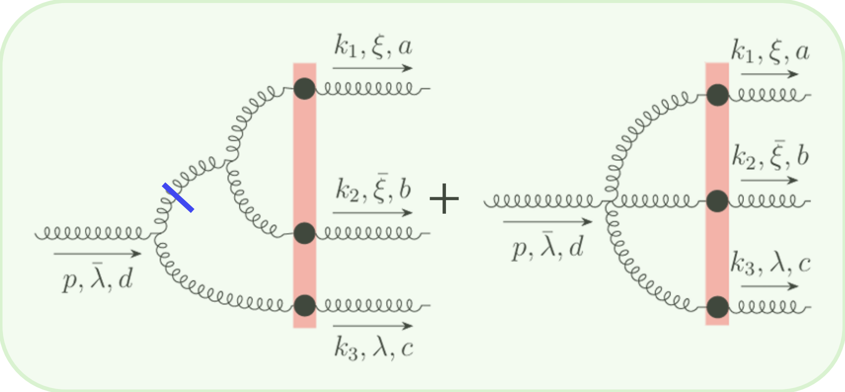


(R11)

For this process we also need to consider permutations of the final state gluons

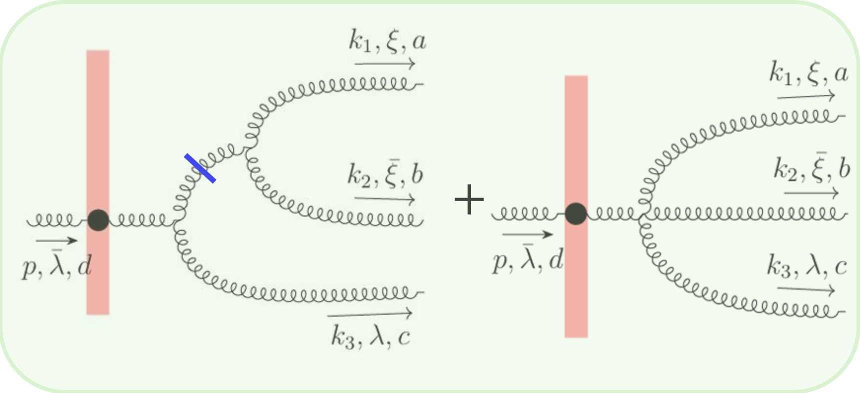
Real corrections to dijet production in pA scattering

Instantaneous parts of diagrams R7 and R9 are absorbed in amplitudes R10 and R11



$$\mathcal{M}^{\bar{\lambda}\lambda\bar{\xi}\xi}_{R7,inst} = \frac{g^2}{4\pi^2}\int d^6\mathbf{\Pi}\Big\{(C_{R10,B} - C_{R10,A})N_{R7,inst}\Big\}$$

$$\mathcal{M}^{\bar{\lambda}\lambda\bar{\xi}\xi}_{R7,inst+R10} = \frac{g^2}{4\pi^2}\int d^6\mathbf{\Pi}\Big\{C_{R10,A}N^{ggg}_{inst1} + C_{R10,B}N^{ggg}_{inst2}\Big\}$$



$$\mathcal{M}^{\bar{\lambda}\lambda\bar{\xi}\xi}_{R9,inst+R11} = -\frac{g^2}{4\pi^2}\int d^6\mathbf{\Pi}\Big\{C_{R11,A}N^{ggg}_{inst1} + C_{R11,B}N^{ggg}_{inst2}\Big\}$$

Real corrections to dijet production in pA scattering

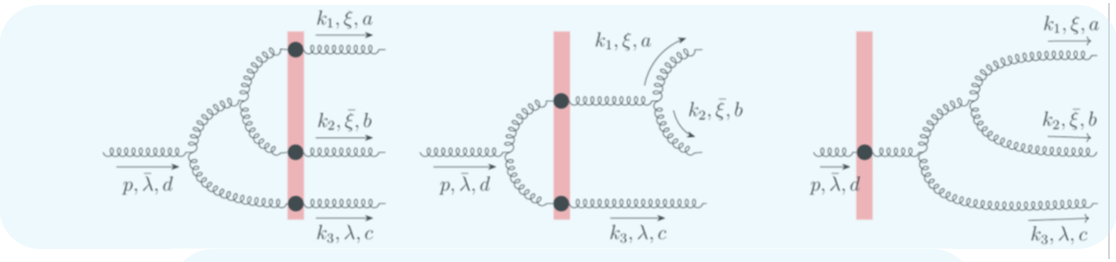
The ggg final state

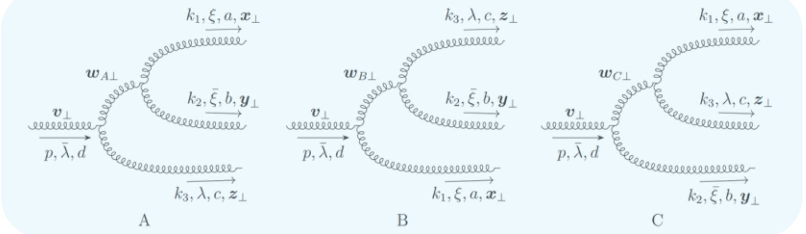
The regular contribution is analogous to other processes. The resulting amplitude for the process is:

