Kt-factorization and dijet production in pA collisions

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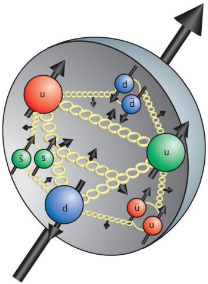
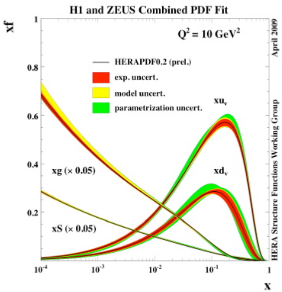
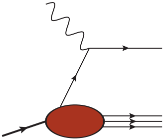
Deep into low-x region of Protons



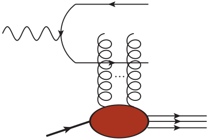


- Partons in the low-x is dominated by gluons, since gluon splitting is enhanced at low-x.
- Resummation of the $\alpha_s \ln \frac{1}{x}$. $\Rightarrow$ BFKL equation $\Rightarrow xf \sim x^{-\lambda}$
- The dynamics becomes non-linear when gluon density is high $\sim 1/\alpha_s$. $\Rightarrow$ BK equation

Dual Descriptions of Deep Inelastic Scattering



Bjorken frame



Dipole frame

Bjorken frame

$$F_2(x, Q^2) = \sum_q e_q^2 x \left[f_q(x, Q^2) + f_{\bar{q}}(x, Q^2) \right].$$

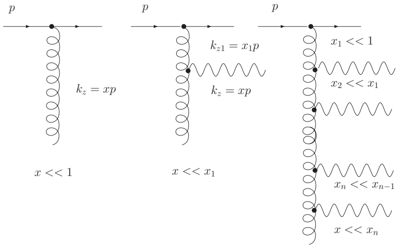
Dipole frame [A. Mueller, 01; Parton Saturation-An Overview]

$$\begin{aligned} F_2(x, Q^2) &= \sum_f e_f^2 \frac{Q^2}{4\pi^2 \alpha_{\mathrm{em}}} \int_0^1 \mathrm{d}z \int \mathrm{d}^2 x_\perp \mathrm{d}^2 y_\perp \left[|\psi_T(z, r_\perp, Q)|^2 + |\psi_L(z, r_\perp, Q)|^2 \right] \\ &\times \left[1 - S^{(2)}(x_\perp, y_\perp) \right], \quad \text{with} \quad r_\perp = x_\perp - y_\perp . \end{aligned}$$

- Bjorken: the partonic picture of a hadron is manifest. Saturation shows up as a limit on the occupation number of quarks and gluons.
- Dipole: the partonic picture is no longer manifest. Saturation appears as the unitarity limit for scattering. Convenient to resum the multiple gluon interactions.

BFKL evolution

[Balitsky, Fadin, Kuraev, Lipatov;74] The infrared sensitivity of Bremsstrahlung favors the emission of small-x gluons:



Probability of emission:

$$dp \sim \alpha_s N_c \frac{dk_z}{k_z} = \alpha_s N_c \frac{dx}{x}$$

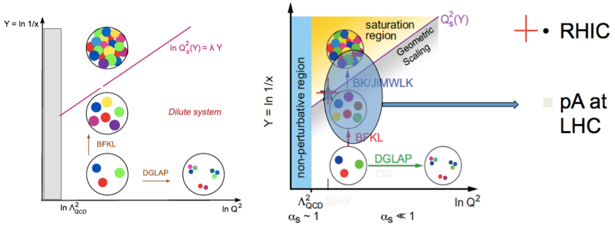
In small-x limit and Leading log approximation:

$$p \sim \sum_{n=0}^{\infty} \alpha_s^n N_c^n \int_x^1 \frac{dx_n}{x_n} \cdots \int_{x_2}^1 \frac{dx_1}{x_1} \sim \exp\left(\alpha_s N_c \ln \frac{1}{x}\right)$$

- Exponential growth of the amplitude as function of rapidity.

