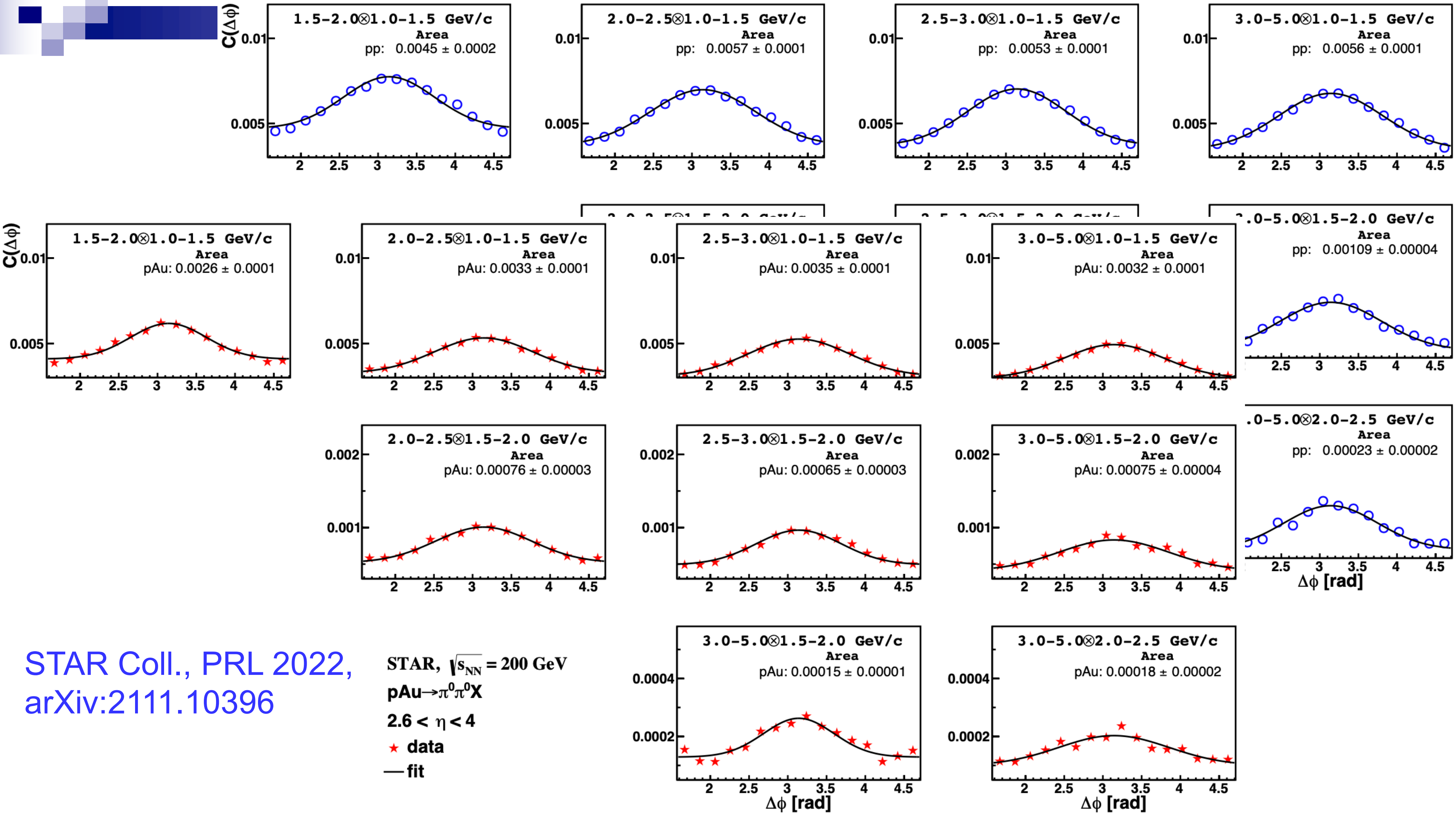
Di-hadron correlation in forward pA collisions at RHIC: how to correctly interpret the results?

Feng Yuan

Lawrence Berkeley National Laboratory

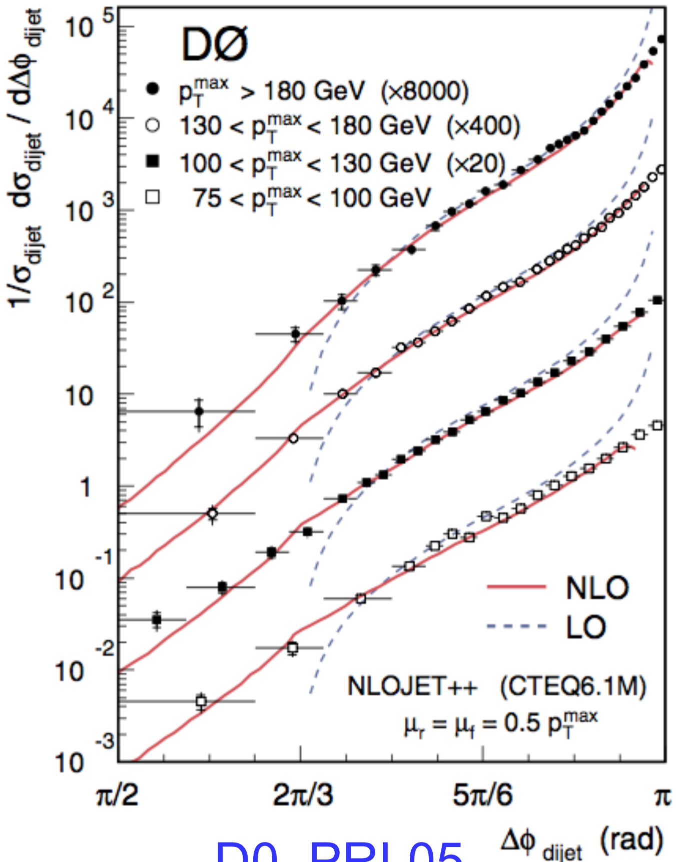
References: Stasto, Xiao, Yuan, PLB 2012;
Stasto, Wei, Xiao, Yuan, PLB 2018; work in progress

