Forward Jet Production within small-x/TMD factorization framework

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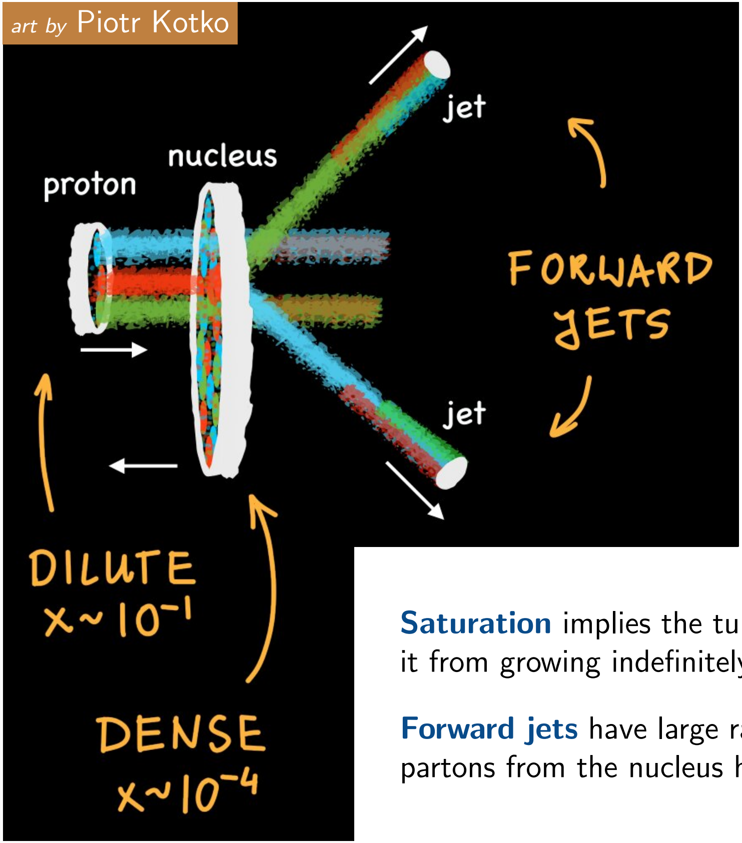
QCD evolution, dilute vs. dense, forward jets



A dilute system carries a few high-x partons contributing to the hard scattering.

A dense system carries many low-x partons.

At high density, gluons are imagined to undergo recombination, and to saturate.

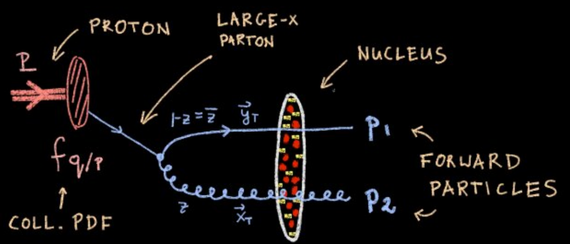
This is modeled with non-linear evolution equations, involving explicit non-vanishing k_T.

Saturation implies the turnover of the gluon density, stopping it from growing indefinitely for small x.

Forward jets have large rapidities, and trigger events in which partons from the nucleus have small x.

art by Piotr Kotko

pA (dilute-dense) collisions within CGC



$$\frac{d\sigma_{qA\to 2j}}{d^3p_1 d^3p_2} \sim \int \frac{d^2x}{(2\pi)^2}\frac{d^2x'}{(2\pi)^2}\frac{d^2y}{(2\pi)^2}\frac{d^2y'}{(2\pi)^2}\, e^{-i\vec{p}_{T1}\cdot(\vec{x}_T-\vec{x}'_T)} e^{-i\vec{p}_{T2}\cdot(\vec{y}_T-\vec{y}'_T)}$$

$$\times \psi_z^*(\vec{x}'_T-\vec{y}'_T)\,\psi_z(\vec{x}_T-\vec{y}_T)$$

QUARK WAVE FUNCTION

$$\times\Big\{S_x^{(6)}(\vec{y}_T,\vec{x}_T,\vec{y}'_T,\vec{x}'_T) - S_x^{(4)}(\vec{y}_T,\vec{x}_T,\bar{z}\vec{y}'_T+z\vec{x}'_T)$$
$$- S_x^{(4)}(\bar{z}\vec{y}_T+z\vec{x}_T,\vec{y}'_T,\vec{x}'_T) - S_x^{(2)}(\bar{z}\vec{y}_T+z\vec{x}_T,\bar{z}\vec{y}'_T+z\vec{x}'_T)\Big\}$$