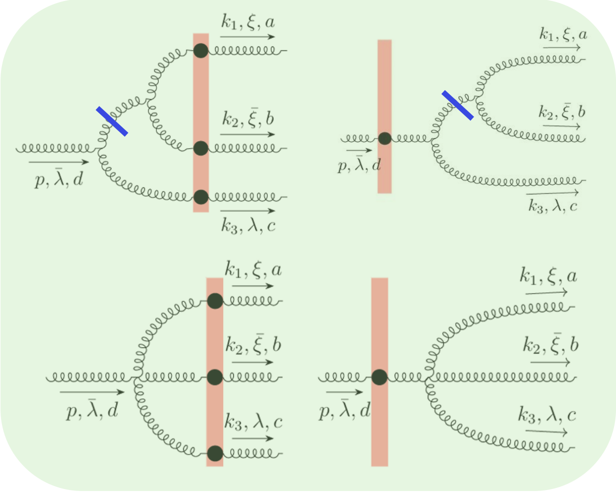
$$\mathcal{M}_{ggg}^{\bar{\lambda}\lambda\bar{\xi}\xi,abcd} = \int \mathrm{d}^6\boldsymbol{\Pi}\Big[\Big\{\{\Theta_{ggg,1A}(C^{abcd}_{R7,A} - C^{abcd}_{R9,A}) - (C^{abcd}_{R8,A} - C^{abcd}_{R9,A})\}\mathcal{N}^{\bar{\lambda}\lambda\bar{\xi}\xi}_{ggg,\mathrm{reg}\,A}$$

$$+ (k_1,\xi,a,\boldsymbol{x}_\perp) \leftrightarrow (k_3,\lambda,c,\boldsymbol{z}_\perp) + (k_2,\bar{\xi},b,\boldsymbol{y}_\perp) \leftrightarrow (k_3,\lambda,c,\boldsymbol{z}_\perp)\Big\}$$

$$+ (C^{abcd}_{R7,A} - C^{abcd}_{R9,A})\overline{\mathcal{N}}^{\bar{\lambda}\lambda\bar{\xi}\xi}_{ggg,\mathrm{inst},A} + (C^{abcd}_{R7,B} - C^{abcd}_{R9,B})\overline{\mathcal{N}}^{\bar{\lambda}\lambda\bar{\xi}\xi}_{ggg,\mathrm{inst},B}\Big],$$







Real corrections to dijet production in pA scattering

The ggg final state

Perturbative factors:

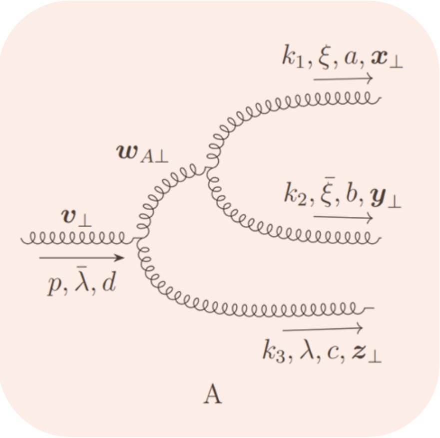
$$\mathcal{N}^{\bar\lambda\lambda\bar\xi\xi}_{ggg,\text{reg }A}(\boldsymbol{x}_\perp,\boldsymbol{y}_\perp,\boldsymbol{z}_\perp) = -\frac{2g^2p^-}{\pi^2}\frac{\boldsymbol{G}^{\eta\bar\xi\xi}_\perp\left(\frac{z_1}{z_1+z_2}\right)\cdot\boldsymbol{r}_{yx}}{\boldsymbol{r}^2_{yx}}\frac{\boldsymbol{G}^{\bar\lambda\lambda\eta}_\perp(z_1+z_2)\cdot\boldsymbol{r}_{w_Az}}{r^2_{w_Az}}$$

$$\overline{\mathcal{N}}^{\bar\lambda\lambda\bar\xi\xi}_{ggg,\text{inst},A} = -\frac{g^2p^-z_1z_2z_3}{2\pi^2X_R^2}\left\{\left(\frac{(z_2-z_1)(1+z_3)}{(z_1+z_2)^2}+1\right)\delta^{\bar\lambda\lambda}\delta^{\xi,-\bar\xi}+\left(\frac{(z_3-z_1)(1+z_2)}{(z_1+z_3)^2}+1\right)\delta^{\bar\lambda\bar\xi}\delta^{\xi,-\lambda}-2\delta^{\bar\lambda\xi}\delta^{\lambda,-\bar\xi}\right\}$$

$$\overline{\mathcal{N}}^{\bar\lambda\lambda\bar\xi\xi}_{ggg,\text{inst},B} = -\frac{g^2p^-z_1z_2z_3}{2\pi^2X_R^2}\left\{\left(\frac{(z_2-z_3)(1+z_1)}{(z_2+z_3)^2}+1\right)\delta^{\bar\lambda\xi}\delta^{\lambda,-\bar\xi}+\left(\frac{(z_1-z_3)(1+z_2)}{(z_1+z_3)^2}+1\right)\delta^{\bar\lambda\bar\xi}\delta^{\xi,-\lambda}-2\delta^{\bar\lambda\lambda}\delta^{\xi,-\bar\xi}\right\}$$

Color factors:

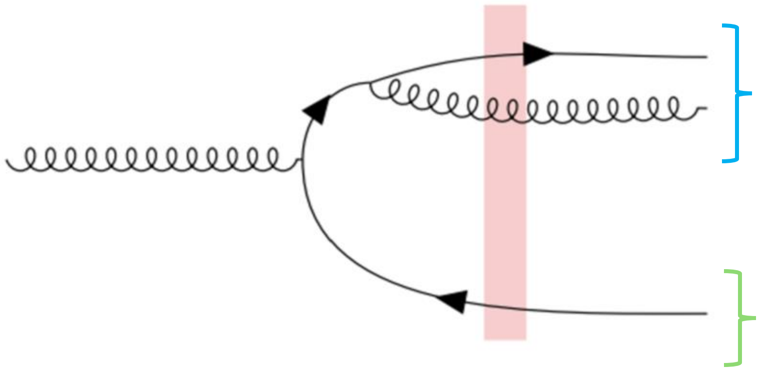
$$\begin{aligned}
C^{abcd}_{R7,A}(\boldsymbol{x}_\perp,\boldsymbol{y}_\perp,\boldsymbol{z}_\perp) &= f^{efg}f^{dhf}U_{ae}(\boldsymbol{x}_\perp)U_{bg}(\boldsymbol{y}_\perp)U_{ch}(\boldsymbol{z}_\perp)\,,\\
C^{abcd}_{R8,A}(\boldsymbol{w}_{A\perp},\boldsymbol{z}_\perp) &= f^{eba}f^{gfd}U_{ef}(\boldsymbol{w}_{A\perp})U_{cg}(\boldsymbol{z}_\perp)\,,\\
C^{abcd}_{R9,A}(\boldsymbol{v}_\perp) &= f^{eba}f^{fce}U_{fd}(\boldsymbol{v}_\perp)\,.
\end{aligned}$$