Acknowledgement: discussions with Elke and Xiaoxuan

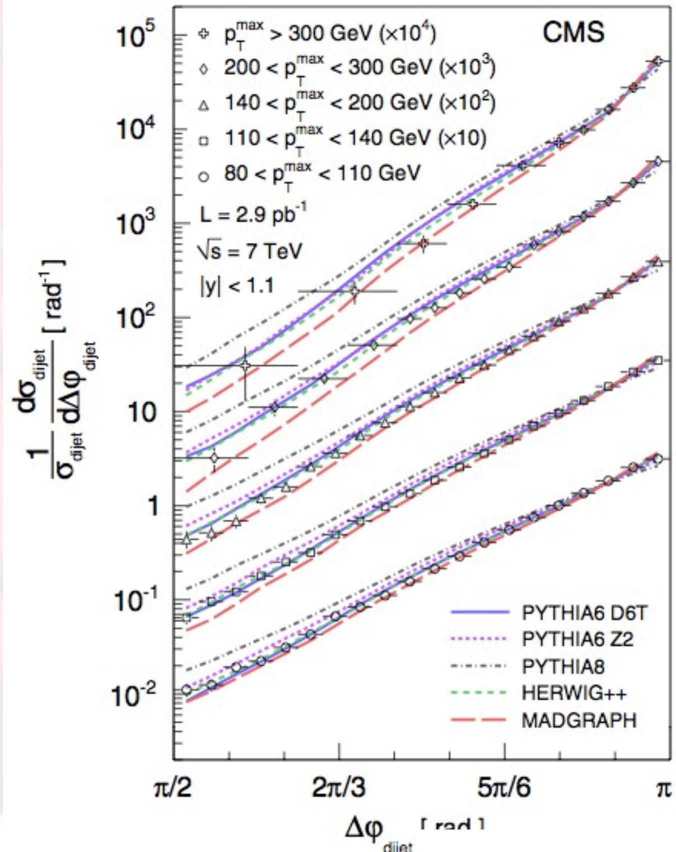


STAR Coll., PRL 2022,
arXiv:2111.10396

Dijet correlation at colliders: beautiful data from Tevatron/LHC



D0, PRL05

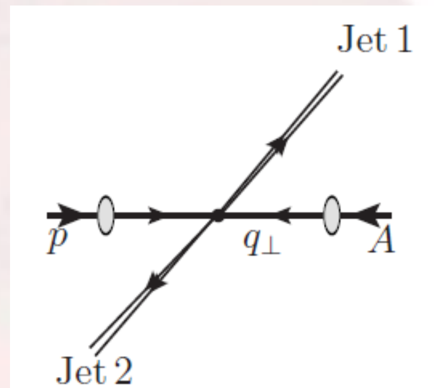


CMS, PRL11

Two particle correlations as probe to the CGC gluon distributions

- Dilute + Dense scattering

$$B + A \to H_1(k_1) + H_2(k_2) + X$$

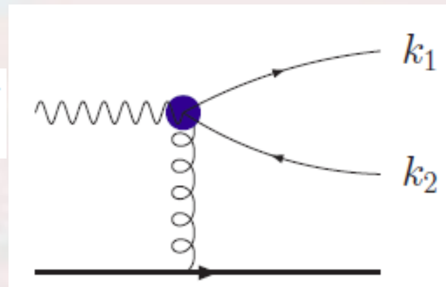


- Correlation limit:

$$|\vec{k}_{1\perp} + \vec{k}_{2\perp}| \ll P_\perp \qquad (\vec{k}_{1\perp} - \vec{k}_{2\perp})/2$$

DIS dijet probes WW gluons

$$\gamma_T^* A \to q(k_1) + \bar{q}(k_2) + X$$

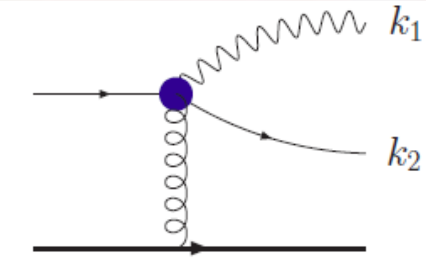


- Hard interaction includes the gluon attachments to both quark and antiquark
- The q_t dependence probes the WW gluon distribution at small-x

Dominguez-Marquet-Xiao-Yuan 2011;
See Tomasz and Farid's talks

Photon-jet correlation probes the dipole gluon distribution

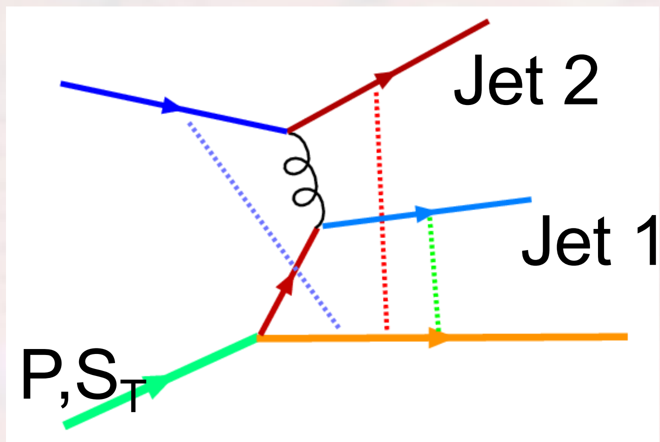
$$pA \to \gamma(k_1) + q(k_2) + X$$

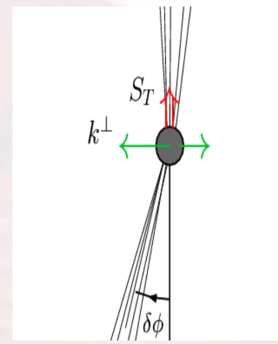


- Naïve kt-factorization would predict the same q_t-dependence

Dijet-correlation at RHIC

- Initial state and/or final state interactions





Boer-Vogelsang 03

Standard (naïve) Factorization breaks!

Becchetta-Bomhof-Mulders-Pijlman, 04-06
Collins-Qiu 08; Vogelsang-Yuan 08
Rogers-Mulders 10; Xiao-Yuan, 10

Modified factorization

- Dilute system on a dense target, in the large Nc limit,

$$
\begin{aligned}
&\frac{d\sigma^{(pA\to \text{Dijet}+X)}}{d\mathcal{P}.\mathcal{S}.} \\
&= \sum_q x_1 q(x_1) \frac{\alpha_s^2}{\hat{s}^2} \left[\mathcal{F}_{qg}^{(1)} H_{qg\to qg}^{(1)} + \mathcal{F}_{qg}^{(2)} H_{qg\to qg}^{(2)}\right] \\
&+ x_1 g(x_1) \frac{\alpha_s^2}{\hat{s}^2} \left[\mathcal{F}_{gg}^{(1)} \left(H_{gg\to q\bar{q}}^{(1)} + H_{gg\to gg}^{(1)}\right)\right. \\
&\left. + \mathcal{F}_{gg}^{(2)} \left(H_{gg\to q\bar{q}}^{(2)} + H_{gg\to gg}^{(2)}\right) + \mathcal{F}_{gg}^{(3)} H_{gg\to gg}^{(3)}\right] ,
\end{aligned}
$$

