The Search for Gluon Saturation in pA Collisions

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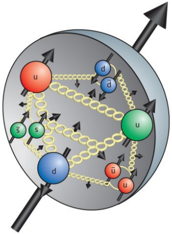
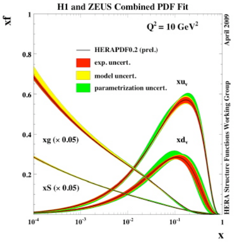
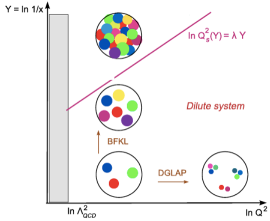
Deep into low-x region



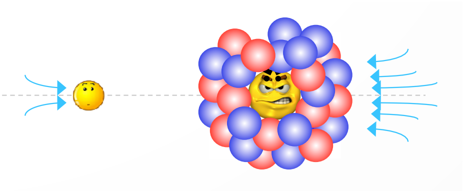




- Partons in the low-x region is dominated by gluons. See HERA data.
- BFKL equation ⇒ Resummation of the $\alpha_s \ln \frac{1}{x}$.
- When too many gluons squeezed in a confined hadron, gluons start to overlap and recombine ⇒ Non-linear dynamics ⇒ BK (JIMWLK) equation
- Use $Q_s(x)$ to separate the saturated dense regime from the dilute regime.
- Core ingredients: Multiple interactions + Small-x (high energy) evolution
- Related theory talks: [Monday: Iancu, Lappi, Beuf; Tuesday: Ramnath, Jackson, Mantysaari; Thursday: Kovner, Lublinsky]

Saturation physics (Color Glass Condensate)

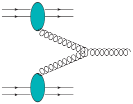
Saturation physics describes high density parton distributions at high energy limit.



- Saturation is an inevitable consequence of QCD dynamics at high energy.
- Eminent question: What are the smoking guns? At what energy scale?
- Using AA collisions to search for saturation is too hard due to factorization issues: Finding a needle in a haystack
- The search for parton saturation is much easier in dilute-dense scatterings.
  - 1. single hadron (pA and eA);
  - 2. dijet (dihadron) correlation (pA and eA).

k_t factorization vs Dilute-Dense factorizations

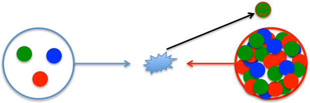
k_t factorization for single inclusive gluon productions in hadron-hadron collision:



$$\frac{d\sigma}{d^2p_T dy} = \frac{2\alpha_s}{C_F\, p_T^2}\times \times \int d^2k_{A,T}\, f_A(x_A, k_{A,T})\, f_B(x_B, p_T - k_{A,T}).$$

- Factorization and NLO correction? Only proved for DY and Higgs !
- For dijet processes in pp, AA collisions, no k_t factorization[Collins, Qiu, 08],[Rogers, Mulders; 10].

Dilute-Dense factorizations



projectile: $x_1 \sim \frac{p_\perp}{\sqrt{s}} e^{+y} \sim 1$ valence

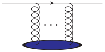
target: $x_2 \sim \frac{p_\perp}{\sqrt{s}} e^{-y} \ll 1$ gluon

- Protons and virtual photons are dilute probes of the dense target hadrons.
- For dijet productions in forward *pA* collisions, effective k_t factorization:

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

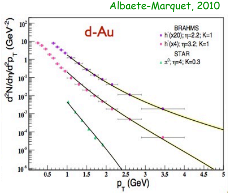
Forward hadron production in pA collisions

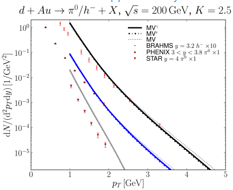
[Dumitru, Jalilian-Marian, 02] Inclusive forward hadron production in pA collisions



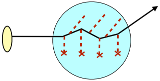
$$p + A \to H + X.$$

$$\frac{d\sigma^{pA\to hX}_{\text{LO}}}{d^2p_\perp dy_h} = \int_\tau^1 \frac{dz}{z^2}\left[\sum_f x_p q_f(x_p,\mu)\mathcal{F}(k_\perp)D_{h/q}(z,\mu) + x_p g(x_p,\mu)\tilde{\mathcal{F}}(k_\perp)D_{h/g}(z,\mu)\right].$$