CORRELATORS OF WILSON LINES

$$S_x^{(2)}(\vec{y}_T,\vec{x}_T) = \frac{1}{N_c}\left\langle \mathrm{Tr}\, U(\vec{y}_T)U^\dagger(\vec{x}_T)\right\rangle_x$$

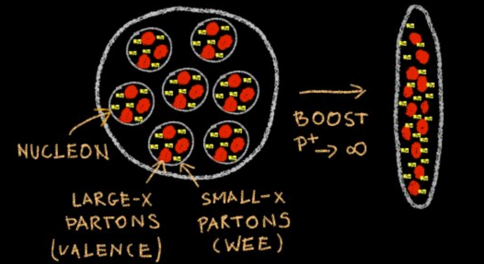
$$S_x^{(4)}(\vec{z}_T,\vec{y}_T,\vec{x}_T) = \frac{1}{2C_FN_c}\left\langle \mathrm{Tr}\left[U(\vec{z}_T)U^\dagger(\vec{y}_T)\right]\mathrm{Tr}\left[U(\vec{y}_T)U^\dagger(\vec{x}_T)\right]\right\rangle_x - S_x^{(2)}(\vec{z}_T,\vec{x}_T)$$

etc...

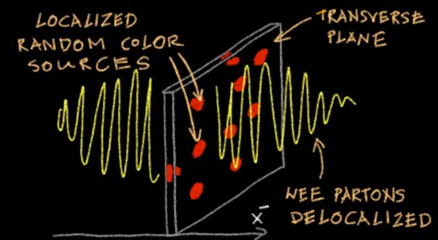
$$U(\vec{x}_T) = \mathscr{P}\exp\left\{ig\int_{-\infty}^{+\infty} dx^+\, A_a^-(x^+,\vec{x}_T)\,t^a\right\}$$

[C. Marquet, 2007]

COLOR FIELD OF THE NUCLEUS



[L. McLerran, R. Venugopalan, 1993]



Large-x partons — the color source for wee partons:

$$(D_\mu F^{\mu\nu})_a(x^-,\vec{x}_T) = \delta^{\nu+}\rho_a(\vec{x}_T)\delta(x^-)$$

RANDOM DISTRIBUTION OF COLOR SOURCES

AVERAGE OVER COLOR SOURCES

GAUSSIAN FUNCTIONAL

B-JIMWLK EVOLUTION IN X → $\mathscr{W}_x[\rho]$

[Balitsky-Jalilian-Marian-Iancu-McLerran -Weigert-Leonidov-Kovner, 1996-2002] art by Piotr Kotko

Small-x Improved TMD Factorization (ITMD)

Factorization formula for forward dijets in p-p and p-A collisions

[PK, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, A. van Hameren, 2015]

$$\frac{d\sigma_{pA\to 2j+X}}{dy_1 dy_2 d^2p_{T1} d^2p_{T2}} \sim \sum_{a,c,d} f_{a/p}(x_1,\mu) \sum_{i=1,2} K^{(i)}_{ag\to cd}(k_T)\, \Phi^{(i)}_{ag\to cd}(x_2,k_T)$$

RAPIDITY — TRANSVERSE MOMENTA — COLLINEAR PROTON PDF — GAUGE INVARIANT OFF-SHELL HARD FACTORS — TMD GLUON DISTRIBUTIONS AT SMALL-X

$x_2 \ll x_1 \qquad |\vec{p}_{T1} + \vec{p}_{T2}| = k_T$

TWO PER CHANNEL
$(g^*q\to gq,\ g^*g\to gg,\ g^*g\to q\bar{q})$

ITMD factorization formula has been proven from the Color Glass Condensate (CGC) theory.