Saturation physics

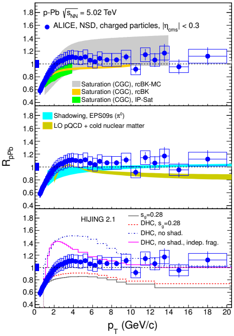
Saturation physics describes the high density matter in the high energy limit.

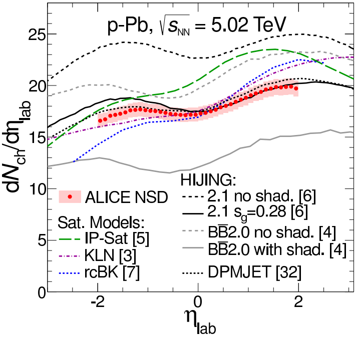


- Initial condition plus small-x evolution ⇒ dense gluon distributions.
- BFKL equation and BK equation
- Saturation phenomena is an inevitable consequence of QCD dynamics at high energy. At what energy scale? How to identify the smoking guns?
- Probing the phase structure of cold nuclei. Forward di-hadron correlation measurements in pA collisions.
- Providing initial condition for heavy ion collisions.
- Require Factorization:

$$\sigma \sim xf(x) \otimes \mathcal{H} \otimes D_h(z)$$

Recent ALICE Data





- Unprecedented opportunities to study saturation physics.
- LO saturation models qualitatively describe data, however, Large uncertainty!
- Issues: Factorization issue and NLO correction!

k_t dependent parton distributions

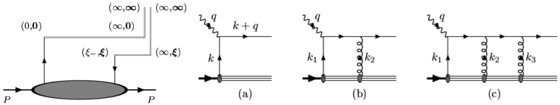
The unintegrated quark distribution

$$f_q(x,k_\perp) = \int \frac{d\xi^- d^2\xi_\perp}{4\pi(2\pi)^2} e^{ixP^+\xi^- + i\xi_\perp\cdot k_\perp} \langle P \left| \bar{\psi}(0)\mathcal{L}^\dagger(0)\gamma^+\mathcal{L}(\xi^-,\xi_\perp)\psi(\xi_\perp,\xi^-) \right| P\rangle$$

as compared to the integrated quark distribution

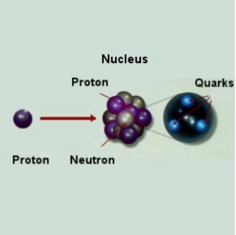
$$f_q(x) = \int \frac{d\xi^-}{4\pi} e^{ixP^+\xi^-} \langle P \left| \bar{\psi}(0)\gamma^+\mathcal{L}(\xi^-)\psi(0,\xi^-) \right| P\rangle$$

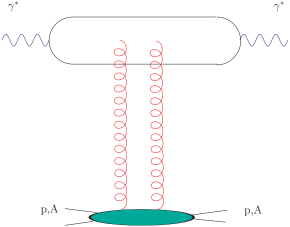
- Gauge invariant definition.
- Light-cone gauge together with proper boundary condition ⇒ parton density interpretation.
- The gauge links come from the resummation of multiple gluon interactions.
- Gauge links may vary among different processes.



Dilute-Dense factorizations

The effective Dilute-Dense factorization





- Protons and virtual photons are dilute probes of the dense gluons inside target hadrons.
- For dijet productions in pA collisions ($2 \to 2$), there is an effective k_t factorization.

$$\frac{d\sigma^{pA\to qfX}}{d^2P_\perp d^2q_\perp dy_1 dy_2} = x_p g(x_p, \mu) x_A g(x_A, q_\perp) \frac{1}{\pi} \frac{d\hat{\sigma}}{d\hat{t}}.$$

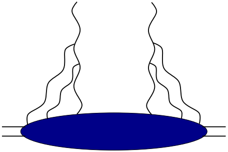
- For dijet processes in pp, AA collisions, there is no k_t factorization[Collins, Qiu, 08],[Rogers, Mulders; 10].
- At forward rapidity y, $x_p \propto e^y$ is large, while $x_A \propto e^{-y}$ is small.
- Ideal opportunity to search gluon saturation.
- One-loop calculation $\Rightarrow$ Systematic framework to test saturation physics predictions.