Dominguez-Marquet-Xiao-Yuan 2011

- Hard partonic cross section

$$H^{(1)}_{qg\to qg} = \frac{\hat{u}^2\left(\hat{s}^2+\hat{u}^2\right)}{-2\hat{s}\hat{u}\hat{t}^2}, \quad H^{(2)}_{qg\to qg} = \frac{\hat{s}^2\left(\hat{s}^2+\hat{u}^2\right)}{-2\hat{s}\hat{u}\hat{t}^2}$$

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

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

$$H^{(3)}_{gg\to gg} = \frac{2\left(\hat{s}^2-\hat{t}\hat{u}\right)^2}{\hat{u}^2\hat{t}^2},$$

  - Although the individual diagram depends on the gauge, the total contribution does not

Dominguez-Marquet-Xiao-Yuan 2011

- Kt-dependent gluon distributions

$$\mathcal{F}_{qg}^{(1)} = xG^{(2)}(x, q_\perp), \quad \mathcal{F}_{qg}^{(2)} = \int xG^{(1)}(q_1) \otimes F(q_2) \ ,$$

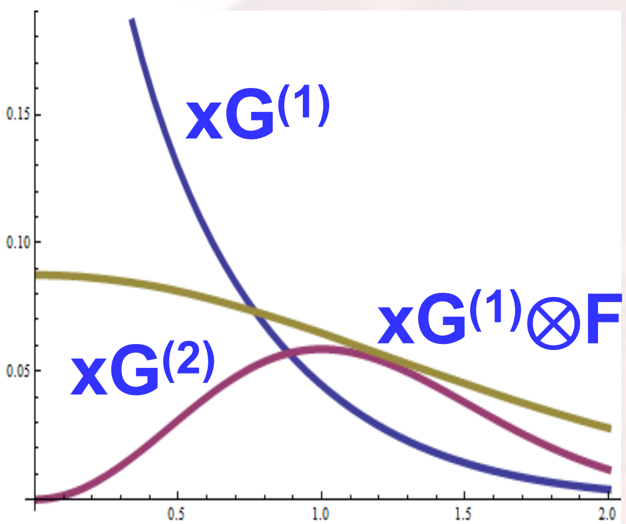
$$\mathcal{F}_{gg}^{(1)} = \int xG^{(2)}(q_1) \otimes F(q_2), \quad \mathcal{F}_{gg}^{(2)} = \int \frac{q_{1\perp} \cdot q_{2\perp}}{q_{1\perp}^2} xG^{(2)}(q_1) \otimes F(q_2)$$

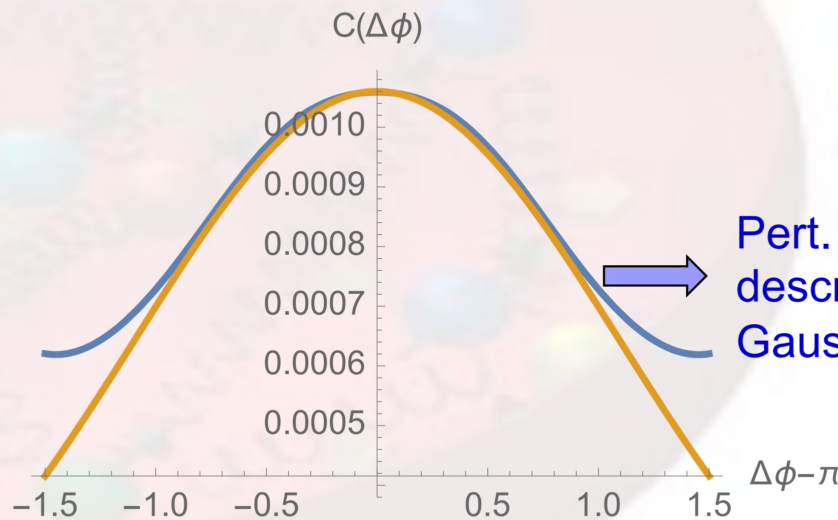
$$\mathcal{F}_{gg}^{(3)} = \int xG^{(1)}(q_1) \otimes F(q_2) \otimes F(q_3) \ ,$$

- Color-dipole/CGC agrees with the above results

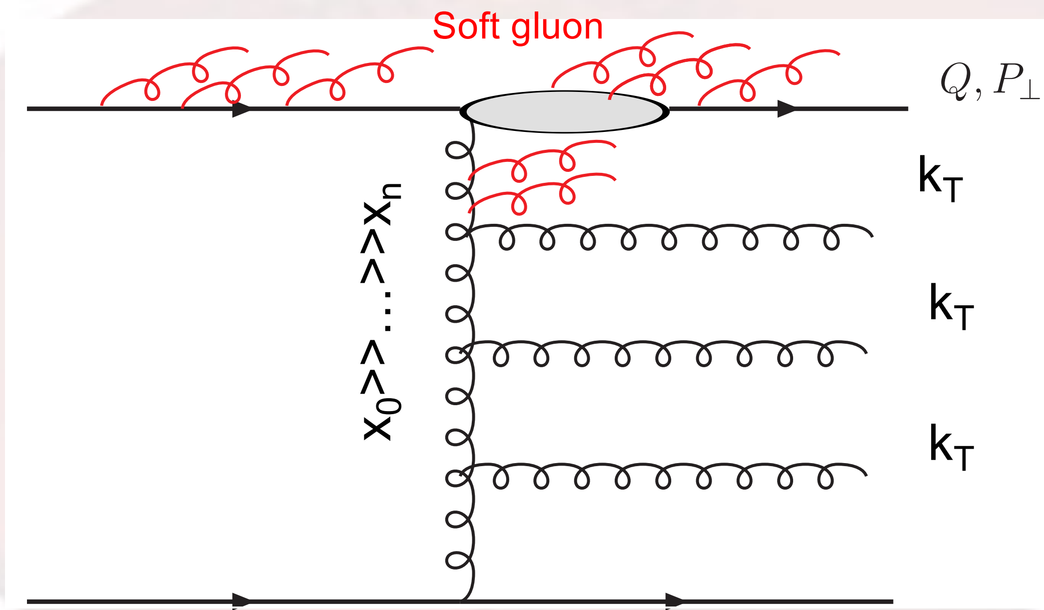
Dominguez-Marquet-Xiao-Yuan 2011

Various gluon distributions and their contributions to the two particle correlation