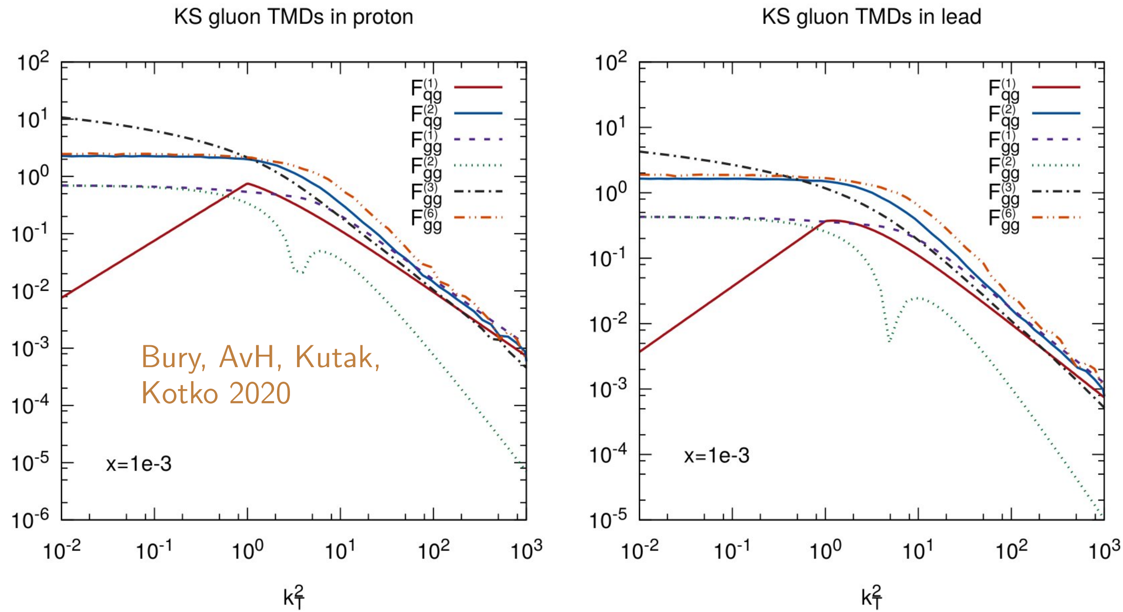
$\Rightarrow$ RESUMMATION OF KINEMATIC TWISTS AND NEGLECTING GENUINE TWSTS.

[T. Altinoluk, R. Boussarie, PK, 2019]

$\Lambda_{QCD} \ll Q_s \ll P_T$

SATURATION SCALE

ITMD gluons



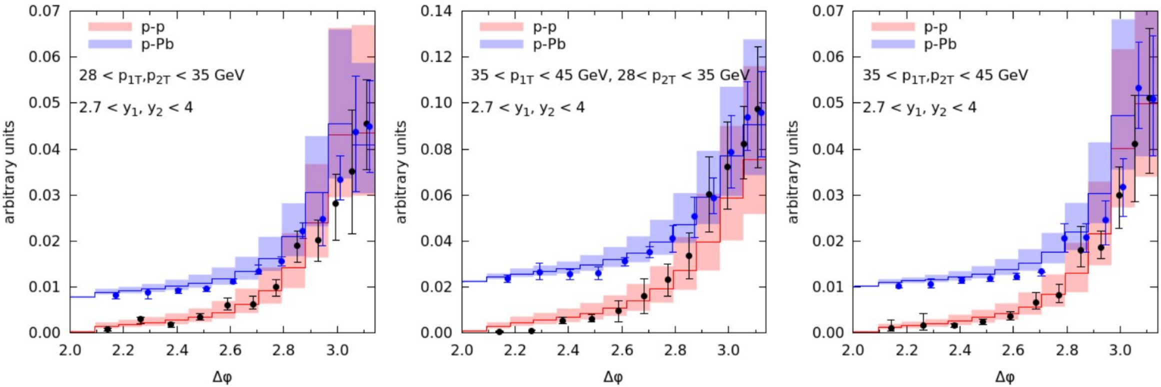
- KS gluon (Kutak, Sapeta 2012) is the dipole-distribution as a solution to the BK equation (Balitsky 1996, Kovchegov 1999) formulated in the momentum space with corrections of higher order, and fitted to F_2 data.
- ITMD gluons follow from the KS gluon

Saturation effects from forward jets

AvH, Kotko, Kutak, Sapeta 2019

Study of saturation using dijet production in p-p and p-pB collisions.
Angle $\Delta\varphi$ between the jets is particularly sensitive to saturation effects.

Data points from ATLAS 2019. Arbitrary normalization and relative shift to to accentuate the difference in shape between p-p and p-Pb.



Calculations where performed within ITMD factorization.
Besides saturation, the inclusion of resummed Sudakov logarithms are essential to reach this accuracy, included here via event-reweighting.
Independent cross-checks with KaTie (`http://bitbucket.org/hameren/katie`) and LxJet (`http://nz42.ifj.edu.pl/~pkotko/LxJet.html`).

Outlook

- Improvement of the Sudakov resummation (starting from eg. Mueller, Xiao, Yuan 2013).
- Inclusion of linearly dependent gluon distributions in higher jet-multiplicity calculations, i.e. extending ITMD* (Bury, AvH, Kotko, Kutak 2020) to complete ITMD.
- Increasing the perturbative order to NLO.

Thank you for your attention.