Sea quark TMD factorization

Factorization in pA qg dijet production

Remarkably, when we take back-to-back limit and integrate out a(n) (anti)quark, expressions simplify drastically and can be expressed in a factorized form in terms of sea quark distributions



Dijet variables

$$\begin{aligned} \boldsymbol{P}_\perp &= \frac{z_g \boldsymbol{k}_{q\perp} - z_q \boldsymbol{k}_{g\perp}}{z_q + z_g}, \\ \boldsymbol{K}_\perp &= \boldsymbol{k}_{q\perp} + \boldsymbol{k}_{g\perp}, \\ \boldsymbol{\Delta} &= \boldsymbol{k}_{q\perp} + \boldsymbol{k}_{g\perp} + \boldsymbol{k}_{\bar{q}\perp}. \end{aligned}$$

We are interested in the limit $\boldsymbol{K}_\perp^2, Q_s^2 \ll \boldsymbol{P}_\perp^2.$

In this limit, integral over antiquark kinematics is dominated by values $k_{\bar{q}\perp} \sim K_\perp$ and $z_{\bar{q}} \sim \frac{K_\perp^2}{P_\perp^2} \ll 1$

Factorization in pA qg dijet production

The amplitudes expressed in momentum space, and expanded in leading powers of $K_\perp/P_\perp$ and $Q_s/P_\perp$ can be expressed as

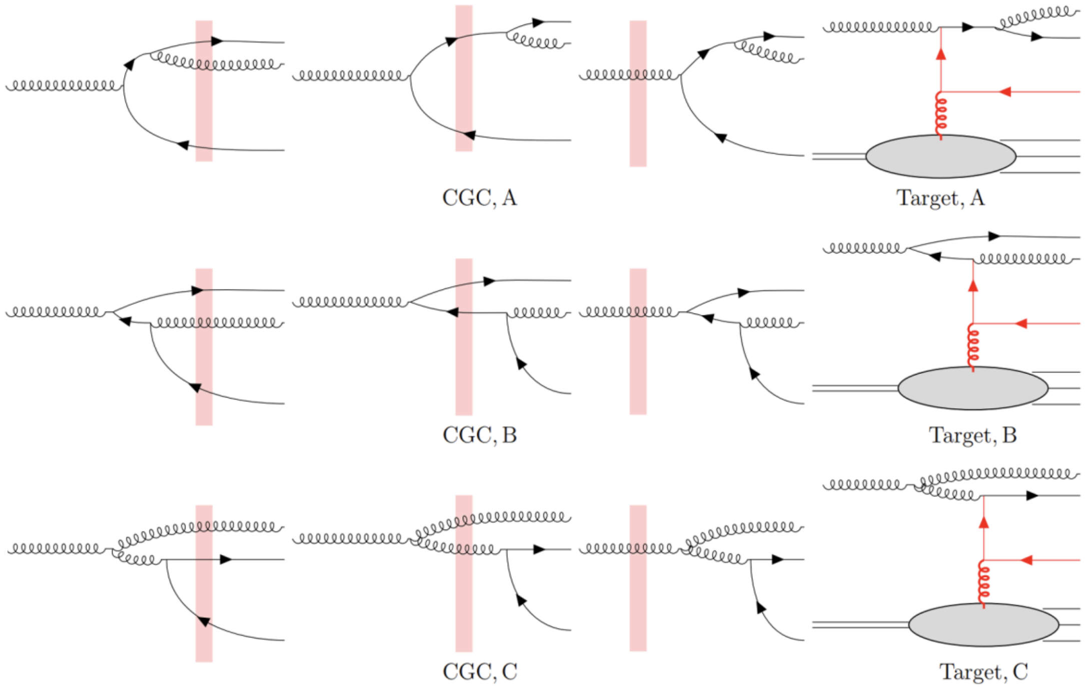
$$(\mathcal{M}_f)^{\lambda\bar{\lambda},ab}_{\sigma\sigma',i\bar{i}} = \left(H^j_f\right)^{\lambda\bar{\lambda}}_{\sigma\sigma'} \int \frac{\mathrm{d}^2 \boldsymbol{q}_{2\perp}}{(2\pi)^2} C^{ab}_{f,i\bar{i}}(\boldsymbol{q}_{2\perp}) \frac{(\boldsymbol{K}_\perp - \boldsymbol{q}_{2\perp})^j}{\frac{z_{\bar{q}}}{z_q z_g}\boldsymbol{P}^2_\perp + (\boldsymbol{K}_\perp - \boldsymbol{q}_{2\perp})^2},$$

With hard factors

$$(H^j_q)^{\lambda\bar{\lambda}}_{\sigma\sigma'} = 8g^2 p^- \sqrt{z_q z_{\bar{q}}}\,\delta^{\sigma,-\sigma'}(z_q\delta^{\sigma,\lambda} + \delta^{\sigma,-\lambda})(-\delta^{\sigma,-\bar{\lambda}})\frac{\epsilon^{*\lambda}_\perp \cdot \boldsymbol{P}_\perp}{\boldsymbol{P}^2_\perp}\epsilon^{\bar{\lambda},j}_\perp,$$

$$\left(H^j_{\bar{q}}\right)^{\lambda\bar{\lambda}}_{\sigma\sigma'} = 8g^2 p^- \sqrt{z_q z_{\bar{q}}}\,\delta^{\sigma,-\sigma'}(\delta^{\sigma',-\lambda})(z_q\delta^{\sigma',\bar{\lambda}} - z_g\delta^{\sigma',-\bar{\lambda}})\frac{\epsilon^{\bar{\lambda}}_\perp \cdot \boldsymbol{P}_\perp}{\boldsymbol{P}^2_\perp}\epsilon^{*\lambda,j}_\perp,$$

$$(H^j_g)^{\lambda\bar{\lambda}}_{\sigma\sigma'} = 8g^2 p^- z_g \sqrt{z_q z_{\bar{q}}}\,\delta^{\sigma,-\sigma'}(\delta^{\sigma,-\eta})\frac{G^{\bar{\lambda}\lambda\eta}_\perp(z_q, z_g) \cdot \boldsymbol{P}_\perp}{\boldsymbol{P}^2_\perp}\epsilon^{\eta,j}_\perp,$$