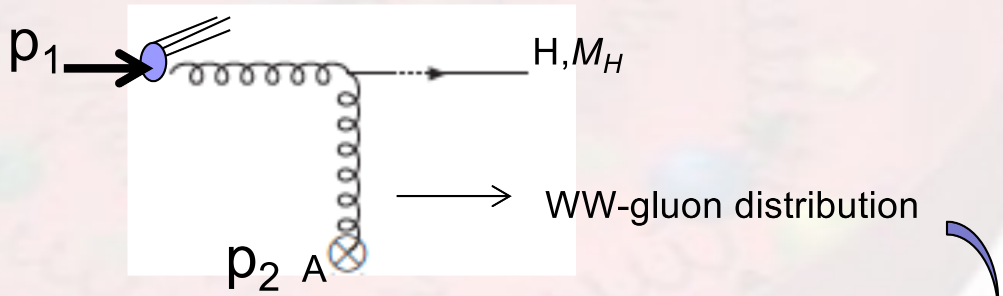
Beyond leading order picture: additional dynamics comes in



- BFKL vs Sudakov resummations (LL)

Sudakov resummation at small-x

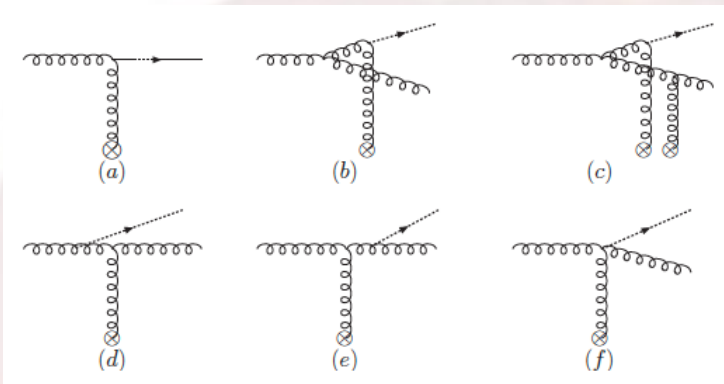
- Take massive scalar particle production p+A->H+X as an example to demonstrate the double logarithms, and resummation

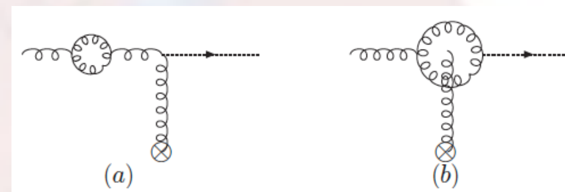


$$\frac{d\sigma^{(\rm LO)}}{dyd^2k_\perp} = \sigma_0 \int \frac{d^2x_\perp d^2x'_\perp}{(2\pi)^2} e^{ik_\perp \cdot r_\perp} x_0 g_p(x_0) S^{(WW)}(x_\perp, x'_\perp)$$

$$S_Y^{WW}(x_\perp, y_\perp) = -\left\langle \mathrm{Tr}\left[\partial_\perp^\beta U(x_\perp) U^\dagger(y_\perp) \partial_\perp^\beta U(y_\perp) U^\dagger(x_\perp)\right]\right\rangle_Y$$

Explicit one-loop calculations





$$x_0 g_p(x_0) \int \frac{d\xi}{\xi} \mathbf{K}_{DMMX} \otimes S^{WW}(x_\perp, y_\perp) + \left(-\frac{1}{\epsilon}\right) S^{WW}(x_\perp, y_\perp) \mathcal{P}_{g/g} \otimes x_0 g(x_0) \ ,$$

- Collinear divergence ➔ DGLAP evolution
- Small-x divergence ➔ BK-type evolution

Dominguiz-Mueller-Munier-Xiao, 2011

Soft vs Collinear gluons

- Radiated gluon momentum

$$k_g = \alpha_g p_1 + \beta_g p_2 + k_{g\perp} \ ,$$

- Soft gluon, $\alpha \sim \beta << 1$
- Collinear gluon, $\alpha \sim 1$, $\beta << 1$
- Small-x collinear gluon, $1-\beta << 1$, $\alpha \rightarrow 0$
  - Rapidity divergence

Final result

- Double logs at one-loop order

$$\frac{d\sigma^{(\mathrm{LO+NLO})}}{dyd^2k_\perp}|_{k_\perp \ll Q} = \sigma_0 \int \frac{d^2x_\perp d^2x'_\perp}{(2\pi)^2} e^{ik_\perp \cdot r_\perp} S^{WW}_{Y=\ln 1/x_a}(x_\perp, x'_\perp) x g_p(x, \mu^2 = \frac{c_0^2}{r_\perp^2})$$
$$\left\{1 + \frac{\alpha_s}{\pi} C_A \left[\beta_0 \ln \frac{Q^2 r_\perp^2}{c_0^2} - \frac{1}{2}\left(\ln \frac{Q^2 r_\perp^2}{c_0^2}\right)^2 + \frac{\pi^2}{2}\right]\right\} ,$$

- Collins-Soper-Sterman resummation (NLL)

$$\frac{d\sigma^{(\mathrm{resum})}}{dyd^2k_\perp}|_{k_\perp \ll Q} = \sigma_0 \int \frac{d^2x_\perp d^2x'_\perp}{(2\pi)^2} e^{ik_\perp \cdot r_\perp} e^{-S_{sud}(Q^2, r_\perp^2)} S^{WW}_{Y=\ln 1/x_a}(x_\perp, x'_\perp)$$
$$\times x g_p(x, \mu^2 = c_0^2/r_\perp^2) \left[1 + \frac{\alpha_s}{\pi}\frac{\pi^2}{2} N_c\right] ,$$

Mueller, Xiao, Yuan 2013

Sudakov resummation in CGC: other examples

- Dijet production in DIS (NLL)
  - Caucal-Salazar-Schenke-Venugopalan 2022, 2023
  - Paels-Altinoluk-Beuf-Marquet 2022
- Sudakov logs can be re-summed consistently in the small-x formalism
- Kinematics of Sudakov logs and small-x evolution are well separated
  - Soft vs collinear gluons

Extend to dijet in hadronic processes: count the leading double logs

- Each incoming parton contributes to a half of the associated color factor
  - Initial gluon radiation, aka, TMDs
- Soft gluon radiation in collinear calculation also demonstrates this rule
  - Sterman, et al
  - Sub-leading logs will be much complicated, usually a matrix form

Mueller, Xiao, Yuan 2013

Beyond the leading double logs: collinear

- Jet size-dependence is computed by averaging the azimuthal angle between the soft gluon and leading jet
- Matrix form due to colored final state   Kidonakis-Sterman 1997