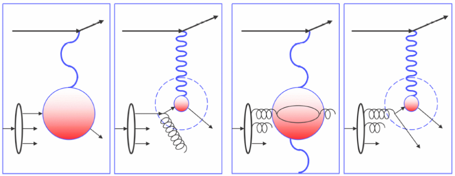
- Caveats: arbitrary choice of the renormalization scale μ and K factor.
- NLO correction? [Dumitru, Hayashigaki, Jalilian-Marian, 06; Altinoluk, Kovner 11] [Chirilli, Xiao and Yuan, 12]

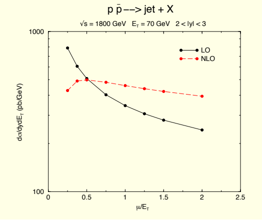


Why do we need NLO calculations?

Large x: valence quarks

Small x: Gluons, sea quarks





- Due to quantum evolution, PDF and FF changes with scale. This introduces large theoretical uncertainties in $xf(x)$ and $D(z)$. Choice of the scale at LO requires information at NLO.
- LO cross section is always a monotonic function of μ, thus it is just order of magnitude estimate.
- NLO calculation significantly reduces the scale dependence. More reliable.
- $K = \frac{\sigma_{LO}+\sigma_{NLO}}{\sigma_{LO}}$ is not a good approximation.
- NLO is vital in establishing the QCD factorization in saturation physics.

NLO Calculation and Factorization

- Factorization is about separation of short distant physics (perturbatively calculable hard factor) from large distant physics (Non perturbative).

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

- NLO (1-loop) calculation always contains various kinds of divergences.
  - Some divergences can be absorbed into the corresponding evolution equations.
  - The rest of divergences should be cancelled.
- Hard factor

$$\mathcal{H} = \mathcal{H}_{\text{LO}}^{(0)} + \frac{\alpha_s}{2\pi}\mathcal{H}_{\text{NLO}}^{(1)} + \cdots$$

should always be finite and free of divergence of any kind.
- NLO vs NLL Naive α_s expansion sometimes is not sufficient!

	LO	NLO	NNLO	$\cdots$
LL	1	$\alpha_s L$	$(\alpha_s L)^2$	$\cdots$
NLL		α_s	$\alpha_s (\alpha_s L)$	$\cdots$
$\cdots$			$\cdots$	$\cdots$

- Evolution $\to$ Resummation of large logs.
  LO evolution resums LL; NLO $\Rightarrow$ NLL.

Factorization for single inclusive hadron productions

Systematic factorization for the $p + A \to H + X$ process [Chirilli, BX and Yuan, 12]

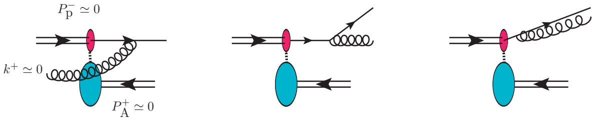
$$\frac{d^3\sigma^{p+A\to h+X}}{dyd^2p_\perp} = \sum_a \int \frac{dz}{z^2}\frac{dx}{x}\xi x f_a(x,\mu) D_{h/c}(z,\mu) \int [dx_\perp] S^Y_{a,c}([x_\perp]) \mathcal{H}_{a\to c}(\alpha_s, \xi, [x_\perp]\mu)$$

Collinear divergence: pdfs

Collinear divergence: fragmentation functs

Rapidity divergence: BK evolution

Finite hard factor



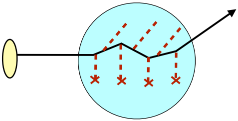
Rapidity Divergence | Collinear Divergence (P) | Collinear Divergence (F)

- The NLO correction arises after subtracting off divergence according to convention and $\overline{MS}$ scheme.
- In principle, by invoking the NLO evolutions, we can promote this NLO calculation up to NLL.

