1. Introduction

In central unit of rapidity in central Au-Au collision dense gluonic system is produced at time $\lesssim \frac{1}{2}$ Fm. This system appears to equilibrate rapidly Forming a quark gluon plasma much denser than cold nuclear matter.

Hard probes are good probes of the density of the matter. Comparing A-A, Deuterium-A and p-p reactions using a hard probe allows one to separate properties of the initial waveFunctions (light-cone gauge) From those of the Final state evolving matter.

p-p, d-Au, Au-Au at $y=0$: Suppression of high momentum particles due to (Final state) energy loss in Au-Au

p-p, d-Au at large y: Strong shadowing observed. Good evidence For Color Glass Condensate (Saturation).

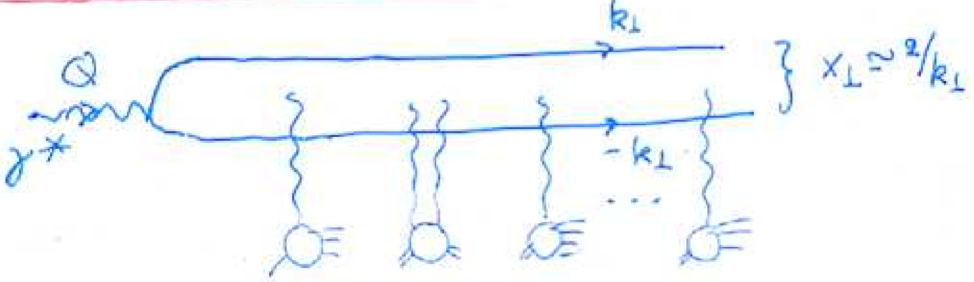
2. Saturation (Color Glass Condensate)

Saturation (CGC) is property of light cone wavefunction. Easiest to view by DIS probe.

A. McLerran-Venugopalan model

Alternative pictures in different frames

Nuclear rest frame



$$F_2 = \frac{Q^2}{8\pi^2 \alpha_{em}} \int d^2b \int_0^1 dz \int d^2x_\perp \, |\Psi_T(x_\perp, z, Q)|^2 \; 2\big(1 - \underbrace{e^{-x_\perp^2 \bar{Q}_s^2/4}}_{S(x_\perp,\, b)}\big)$$

is Glauber-type formula.

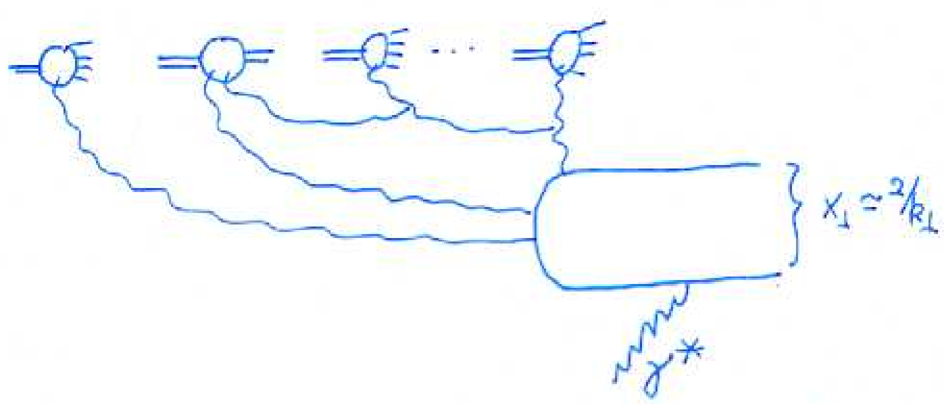
$$\frac{1}{4} x_\perp^2 \bar{Q}_s^2 = \frac{1}{2}\sigma_{q\bar{q}}(x_\perp)\, 2\sqrt{R^2-b^2}\,\rho \quad \text{nuclear density}$$

$$Q_s^2 = \frac{4\pi^2 \alpha N_c}{N_c^2-1} \, 2\sqrt{R^2-b^2}\,\rho\, x G_p \quad ; \quad \bar{Q}_s^2 = \frac{C_F}{N_c} Q_s^2$$

$\bar{Q}_s$ sets scale where S goes from 1 (weak interaction) to 0 (unitarity limit).