A Tale of Two Gluon Distributions

In small-x physics, two gluon distributions are widely used:[Kharzeev, Kovchegov, Tuchin; 03]

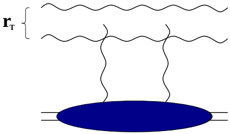
I. Weizsäcker Williams gluon distribution ([KM, 98] and MV model):

$$xG^{(1)} = \frac{S_\perp}{\pi^2\alpha_s}\frac{N_c^2-1}{N_c} \times \int \frac{d^2r_\perp}{(2\pi)^2}\frac{e^{-ik_\perp\cdot r_\perp}}{r_\perp^2}\left(1-e^{-\frac{r_\perp^2 Q_{sg}^2}{2}}\right) \Leftarrow$$



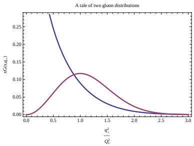
II. Color Dipole gluon distributions:

$$xG^{(2)} = \frac{S_\perp N_c}{2\pi^2\alpha_s}k_\perp^2 \times \int \frac{d^2r_\perp}{(2\pi)^2}e^{-ik_\perp\cdot r_\perp}e^{-\frac{r_\perp^2 Q_{sq}^2}{4}} \Leftarrow$$



Remarks:

- The WW gluon distribution simply counts the number of gluons.
- The Color Dipole gluon distribution often appears in calculations.

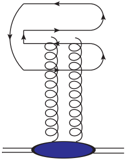


A Tale of Two Gluon Distributions

[F. Dominguez, BX and F. Yuan, Phys.Rev.Lett. 106, 022301 (2011)]

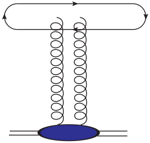
I. Weizsäcker Williams gluon distribution

$$xG^{(1)} = \frac{S_\perp}{\pi^2\alpha_s}\frac{N_c^2-1}{N_c} \times \int \frac{d^2r_\perp}{(2\pi)^2}\frac{e^{-ik_\perp\cdot r_\perp}}{r_\perp^2}\left(1-e^{-\frac{r_\perp^2 Q_{sg}^2}{2}}\right) \quad \Leftarrow$$



II. Color Dipole gluon distribution:

$$xG^{(2)} = \frac{S_\perp N_c}{2\pi^2\alpha_s}k_\perp^2 \times \int \frac{d^2r_\perp}{(2\pi)^2}e^{-ik_\perp\cdot r_\perp}e^{-\frac{r_\perp^2 Q_{sq}^2}{4}} \quad \Leftarrow$$



- Quadrupole ⇒ Weizsäcker Williams gluon distribution;
- Dipole ⇒ Color Dipole gluon distribution;
- [F. Dominguez, C. Marquet, A. Stasto and BX, 12] Dipoles and quadrupoles are the only two objects which enter the cross section in large N_c limit for a set of processes.
- Generalized universality in the large N_c limit.

A Tale of Two Gluon Distributions

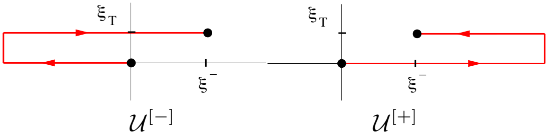
In terms of operators (known from TMD factorization), we find these two gluon distributions can be defined as follows: [F. Dominguez, BX and F. Yuan, Phys.Rev.Lett. 106, 022301 (2011)]

I. Weizsäcker Williams gluon distribution:

$$xG^{(1)} = 2\int \frac{d\xi^- d\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} \mathrm{Tr}\langle P|F^{+i}(\xi^-,\xi_\perp)\mathcal{U}^{[+]\dagger}F^{+i}(0)\mathcal{U}^{[+]}|P\rangle.$$

II. Color Dipole gluon distributions:

$$xG^{(2)} = 2\int \frac{d\xi^- d\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} \mathrm{Tr}\langle P|F^{+i}(\xi^-,\xi_\perp)\mathcal{U}^{[-]\dagger}F^{+i}(0)\mathcal{U}^{[+]}|P\rangle.$$



Remarks:

- The WW gluon distribution is the conventional gluon distributions. In light-cone gauge, it is the gluon density. (Either initial or final state interactions.)
- The dipole gluon distribution has no such interpretation. (Both initial and final state interactions.)
- Two topologically different gauge invariant definitions.