Numerical implementation of the NLO result

Single inclusive hadron production up to NLO

$$d\sigma = \int x f_a(x) \otimes D_a(z) \otimes \mathcal{F}_a^{x_g}(k_\perp) \otimes \mathcal{H}^{(0)} + \frac{\alpha_s}{2\pi} \int x f_a(x) \otimes D_b(z) \otimes \mathcal{F}_{(N)ab}^{x_g} \otimes \mathcal{H}_{ab}^{(1)}.$$

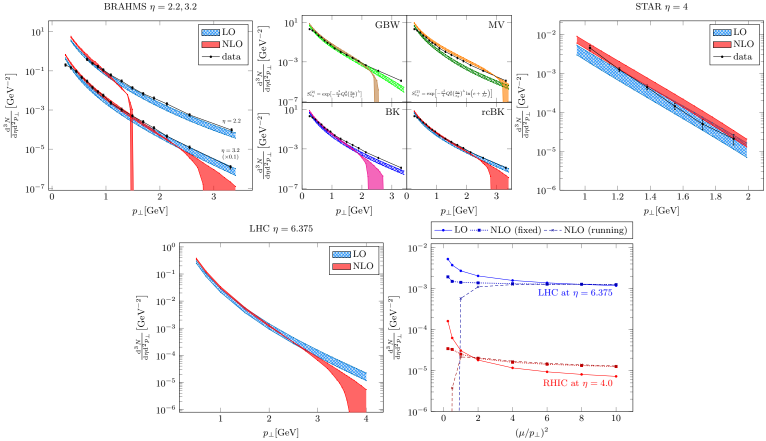


Consistent implementation should include all the NLO α_s corrections.

- NLO parton distributions. (MSTW or CTEQ)
- NLO fragmentation function. (DSS or others.)
- Use NLO hard factors. (11 in total)
- Use the one-loop approximation for the running coupling
- rcBK evolution equation for the dipole gluon distribution [Balitsky, Chirilli, 08; Kovchegov, Weigert, 07]. Full NLO BK evolution not available.
- The first most complete NLO results. [Stasto, Xiao, Zaslavsky, 13]

Numerical implementation of the NLO result

[Albacete, Dumitru, Fujii, Nara, 12] [Stasto, Xiao, Zaslavsky, 13]



- Agree with data for low $p_\perp$, and reduced scale dependence, no K factor.
- For large $p_\perp$, NLO correction dominates and becomes negative.
- Additional resummation ? or Kinematic constraints ? [G. Beuf]

Two Different Gluon Distributions

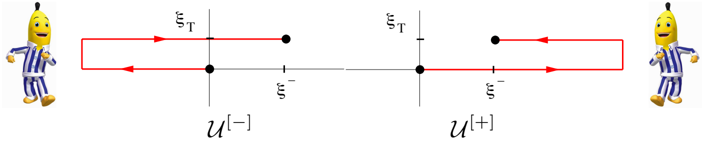
[F.Dominguez, C.Marquet, BX and F. Yuan, 11]

I. Weizsäcker Williams gluon distribution: Gauge Invariant definitions

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

II. Color Dipole gluon distributions: Gauge Invariant definitions

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

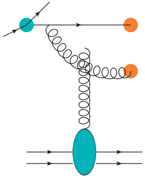


- The WW gluon distribution is the conventional gluon distributions. Quadrupole $\Rightarrow$ Direct measurement: DIS dijet, etc.
- The dipole gluon distribution has no such interpretation. Dipole $\Rightarrow$ γ-jet correlation in pA.

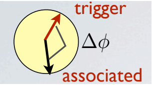
Dihadron correlations in *dAu* collisions (STAR and PHENIX)

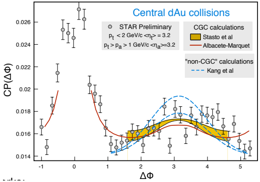
Predicted by [C. Marquet]. Further calculated [Marquet, Albacete, 10]; [Stasto, BX, Yuan, 11] [Lappi, Mantysaari, 13] Need to have both gluon distributions.