$Q_s \simeq 1$ GeV for large

Bjorken Frame (P_3 large for nucleus)



Now describe quark sea in large nucleus by

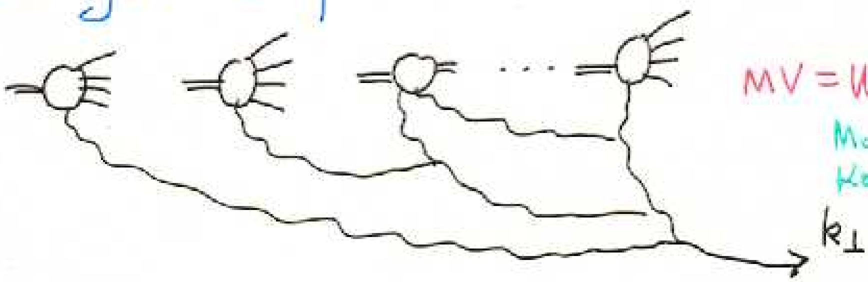
$$f_q(k_\perp, b) \simeq \frac{d\, x(q_F + \bar{q}_F)}{d^2k_\perp d^2b} \frac{(2\pi)^3}{2 \cdot 2 \cdot N_c}$$

spins particle-antiparticle

$$S \simeq 0 \overset{k_\perp < \bar{Q}_s}{\Longleftrightarrow} f_q \simeq \frac{1}{\pi}$$

– Saturation
Color Glass Condensate

For gluons picture is



MV = Weizsäcker-Williams
McLerran Venugopalan
Kovchegov

$$f_g = \frac{1}{\alpha N_c} \int \frac{d^2x_\perp}{\pi x_\perp^2} e^{-ik_\perp \cdot x_\perp} \left(1 - e^{-x_\perp^2 Q_s^2/4}\right) \simeq \frac{1}{\alpha N_c} \int_1^\infty \frac{dt}{t} e^{-t\, k_\perp^2/Q_s^2}$$

$$f_g \simeq \frac{1}{\alpha N_c}$$

Color Glass Condensate

Unitarity limit (Nuclear rest Frame) $\leftrightarrow$ Saturation (Bjorken Frame)

In M-V model

Gluons classical

no shadowing, just rearrangement of gluons in nuclear wavefunction.

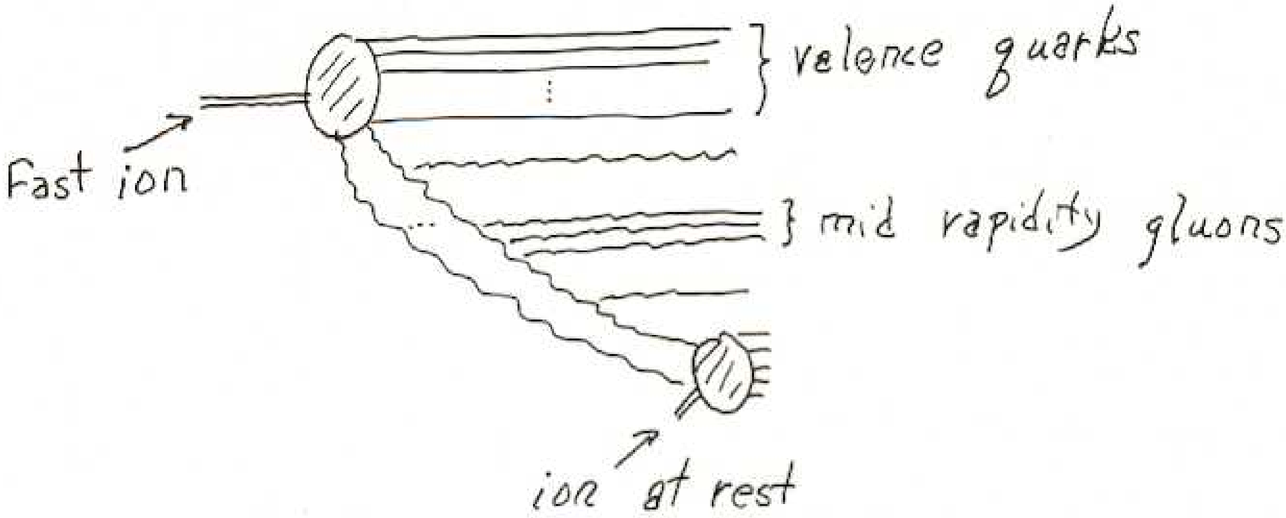
Quarks quantum (one loop)

quark distribution is shadowed, but there is no leading twist shadowing

Probably a reasonable starting point For $y \simeq 0$ in RHIC central collisions.