A Tale of Two Gluon Distributions

In terms of operators, we find these two gluon distributions can be defined as follows: [F. Dominguez, C. Marquet, BX and F. Yuan, 11]

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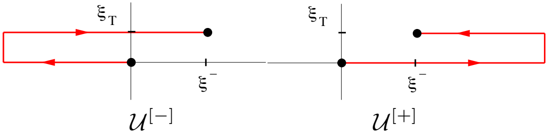
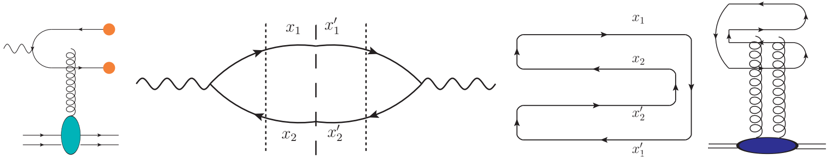


Questions:

- Can we distinguish these two gluon distributions?
- How to measure $xG^{(1)}$ directly? DIS dijet. EIC (Golden Measurement) and LHeC.
- How to measure $xG^{(2)}$ directly? Direct γ+Jet in pA collisions. For single-inclusive particle production in pA up to all order.
- What happens in gluon+jet production in pA collisions? Need both gluon distributions.

DIS dijet

[F. Dominguez, C. Marquet, BX and F. Yuan, 11]

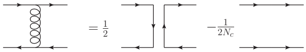


$$\frac{d\sigma^{\gamma_T^* A\to q\bar{q}+X}}{d\mathcal{P}.\mathcal{S}.} \propto N_c\alpha_{em}e_q^2\int\frac{\mathrm{d}^2x_1}{(2\pi)^2}\frac{\mathrm{d}^2x_1'}{(2\pi)^2}\frac{\mathrm{d}^2x_2}{(2\pi)^2}\frac{\mathrm{d}^2x_2'}{(2\pi)^2}e^{-ik_{1\perp}\cdot(x_1-x_1')}$$
$$\times e^{-ik_{2\perp}\cdot(x_2-x_2')}\sum\psi_T^*(x_1-x_2)\psi_T(x_1'-x_2')$$
$$\underbrace{\left[1+S_{x_g}^{(4)}(x_1,x_2;x_2',x_1')-S_{x_g}^{(2)}(x_1,x_2)-S_{x_g}^{(2)}(x_2',x_1')\right]}_{-u_iu_j'\frac{1}{N_c}\langle\mathrm{Tr}\left[\partial^iU(v)\right]U^\dagger(v')\left[\partial^jU(v')\right]U^\dagger(v)\rangle_{x_g}\Rightarrow\text{Operator Def}},$$

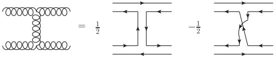
- In the dijet correlation limit, where $u=x_1-x_2\ll v=zx_1+(1-z)x_2$
- $S_{x_g}^{(4)}(x_1,x_2;x_2',x_1')=\frac{1}{N_c}\left\langle\mathrm{Tr}U(x_1)U^\dagger(x_1')U(x_2')U^\dagger(x_2)\right\rangle_{x_g}\neq S_{x_g}^{(2)}(x_1,x_2)S_{x_g}^{(2)}(x_2',x_1')$
- Same result obtained from the TMD factorization approach.