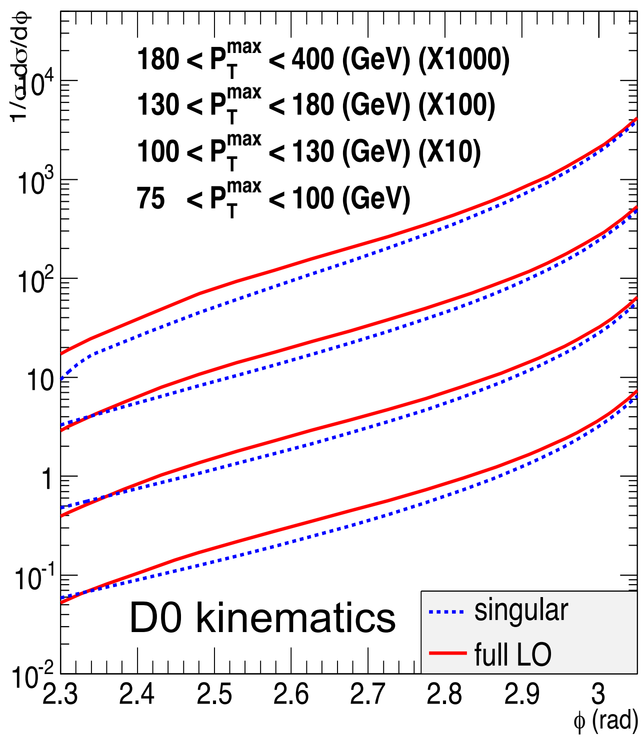
$$x_1 f_a(x_1, \mu = b_0/b_\perp) x_2 f_b(x_2, \mu = b_0/b_\perp) e^{-S_{\text{Sud}}(Q^2, b_\perp)}$$
$$\text{Tr}\left[\mathbf{H}_{ab\to cd} \exp[-\int_{b_0/b_\perp}^{Q} \frac{d\mu}{\mu} \gamma^{s\dagger}] \mathbf{S}_{ab\to cd} \exp[-\int_{b_0/b_\perp}^{Q} \frac{d\mu}{\mu} \gamma^{s}]\right]$$

(Sun, C.-P. Yuan, F. Yuan, PRL 2014)

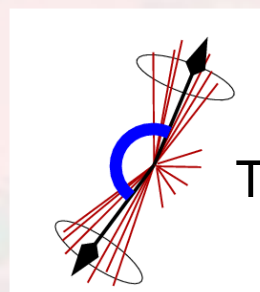
$$S_{\text{Sud}}(Q^2, b_\perp) = \int_{b_0^2/b_\perp^2}^{Q^2} \frac{d\mu^2}{\mu^2} \left[\ln\left(\frac{Q^2}{\mu^2}\right) A + B + D_1 \ln \frac{Q^2}{P_T^2 R_1^2} + D_2 \ln \frac{Q^2}{P_T^2 R_2^2}\right]$$

D: color-factor for the jet
R: jet size

Compare to the full calculations



$$
\frac{\alpha_s}{2\pi^2}\frac{1}{q_\perp^2}\sum_{ab,a'b'}\sigma_0\int\frac{dx_1'}{x_1'}\frac{dx_2'}{x_2'}x_1'\,f_a(x_1',\mu)x_2'\,f_b(x_2',\mu)
$$
$$
\times\Big\{h^{(0)}_{a'b'\to cd}\big[\xi_1\mathcal{P}_{a'/a}(\xi_1)\delta(1-\xi_2)+\xi_2\mathcal{P}_{b'/b}(\xi_2)\delta(1-\xi_1)
$$
$$
+\delta(1-\xi_1)\delta(1-\xi_2)\delta_{aa'}\delta_{bb'}\left((C_a+C_b)\ln\frac{Q^2}{q_\perp^2}+C_c\ln\frac{1}{R_1^2}+C_d\ln\frac{1}{R_2^2}\right)\big]
$$
$$
+\delta(1-\xi_1)\delta(1-\xi_2)\delta_{aa'}\delta_{bb'}\Gamma_{sn}^{ab\to cd}\Big\}\;, \qquad (10
$$

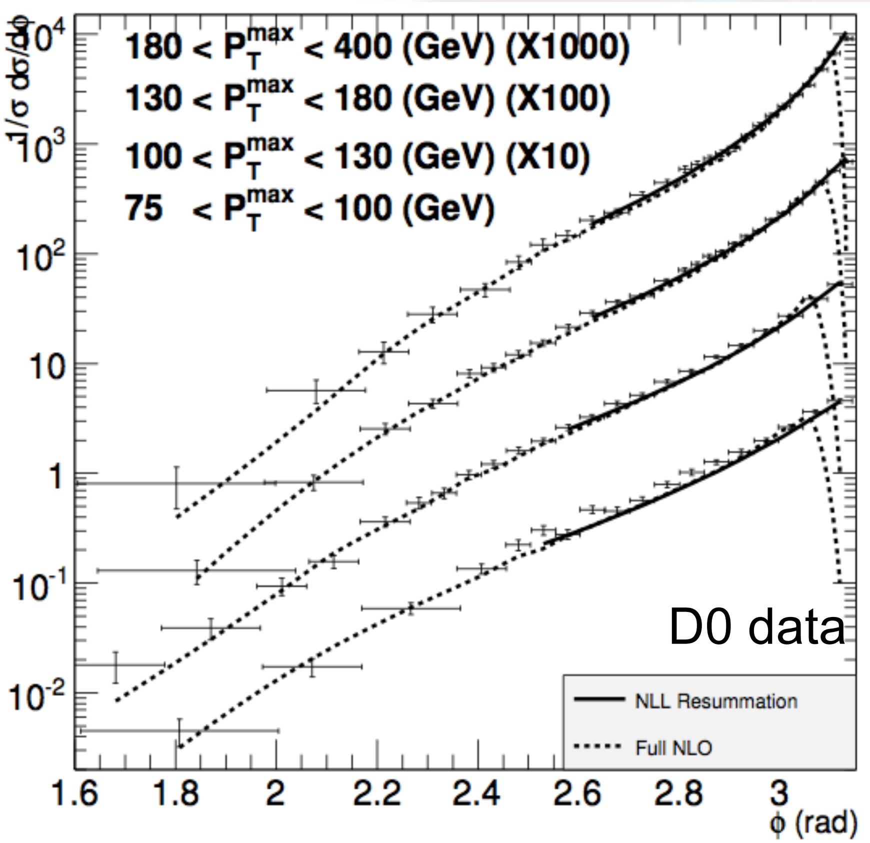


Leading P_T

Total $q_T \approx P_T \mathrm{Sin}(\Delta\phi)$

full LO: Nagy 2002, NLOJET++

Compare to the data



NLL Resummation:
Sun,C.P.Yuan, F.Yuan, PRL2014

$$x_1 f_a(x_1, \mu = b_0/b_\perp) x_2 f_b(x_2, \mu = b_0/b_\perp) e^{-S_{\rm Sud}(Q^2, b_\perp)}$$