3. Heavy Ion Collision (Semiclassical Picture)

Take one ion at rest



Picture: Gluons in the fast ion having $k_\perp \lesssim Q_s$ are freed in the collision. Gluons having $k_\perp \gtrsim Q_s$ are not.

Numerical simulations by Krasnitz, Nara and Venugopalan confirm this picture with about $\frac{1}{2}$ the gluons being freed. Collision increases $\langle k_\perp \rangle$ by $\approx 50\%$. KNV Lappi

Phenomenology by Kharzeev, Levin, Nardi ...; Baier et al.

Wave Function relevant to DIS comes in directly in initial condition after a heavy ion collision.

4. BFKL evolution and anomalous scaling

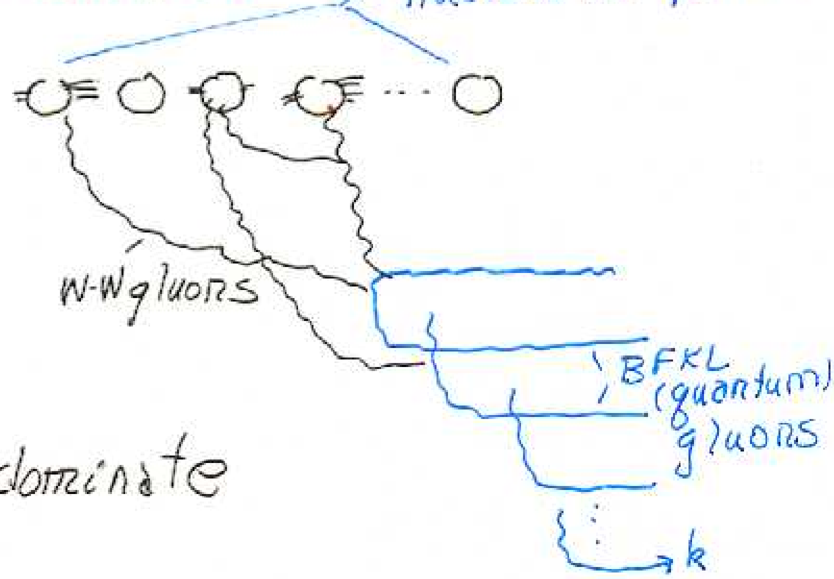
Saturation momentum can be large ($\gg \Lambda_{QCD}$) for two reasons:

(i) Large nucleus, at high momentum, has large number of Weizsäcker-Williams gluons

$$Q_s^2(b) \sim 2\sqrt{R^2-b^2}\,\rho \sim A^{1/3}$$

(ii) BFKL evolution, at small x, gives large number of gluons.

Combine; big nucleus at small x



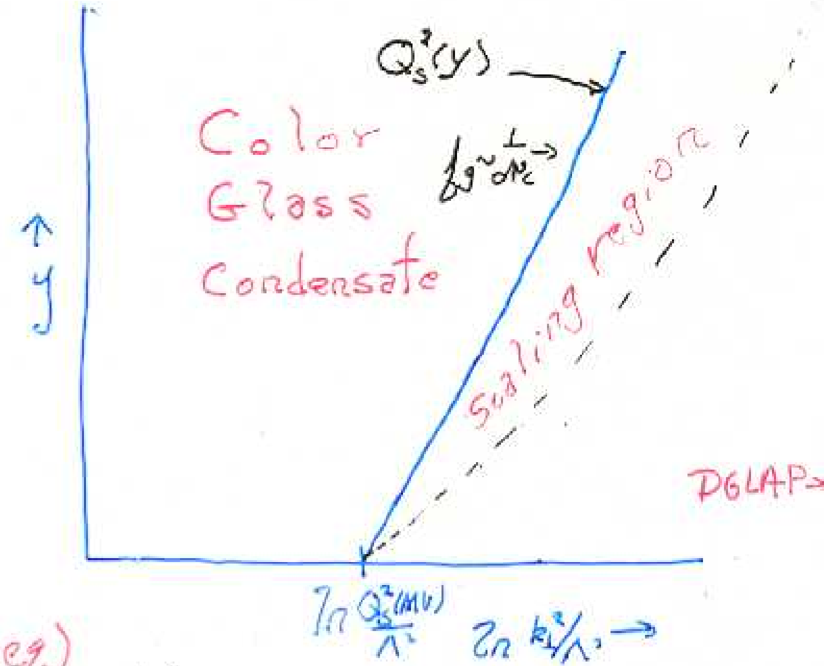
$$\frac{dN_g(b,y)}{dy} \sim \underbrace{\alpha N_g(b,y)}_{\text{random charges dominate}}$$