Dijet processes in the large N_c limit

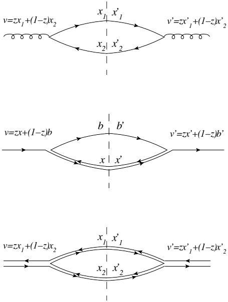
The Fierz identity:



and

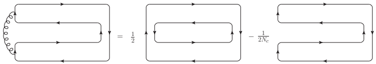


Graphical representation of dijet processes



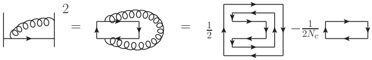
$g \to q\bar{q}$:

$\Rightarrow$



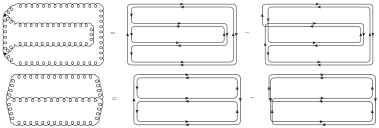
$q \to qg$

$\Rightarrow$



$g \to gg$

$\Rightarrow$



The Octupole and the Sextupole are suppressed.

Gluon+quark jets correlation

Including all the $qg \to qg$, $gg \to gg$ and $gg \to q\bar{q}$ channels, a lengthy calculation gives

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

with the various gluon distributions defined as

$$\begin{aligned}\mathcal{F}_{qg}^{(1)} &= xG^{(2)}(x,q_\perp),\ \ \mathcal{F}_{qg}^{(2)} = \int xG^{(1)} \otimes F\,, \\ \mathcal{F}_{gg}^{(1)} &= \int xG^{(2)} \otimes F,\ \ \mathcal{F}_{gg}^{(2)} = -\int \frac{q_{1\perp}\cdot q_{2\perp}}{q_{1\perp}^2} xG^{(2)} \otimes F\,, \\ \mathcal{F}_{gg}^{(3)} &= \int xG^{(1)}(q_1)\otimes F \otimes F\,,\end{aligned}$$

where $F = \int \frac{d^2 r_\perp}{(2\pi)^2} e^{-iq_\perp\cdot r_\perp}\frac{1}{N_c}\left\langle \text{Tr}U(r_\perp)U^\dagger(0)\right\rangle_{x_g}$.

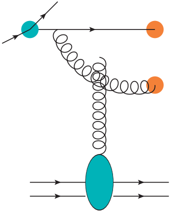
Remarks:

- All the above gluon distributions can be written as combinations and convolutions of two fundamental gluon distributions.
- This describes the dihadron correlation data measured at RHIC in forward dAu collisions.

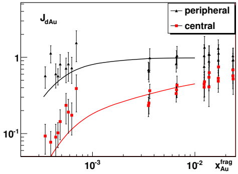
Comparing to STAR and PHENIX data measured in *dAu* collisions

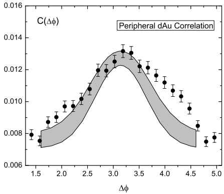
Physics predicted by C. Marquet. Further calculated in[A. Stasto, BX, F. Yuan, 11]
For away side peak in both peripheral and central *dAu* collisions

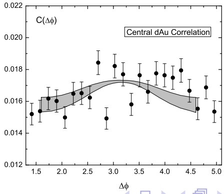
$$C(\Delta\phi) = \frac{\int_{|p_{1\perp}|,|p_{2\perp}|} \frac{d\sigma^{pA\to h_1 h_2}}{dy_1 dy_2 d^2p_{1\perp} d^2p_{2\perp}}}{\int_{|p_{1\perp}|} \frac{d\sigma^{pA\to h_1}}{dy_1 d^2p_{1\perp}}} \qquad J_{dA} = \frac{1}{\langle N_{\rm coll}\rangle} \frac{\sigma^{\rm pair}_{dA}/\sigma_{dA}}{\sigma^{\rm pair}_{pp}/\sigma_{pp}}$$