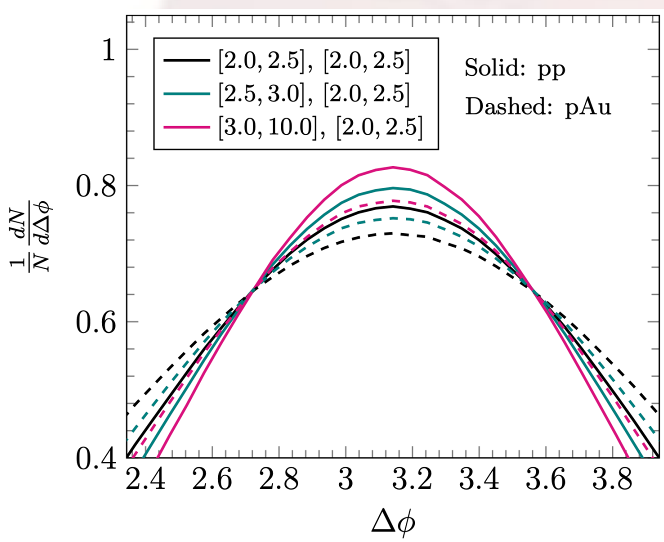
$$\mathrm{Tr}\left[\mathbf{H}_{ab\to cd} \exp[-\int_{b_0/b_\perp}^{Q} \frac{d\mu}{\mu} \gamma^{s\dagger}] \mathbf{S}_{ab\to cd} \exp[-\int_{b_0/b_\perp}^{Q} \frac{d\mu}{\mu} \gamma^{s}]\right]$$

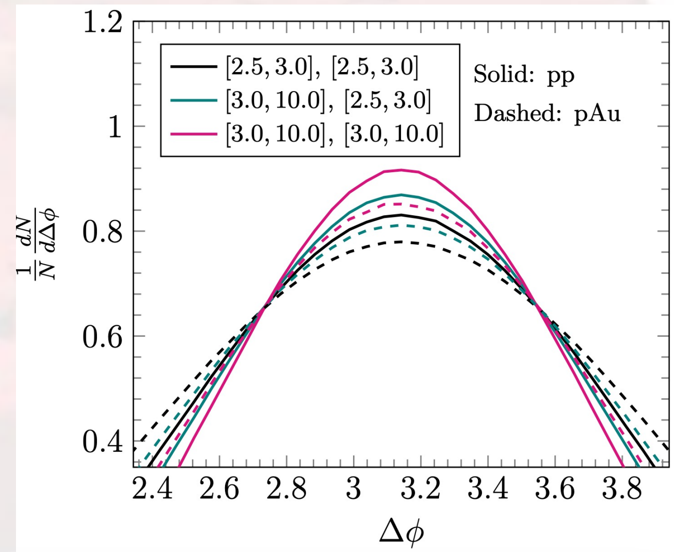
Full NLO: Nagy 2002, NLOJET++

Include Sudakov effects in the CGC for di-hadron correlations

- Unintegrated gluon distributions w/ Sudakov, e.g.,

$$\mathcal{F}_{qg}^{(a)}(x_g, q_\perp) = \frac{-N_c S_\perp}{2\pi^2 \alpha_s} \int_0^\infty \frac{b_\perp db_\perp}{2\pi} J_0(q_\perp b_\perp) e^{-S_{\rm Sud}^{q+g\to q+g}(b_\perp)} \nabla_{b_\perp}^2 S_{x_g}(b_\perp)$$

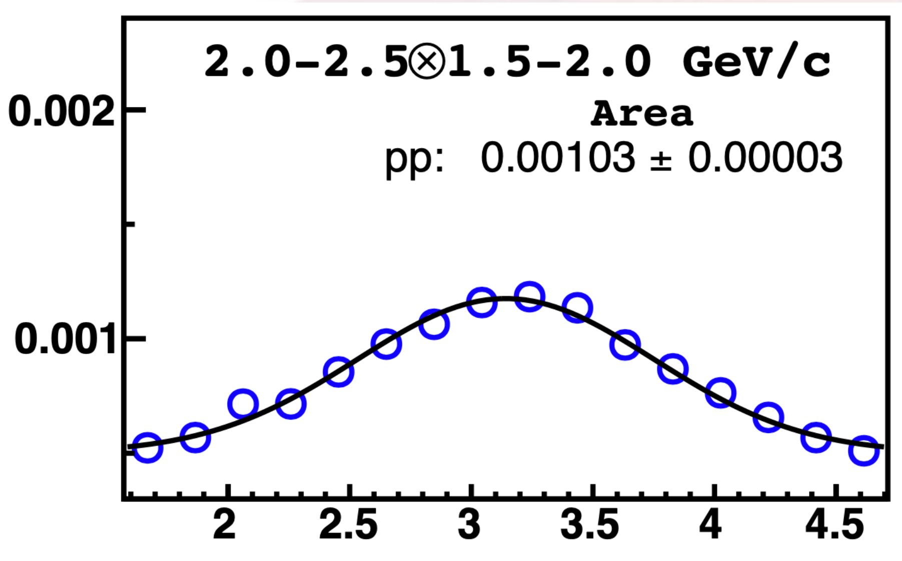


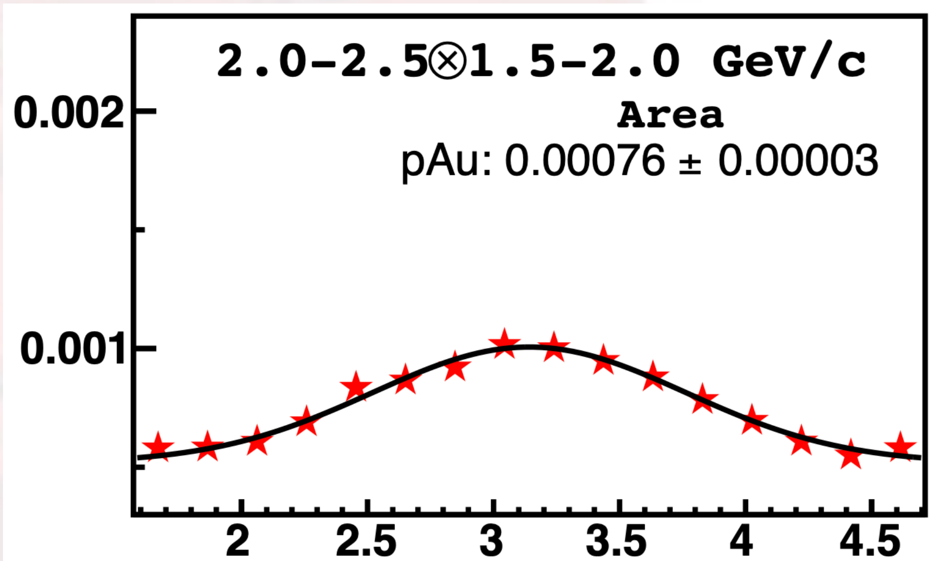


Stasto, Wei, Xiao, Yuan, 2018, [1805.05712]