$$N_g(b,y) \simeq \underbrace{N_g(b,0)}_{\text{W-W}}\;\underbrace{e^{\alpha y}}_{\text{BFKL enhancement}}$$

In scaling region

(i) $f_g \ll \frac{1}{\alpha N_c}$

(ii) leading twist (BFKL) dynamics



In scaling region (From Kovchegov eq.)

$$\frac{k_\perp^2\, dN_g(k_\perp, b, y)}{d^2b\, d^2k_\perp\, dy} \simeq C_1 \frac{k_\perp^2}{\alpha}\left(Q_s^2(y)/k_\perp^2\right)^{1-\lambda_0}\left[\ln k_\perp^2/Q_s^2 + C_2\right]$$

A.M + Dionysis T.
S. Munier + R. Peschanski
McLerran, Kharzeev Levin
Kharzeev, Kovchegov Tuchin
⋮

$$Q_s^2(y) = Q_s^2(MV)\,\frac{e^{\frac{2\alpha N_c}{\pi}\frac{\chi(\lambda_0)}{1-\lambda_0}y}}{[\alpha y]^{\frac{3}{2(1-\lambda_0)}}} \times C_3$$

Nice numerical calculations by Albacete, Armesto Kovner, Salgado, Wiedemann and by Weigert + Rummukainen, and Kwiecinski, Stasto et al.

Comments:

(i) A-dependence of unintegrated gluon distribution is $A^{1/3(1-\lambda_0)}$ rather than $A^{1/3}$. $1-\lambda_0 \simeq 0.63$. Suppression of gluon density in scaling region is shadowing due to closeness to saturation. This is leading twist shadowing. Note genuine DGLAP evolution has $\lambda=0$ and does not give shadowing. In BRAMS region $Q_s^2(y) \simeq 2 \cdot Q_s^2(MV)$.

(ii) Size of scaling region determined by amount of BFKL evolution. Numerical studies, Albacete et al., Baier et al., KKT, suggest rapid turn-on of BFKL effects.

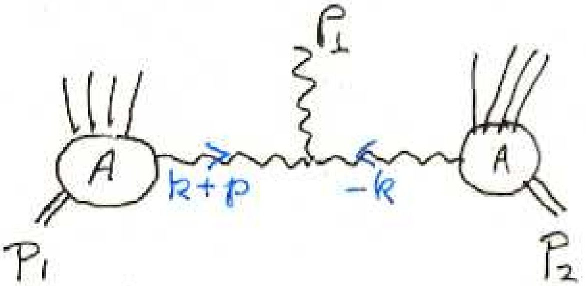
(iii) Details of prefactors still to be understood.

Question: Is Kovchegov equation adequate for prefactors in Q_s^2 and in $k_\perp^2 \frac{dN_g}{dy\, d^2k_\perp d^2b}$?

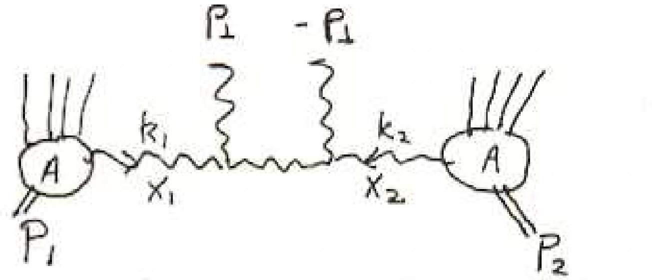
(iv) Chance to do exciting small-x physics in forward region at RHIC. Better understand high occupancy gluon systems. Better understand start of thermalization.