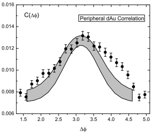
$$C(\Delta\phi) = \frac{\int_{|p_{1\perp}|,|p_{2\perp}|} \frac{d\sigma^{pA\to h_1 h_2}}{dy_1 dy_2 d^2p_{1\perp} d^2p_{2\perp}}}{\int_{|p_{1\perp}|} \frac{d\sigma^{pA\to h_1}}{dy_1 d^2p_{1\perp}}} \qquad J_{dA} = \frac{1}{\langle N_{\mathrm{coll}}\rangle} \frac{\sigma^{\mathrm{pair}}_{dA}/\sigma_{dA}}{\sigma^{\mathrm{pair}}_{pp}/\sigma_{pp}}$$

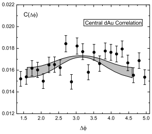


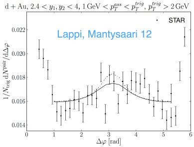
$\Rightarrow$

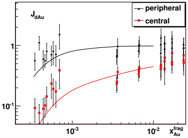






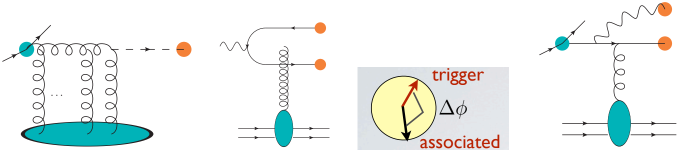






Dijet processes at one-loop order

Using various dijet processes to distinguish these gluon distributions.

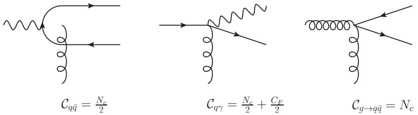


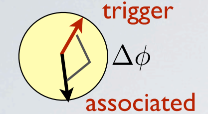
Comments:

- What happens at one loop order for back-to-back dijet processes? $(P_\perp \equiv \frac{1}{2}|k_{1\perp} - k_{2\perp}| \gg q_\perp \equiv |k_{1\perp} + k_{2\perp}|)$
- Can we prove the factorization for dijet productions?
- Small-x $\left[\frac{\alpha_s N_c}{2\pi} \ln \frac{1}{x}\right]^n$ resummation vs Sudakov (CSS) $\left[\frac{\alpha_s C_R}{2\pi} \ln^2 \frac{Q_1^2}{Q_2^2}\right]^n$ resummation. Consistently resum both types of logarithms at the same time? Unified description of the *CSS* and small-x evolution?

Sudakov factor for dijet productions in pA collisions and DIS

Consider the dijet productions in pA collisions:[A. Mueller, BX, F. Yuan, 13]





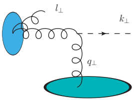
$$\frac{d\sigma}{dy_1 dy_2 dP_\perp^2 d^2k_\perp} \propto H(P_\perp^2) \int d^2x_\perp d^2y_\perp e^{ik_\perp\cdot R_\perp} e^{-\mathcal{S}_{sud}(P_\perp, R_\perp)} \widetilde{W}_{x_A}(x_\perp, y_\perp) \, .$$

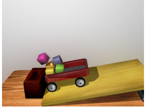
Comments:

- For back-to-back dijet processes, $M_J^2 \sim P_\perp^2 \gg k_\perp^2$

$$\mathcal{S}_{\text{sud}} = \frac{\alpha_s \mathcal{C}}{2\pi} \ln^2 \frac{P_\perp^2 R_\perp^2}{c_0^2} \quad \text{with} \quad R_\perp \sim \frac{1}{k_\perp}.$$

- Probability interpretation of the Sudakov factor (Parton shower)





- Competition between Sudakov and Saturation suppressions.

Conclusion

- Inclusive forward hadron productions in pA collisions in the small-x saturation formalism at one-loop order. (More work).
- Towards the test of saturation physics beyond LL (More precise).
- Dijet (dihadron) correlation in pA collisions. (More striking)
- One-loop calculation for hard processes in pA collisions, Sudakov factor. (More complete)