Real data teach us more on the physics

- Compare pp to pA

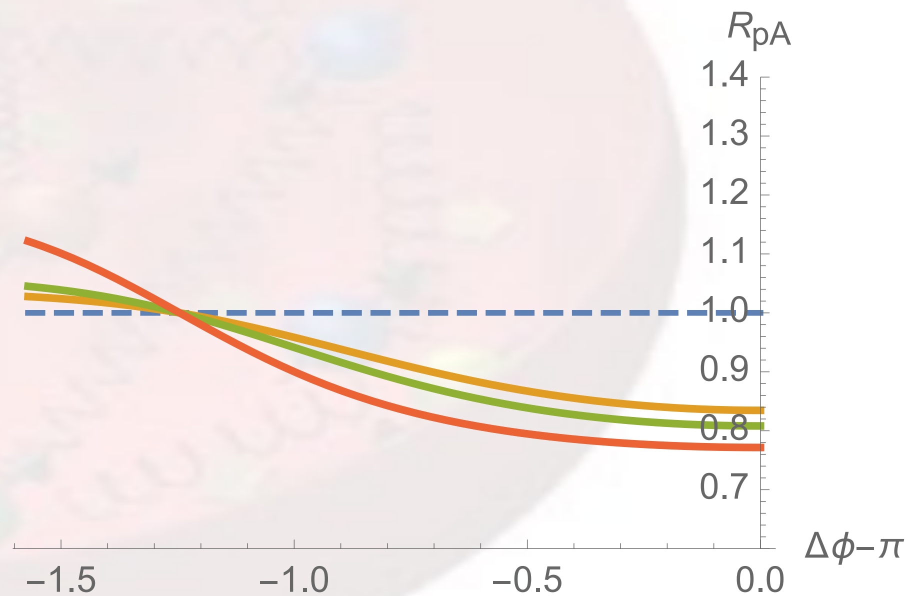




STAR Coll., PRL 2022, arXiv:2111.10396

Simple extraction of nuclear suppression indicates a Pt-broadening effects

- Suppression factor depends on the background subtraction
  - STAR fit: constant background+simple Gaussian shows no Pt-broadening
- Pt-broadening is not as profound as our previous predictions
  - It may change if different background subtraction used

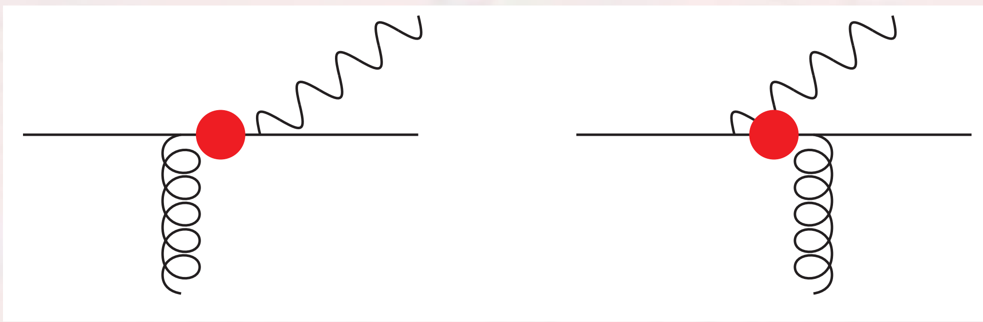


Looking forward

- We need more data
  - Cross check the background! E.g., through charged particle pairs, mixed pairs etc., and photon+hadron correlations
- We need theory developments
  - Complete NLL resummation for dijet in hadronic collisions in CGC (collinear framework done)
  - Need BK-JIMWLK evolution for all different UGDs, at least qualitatively