Factorization in pA qg dijet production

and color factors:

$$C^{ab}_{f,i\bar{i}}(\boldsymbol{q_{2\perp}}) = \int \mathrm{d}^2\boldsymbol{x}_\perp \mathrm{d}^2\boldsymbol{y}_\perp e^{-i\boldsymbol{q_{2\perp}}\cdot\boldsymbol{x}_\perp} e^{-i(\boldsymbol{\Delta}_\perp - \boldsymbol{q_{2\perp}})\cdot\boldsymbol{y}_\perp} C^{ab}_{f,i\bar{i}}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp),$$

$$C^{ab}_{q,i\bar{i}}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp) = \left[t^a V(\boldsymbol{x}_\perp) t^b V^\dagger(\boldsymbol{y}_\perp) - t^a V(\boldsymbol{x}_\perp) t^b V^\dagger(\boldsymbol{x}_\perp)\right]_{i\bar{i}},$$

$$C^{ab}_{\bar{q},i\bar{i}}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp) = \left[V(\boldsymbol{x}_\perp) t^b V^\dagger(\boldsymbol{x}_\perp) t^a V(\boldsymbol{x}_\perp) V^\dagger(\boldsymbol{y}_\perp) - V(\boldsymbol{x}_\perp) t^b V^\dagger(\boldsymbol{x}_\perp) t^a\right]_{i\bar{i}},$$

$$C^{ab}_{g,i\bar{i}}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp) = C^{ab}_{q,i\bar{i}}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp) - C^{ab}_{\bar{q},i\bar{i}}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp).$$

Squaring these amplitudes, and integrating over antiquark kinematics

$$\frac{\mathrm{d}\sigma^{gA\to gqX}}{\mathrm{d}^2\boldsymbol{P}_\perp \mathrm{d}^2\boldsymbol{K}_\perp \mathrm{d}z_q \mathrm{d}z_g} = \delta(1 - z_q - z_g)\frac{\alpha_s^2(1+z_g^2)}{2z_q\boldsymbol{P}_\perp^4}\frac{N_c^2}{(N_c^2-1)}$$
$$\times\left[xq^{(3)}(x,\boldsymbol{K}_\perp) + \left(z_g^2 - \frac{z_q^2}{N_c^2}\right) xq^{(2)}(x,\boldsymbol{K}_\perp) - \frac{1}{N_c^2}\left((1+z_g)^2 - \frac{z_q^2}{N_c^2}\right) xq^{(1)}(x,\boldsymbol{K}_\perp)\right]$$

Sea quark TMD distributions

Factorization in pA qg dijet production

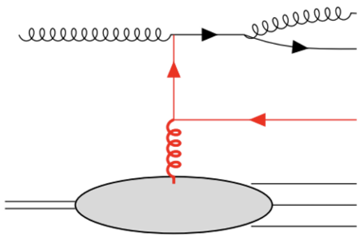
CGC gives **explicit expressions** for quark TMD distributions which have a general universality following a process dependent gauge link color flow (C. J. Bomhof, P. J. Mulders, F. Pijlman, 2006). They are built from two fundamental distributions

number of wilson loops

$$xq^{(n)}(x, \boldsymbol{K}_\perp) = \int \mathrm{d}^2\boldsymbol{b}_\perp \mathrm{d}^2\boldsymbol{q}_\perp \left\langle \mathcal{D}_F^{(n-1)}(\boldsymbol{b}_\perp, \boldsymbol{q}_\perp)\mathcal{Q}(\boldsymbol{b}_\perp, \boldsymbol{K}_\perp - \boldsymbol{q}_\perp)\right\rangle_x$$

$$\mathcal{D}_F^{(n)}(\boldsymbol{b}_\perp, \boldsymbol{q}_\perp) \equiv \int \mathrm{d}^2\boldsymbol{r}_\perp e^{i\boldsymbol{r}_\perp\cdot\boldsymbol{q}_\perp}\left(\frac{1}{N_c}\mathrm{Tr}\left[V(\boldsymbol{b}_\perp + \boldsymbol{r}_\perp/2)V^\dagger(\boldsymbol{b}_\perp - \boldsymbol{r}_\perp/2)\right]\right)^n ,$$

$$\mathcal{Q}(\boldsymbol{b}_\perp, \boldsymbol{K}_\perp) \equiv \frac{N_c}{4\pi^4}\int \mathrm{d}^2\boldsymbol{q}_\perp \mathcal{D}_F^{(1)}(\boldsymbol{b}_\perp, \boldsymbol{q}_\perp)\left[1 - \frac{(\boldsymbol{K}_\perp - \boldsymbol{q}_\perp)\cdot\boldsymbol{K}_\perp}{(\boldsymbol{K}_\perp - \boldsymbol{q}_\perp)^2 - \boldsymbol{K}_\perp^2}\ln\left(\frac{(\boldsymbol{K}_\perp - \boldsymbol{q}_\perp)^2}{\boldsymbol{K}_\perp^2}\right)\right]$$



α Unintegrated Gluon Distribution

α TMD gluon to quark-antiquark splitting function

We proved that *this factorization holds* for the rest of the processes with a(n) (anti)quark in the final state in pA scattering and DIS

arXiv: (2503.16162)