$\Rightarrow$



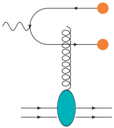


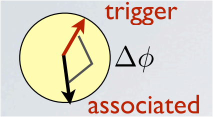


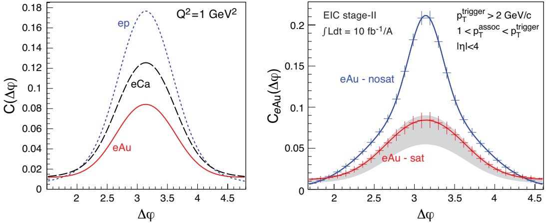
Di-Hadron correlations in DIS

Di-pion correlations at EIC[J. H. Lee, BX, L. Zheng]

$$C(\Delta\phi) = \frac{\int_{|p_{1\perp}|,|p_{2\perp}|} \frac{d\sigma^{eA\to h_1 h_2}}{dy_1 dy_2 d^2p_{1\perp} d^2p_{2\perp}}}{\int_{|p_{1\perp}|} \frac{d\sigma^{eA\to h_1}}{dy_1 d^2p_{1\perp}}}$$



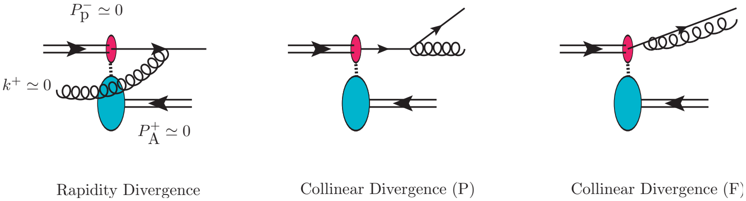




- EIC stage II energy 30 × 100GeV.
- Caveat: 1. NLO contribution? 2. Need more study on evolution of quadrupoles.
- Physical picture: Dense gluonic matter suppresses the away side peak.

Factorization for single inclusive hadron productions

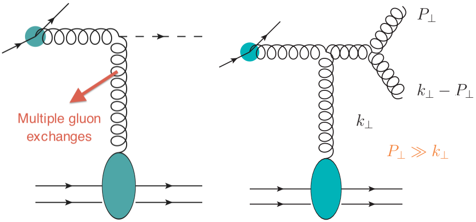
- [G. Chirilli, BX and F. Yuan, Phys. Rev. Lett. 108, 122301 (2012)]Obtain a systematic factorization for the $p + A \to H + X$ process by systematically remove all the divergences!
- Gluons in different kinematical region give different divergences. 1.soft, collinear to the target nucleus; 2. collinear to the initial quark; 3. collinear to the final quark.



- All the rapidity divergence is absorbed into the UGD $\mathcal{F}(k_\perp)$ while collinear divergences are either factorized into collinear parton distributions or fragmentation functions.
- Large N_c limit $\Rightarrow$ dipole amplitudes only. Easy to prove for all order.

Sudakov double logarithmic suppression factors in pA collisions

Consider one-loop calculation for the forward Higgs productions and dijet productions in pA collisions: [A. Mueller, BX and F. Yuan, arXiv:1210.5792]



Comments:

- The one-loop calculation between Higgs productions and dijet productions are very similar since both $M_H \gg k_\perp$ and $M_J \sim P_\perp \gg k_\perp$.
- Additional suppression factor $\exp[-S_{\rm sud}(Q^2, r_\perp^2)]$ where $Q = M_H$ or M_J and $r_\perp \sim 1/k_\perp$

$$S_{\rm sud}(Q^2, r_\perp^2) = \frac{\alpha_s N_c}{2\pi} \ln^2 \frac{Q^2 r_\perp^2}{c^2} \quad \text{with} \quad c = 2e^{-\gamma_E}.$$

- Small-x evolution (such as JIMWLK) is incapable of resumming the Sudakov factor.
- Competition between the Sudakov and saturation effect.

Conclusion

- LO dijet calculation in DIS and pA collisions probe different gluon distributions.
- Inclusive forward hadron productions in pA collisions in the small-x saturation formalism at one-loop order. The numerical calculation is under study.
- One-loop calculation for massive scalar productions in pA collisions.
- One-loop calculation for dijet productions is coming soon.
  [Work in progress with A. Mueller and F. Yuan]
- Interesting time to study high density QCD both theoretically and experimentally.