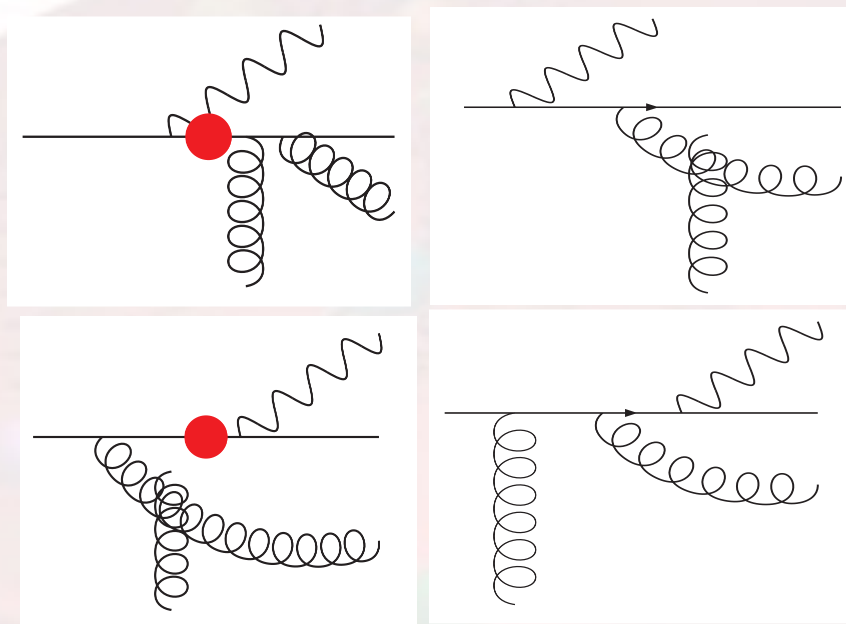
Photon-Jet correlation

- Leading order



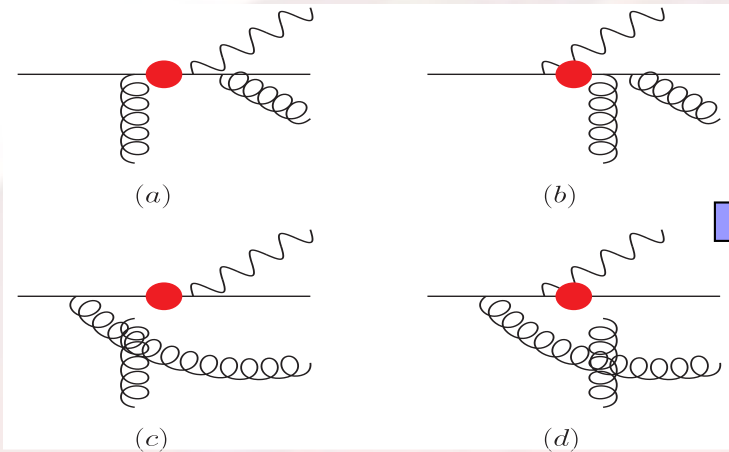
Dipole gluon distribution

BK-evolution



$$\frac{\partial}{\partial Y} S_Y^{(2)}(x_\perp, y_\perp) = -\frac{\alpha_s N_c}{2\pi^2} \int \frac{d^2 b_\perp (x_\perp - y_\perp)^2}{(x_\perp - b_\perp)^2 (y_\perp - b_\perp)^2} \left[S_Y^{(2)}(x_\perp, y_\perp) - S_Y^{(4)}(x_\perp, b_\perp, y_\perp) \right]$$

Soft gluon radiation



$$\left(-\frac{\alpha_s}{2\pi}\frac{C_F+C_A}{2}\right)\ln^2\left(\frac{Q^2(x_\perp-y_\perp)^2}{c_0^2}\right)$$

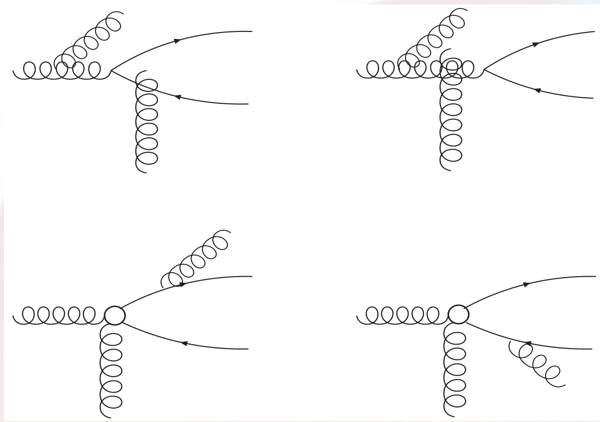
- A^2 from (a,b) contribute to $C_F/2$ (jet)
- A^2 from (c,d) contribute to C_F
- Interference contribute to 1/2Nc

Di-jet correlations in pA

- Effective kt-factorization

$$\frac{d\sigma^{(pA\to \text{Dijet}+X)}}{d\mathcal{P}.\mathcal{S}.} = \sum_q x_1 q(x_1)\frac{\alpha_s^2}{\hat{s}^2}\left[\mathcal{F}_{qg}^{(1)} H_{qg\to qg}^{(1)} + \mathcal{F}_{qg}^{(2)} H_{qg\to qg}^{(2)}\right] + x_1 g(x_1)\frac{\alpha_s^2}{\hat{s}^2}\left[\mathcal{F}_{gg}^{(1)}\left(H_{gg\to q\bar{q}}^{(1)} + H_{gg\to gg}^{(1)}\right) + \mathcal{F}_{gg}^{(2)}\left(H_{gg\to q\bar{q}}^{(2)} + H_{gg\to gg}^{(2)}\right) + \mathcal{F}_{gg}^{(3)} H_{gg\to gg}^{(3)}\right] ,$$

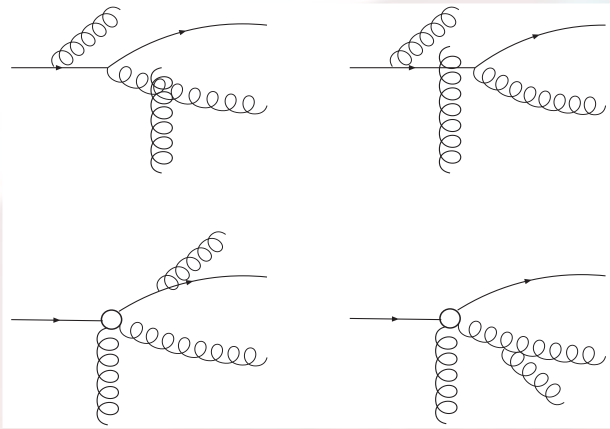
$gg \rightarrow qq$



$$\Rightarrow \left(-\frac{\alpha_s}{2\pi}N_c\right)\ln^2\left(\frac{Q^2(x_\perp-y_\perp)^2}{c_0^2}\right)$$

- $|A_1|^2 \rightarrow C_A$, $|A_2|^2 \rightarrow C_F/2$, $|A_3|^2 \rightarrow C_F/2$
- $2A_1^*(A_2+A_3) \rightarrow -Nc/2$
- $2A_2^*A_3$, 1/Nc suppressed

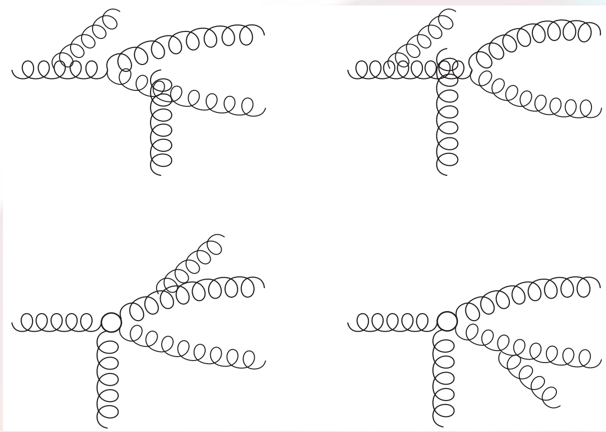
$qg \rightarrow qg$



$$\Rightarrow \left(-\frac{\alpha_s}{2\pi}\frac{C_F+C_A}{2}\right)\ln^2\left(\frac{Q^2(x_\perp-y_\perp)^2}{c_0^2}\right)$$

- $|A_1|^2 \rightarrow C_F$, $|A_2|^2 \rightarrow C_F/2$, $|A_3|^2 \rightarrow C_A/2$
- $2A_3^*(A_1+A_2) \rightarrow -Nc/2$
- $2A_1^*A_2$, large Nc suppressed

$gg \to gg$



$$\Rightarrow \left(-\frac{\alpha_s}{2\pi}N_c\right)\ln^2\left(\frac{Q^2(x_\perp - y_\perp)^2}{c_0^2}\right)$$

- $|A_1|^2 \to C_A$, $|A_2|^2 \to C_A/2$, $|A_3|^2 \to C_A/2$
- $2A_1^*(A_2+A_3)+2A_2^*A_3 \to -Nc$