Numerical results

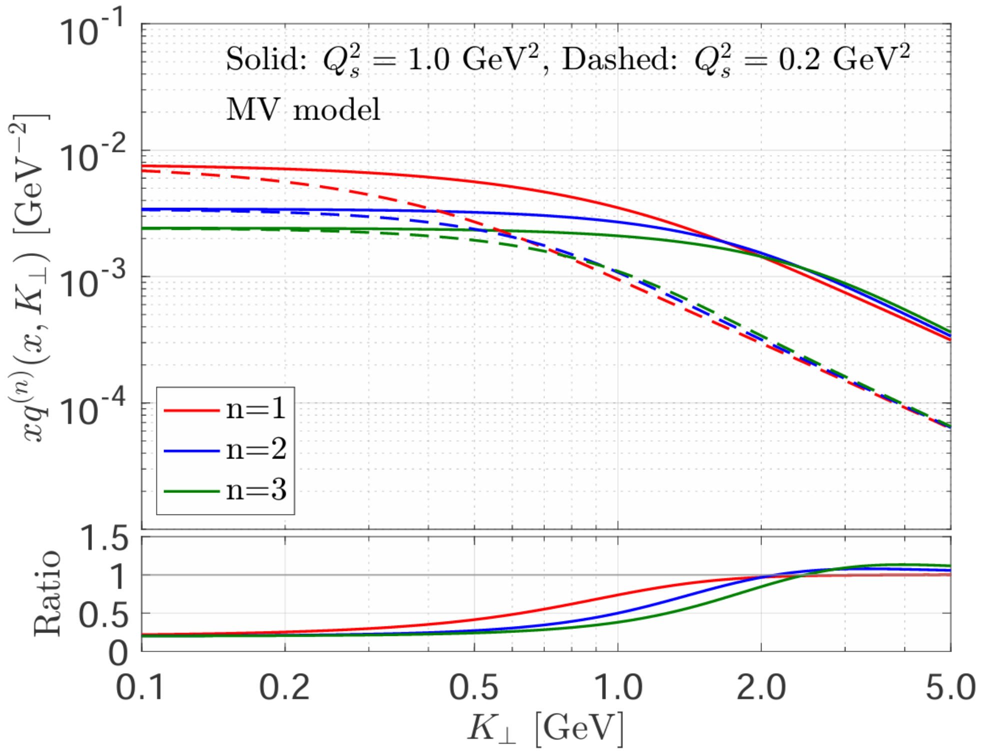
Numerical results

Using the MV model, assuming translational invariance and using the mean field approximation we compute the distributions for proton ($Q_s^2 = 0.2\ GeV^2$) and a nucleus ($Q_s^2 = 1\ GeV^2$)

$$xq^{(n)}(x, \boldsymbol{K}_\perp) = \int \mathrm{d}^2\boldsymbol{b}_\perp \mathrm{d}^2\boldsymbol{q}_\perp \left\langle \mathcal{D}_F^{(n-1)}(\boldsymbol{b}_\perp, \boldsymbol{q}_\perp)\mathcal{Q}(\boldsymbol{b}_\perp, \boldsymbol{K}_\perp - \boldsymbol{q}_\perp)\right\rangle_x$$

$$D_{x_A}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp) = D_{x_A}(\boldsymbol{r}_\perp) = \exp\left\{-\frac{1}{4}\alpha_s C_F \mu^2 r_\perp^2 \ln\left(\frac{1}{\lambda r_\perp} + e\right)\right\}$$

Higher values of n show higher suppression!



Numerical results

High energy evolution

Evolution equation given by

$$\frac{\mathrm{d}}{\mathrm{d}Y}\langle\mathcal{O}\rangle_Y = H_{\mathrm{JIMWLK}}\,\langle\mathcal{O}\rangle_Y$$

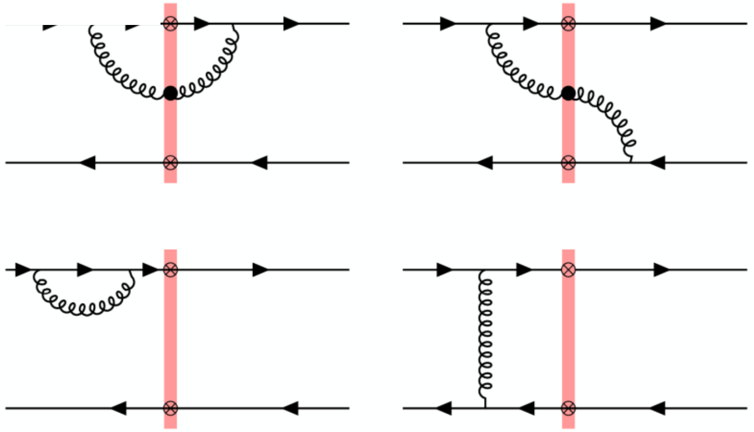
$$Y = \ln\,\frac{x_0}{x}$$

$$H_{\mathrm{JIMWLK}} \equiv \frac{\alpha_s}{4\pi^2}\int \mathrm{d}^2\boldsymbol{z}_\perp \sum_{j,k}\frac{(\boldsymbol{x}_{j\perp}-\boldsymbol{x}_{k\perp})^2}{(\boldsymbol{x}_{j\perp}-\boldsymbol{z}_\perp)^2\,(\boldsymbol{x}_{k\perp}-\boldsymbol{z}_\perp)^2}$$
$$\left[T^a_{x_j,L} - U_{ac}(\boldsymbol{z}_\perp)T^c_{x_j,R}\right]\left[T^a_{x_k,L} - U_{ac}(\boldsymbol{z}_\perp)T^c_{x_k,R}\right]$$

Left and right generators: generate a soft gluon to left or right of Wilson line at x_j

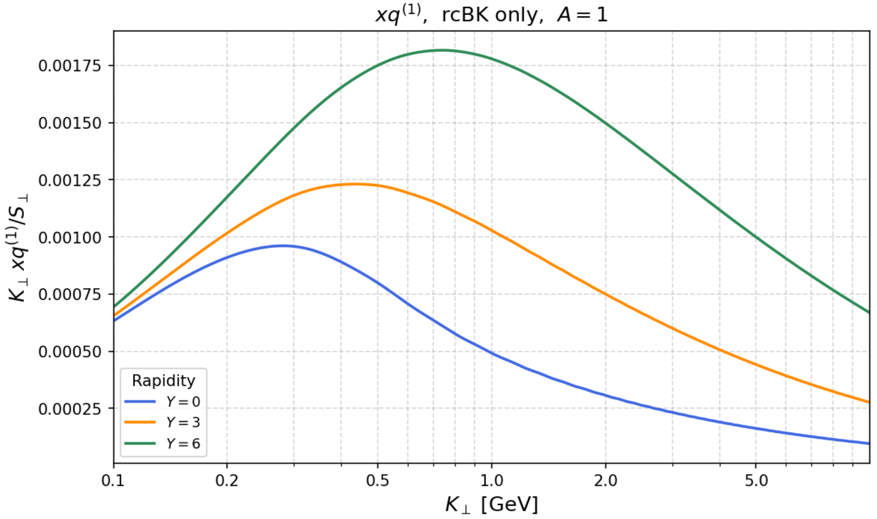
In the large N_c limit, it simplifies to BK evolution equation. For dipole correlator:

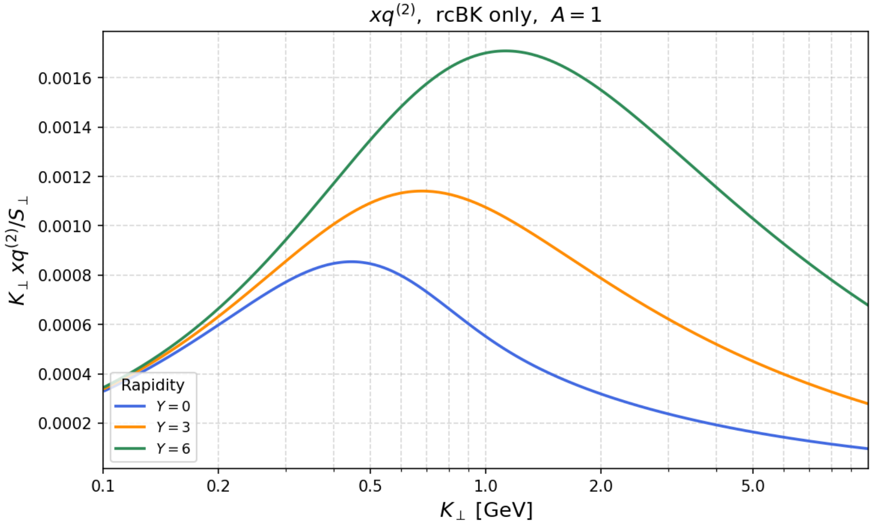
$$\partial_Y D_Y(\boldsymbol{w}_\perp,\boldsymbol{w}'_\perp) = \frac{\alpha_s N_c}{2\pi^2}\int \mathrm{d}^2\boldsymbol{z}_\perp \frac{(\boldsymbol{w}_\perp-\boldsymbol{w}'_\perp)^2}{(\boldsymbol{w}_\perp-\boldsymbol{z}_\perp)^2\,(\boldsymbol{z}_\perp-\boldsymbol{w}'_\perp)^2}$$
$$\times\left[D_Y(\boldsymbol{w}_\perp,\boldsymbol{z}_\perp)\,D_Y(\boldsymbol{z}_\perp,\boldsymbol{w}'_\perp) - D_Y(\boldsymbol{w}_\perp,\boldsymbol{w}'_\perp)\right]$$

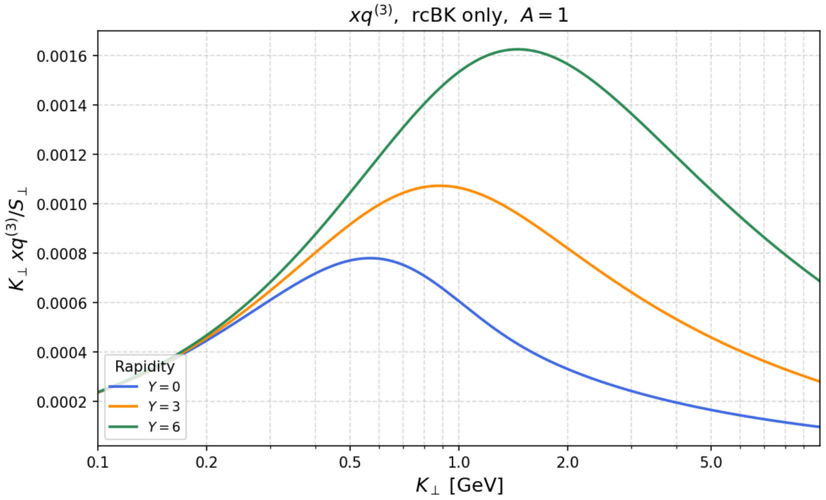


Numerical results

High energy evolution







Saturation scale increases as we evolve to smaller values of x

Numerical results

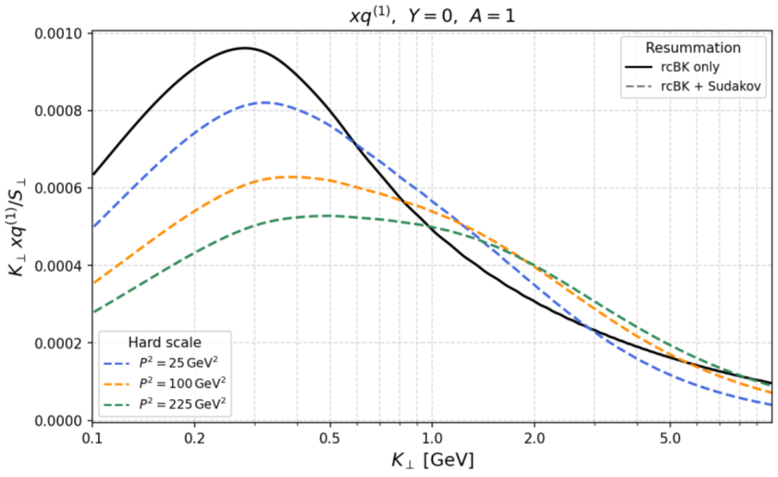
CSS evolution

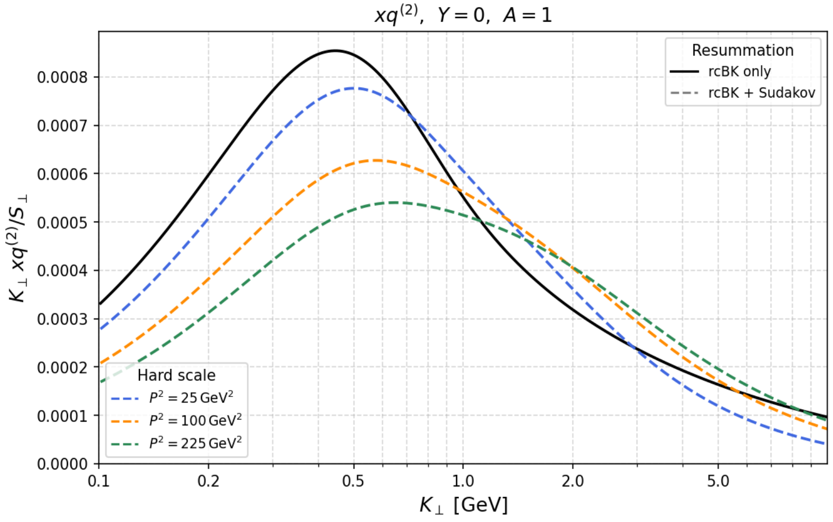
Resums double and single logarithms of the ratio $\frac{P_\perp}{K_\perp}$.
Solution in coord. space given by a multiplicative *Sudakov factor*

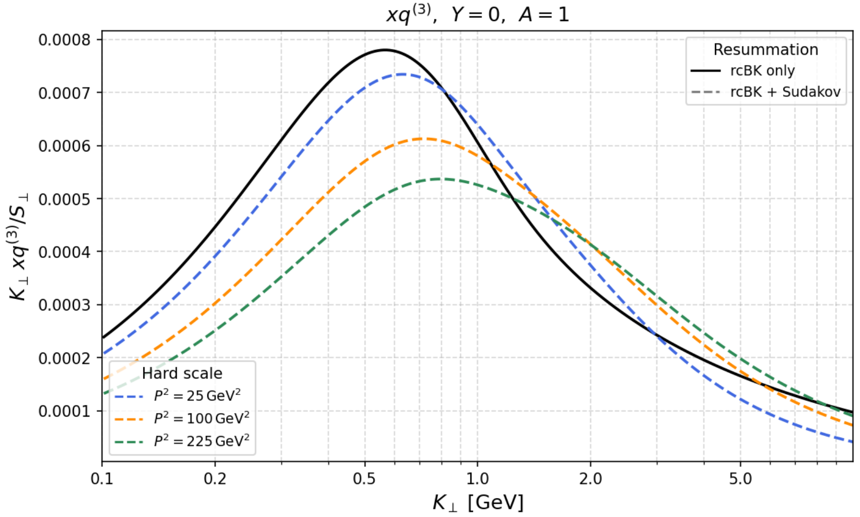
$$xq^{(n)}(x, \boldsymbol{K}_\perp) = S_\perp \int \frac{d^2\boldsymbol{r}_\perp}{(2\pi)^2} e^{-i\boldsymbol{K}_\perp \cdot \boldsymbol{r}_\perp} x\tilde{q}^{(n)}(x, \boldsymbol{r}_\perp)\, e^{-S_{sud}(r_\perp^2, \mu_f^2)}$$

$$S_{sud} = \int_{\mu_b^2}^{\mu_f^2} \frac{d\mu^2}{\mu^2} \left(A \ln \frac{\mu_f^2}{\mu^2} + B \right)$$

Hard scale given by $\mu_f = P_\perp$.
We employ coefficients for single quark



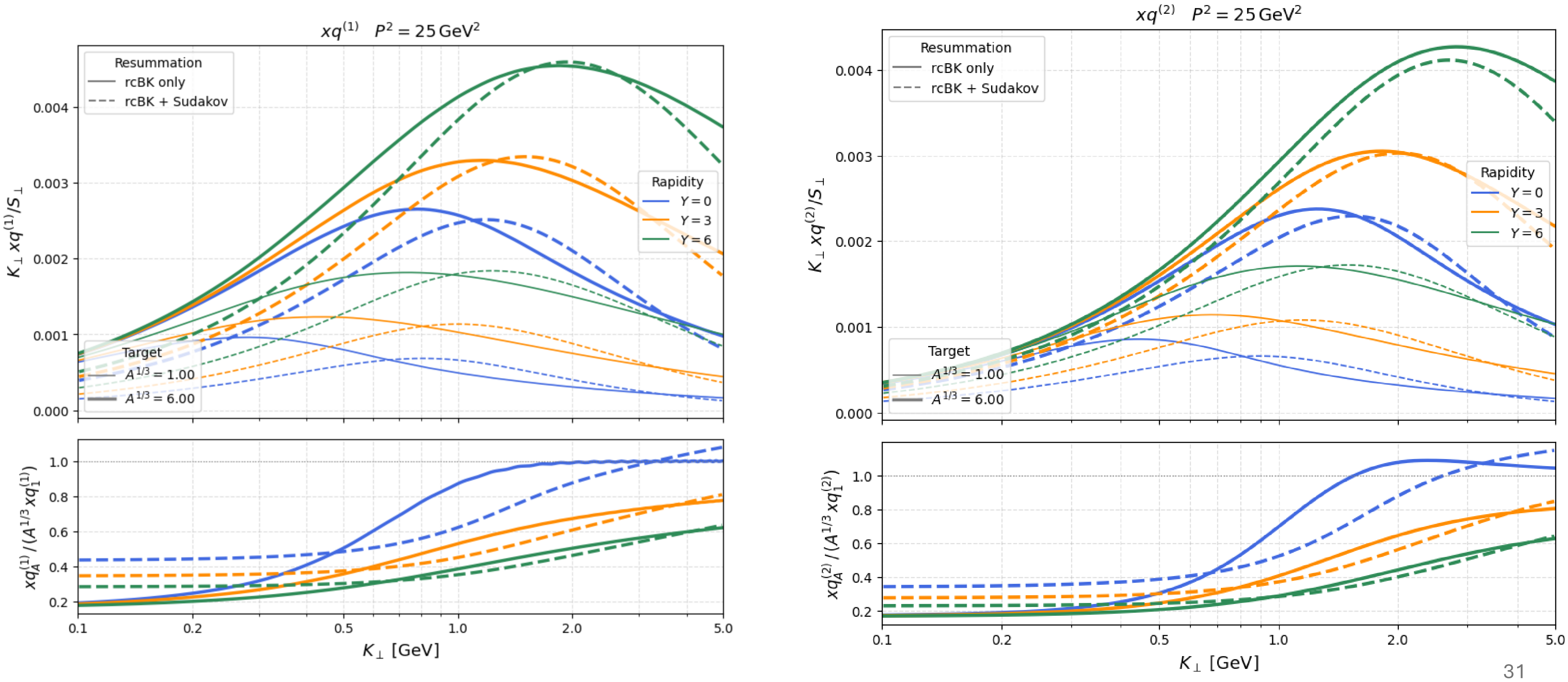




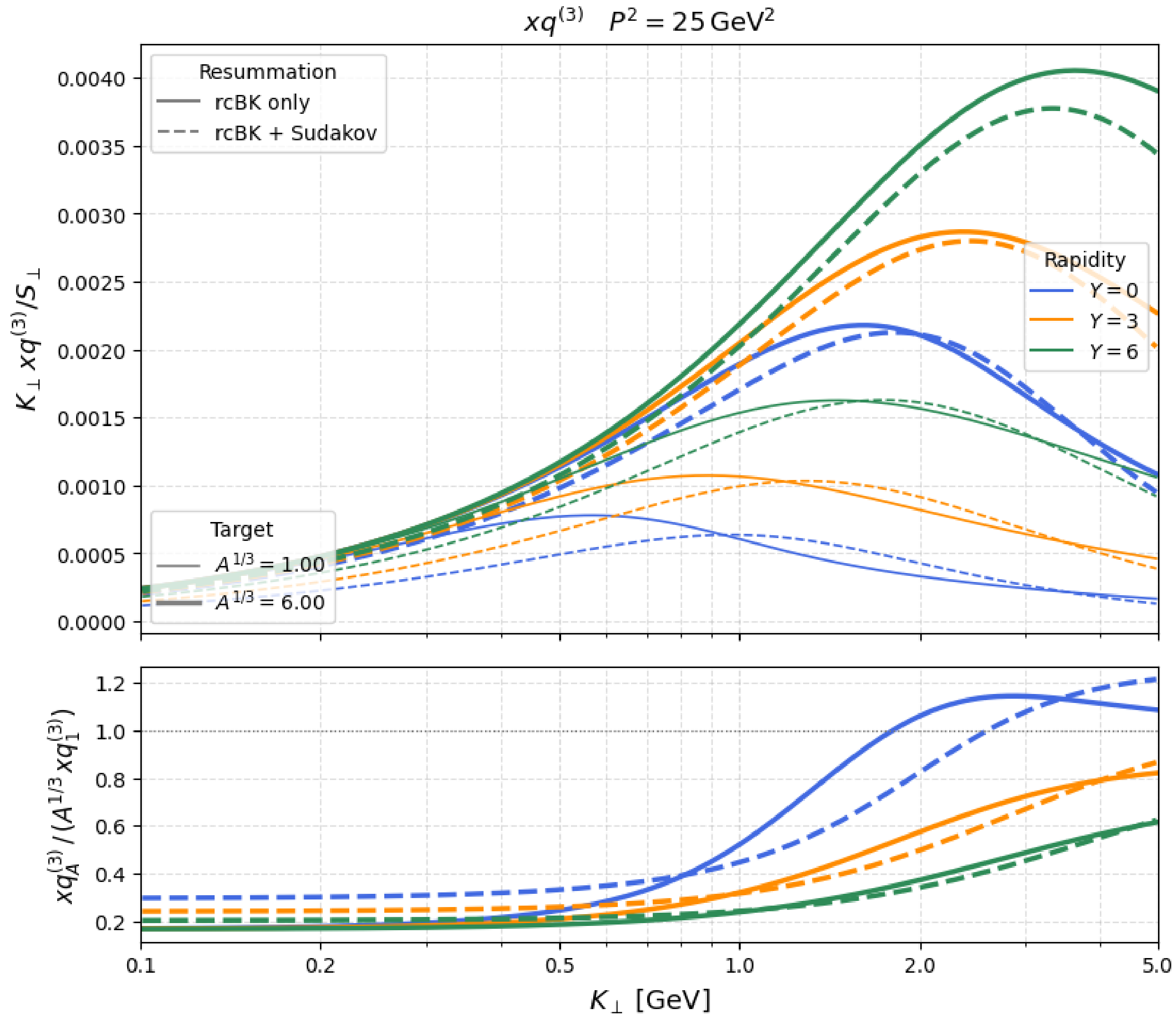
Broadening of distributions as $P_\perp$ increases

Numerical results

Nuclear modification ratio between proton and nucleus with small-x and CSS evolution



Numerical results



Summary and outlook

- Dijet production is an important observable to look for saturation
- NLO corrections are important to increase the precision of the predictions for this observable
- We calculated the real corrections of gluon initiated channel processes in pA collisions
- In the back-to-back limit, we showed that these corrections simplify significantly when integrating out an (anti)quark, and can be expressed in a factorized form in terms of hard factors and sea-quark TMD distributions
- The CGC approach allows us to write explicit expressions for these distributions
- We will compute the real corrections for an integrated gluon which requires more careful treatment due to various logarithmic divergences.
- We will compute the virtual corrections

Acknowledgements

I am grateful for the financial support provided by SUBATECH for sponsoring this visit!