5. Hard Scattering at RHIC

A. High-$p_\perp$ jets (particles) at central rapidity



vs



When $p_\perp$ in scaling region
Unintegrated gluon distributions

when $p_\perp$ outside scaling region; Normal gluon distrib.
Hard Scattering Formalism

Hard Scattering Formalism can be used also in scaling region, but then a resummation of higher order terms in the hard part must be done. Scaling region is leading twist.

B. Kinematics (central rapidity)

Use hard scattering picture; take $p_\perp = 5\,\text{GeV}$ and $x_1 = x_2$.

$$x_1 x_2 s = x^2 \cdot 4\times10^4\ \text{GeV}^2 = 4p_\perp^2 \Rightarrow x = 0.05$$

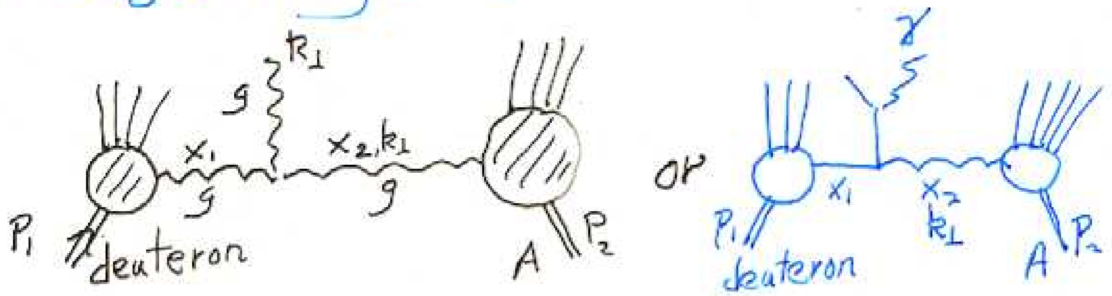
$$k_{1z} \simeq 5\,\text{GeV} \Rightarrow (\Delta z)_k \simeq \tfrac{1}{25}\ \text{fm}$$

$$(\Delta z)_A \simeq 10\,\text{fm} \cdot \tfrac{1}{100} \simeq \tfrac{1}{10}\ \text{fm}$$

Coherence marginal!

Hard to get much evolution!

B. Large-x region



$x_1 x_2 s \simeq k_\perp^2$ $\qquad$ $x_1 x_2 s = k_\perp^2 + M^2$

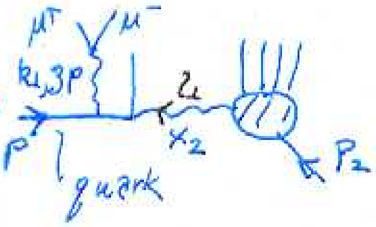
$x_2 \Rightarrow x_2 e^{-y}$ if one goes away from $y=0$.

$y \simeq 3$ decreases x_2 by Factor of 20

get to $x \simeq 0.001$ region where anomalous scaling (shadowing) can be expected to be important.

C. μ-pair production

Jalilian-Marian, Gelis
Kopeliovich, Raufeisen
Tarasov, Johnson
Baier, Shiff, A.M.



$$\frac{d\sigma}{d^2b\, d^2k_\perp\, d\ln z} = \frac{\alpha_{em}^2 \alpha_s}{3\pi^2 N_c}\left[1+(1-z)^2\right]\int \frac{d^2 l_\perp}{l_\perp^2}\, \phi(l_\perp, x_2, b)\left\{ \frac{z^2 l_\perp^2}{k_\perp^2+\eta^2}\cdot\frac{1}{(k_\perp - z l_\perp)^2+\eta^2} - \eta^2\left[\frac{1}{k_\perp^2+\eta^2} - \frac{1}{(k_\perp - z l_\perp)^2+\eta^2}\right]^2\right\}$$

$$\eta^2 = M^2_{\mu^+\mu^-}(1-z)$$

$$\phi(l_\perp, x_2, b) = C_1\left(Q_s^2(x_2)/l_\perp^2\right)^{1-\lambda_0}\left[\ln l_\perp^2 / Q_s^2(x_2) + C_2\right]$$

A-dependence $A^1 A^{-\lambda_0/3}$ related to $k_\perp$-dependence

↑ shadowing

Summary

M-V or Semiclassical Saturation

Probably dominates central region in Au-Au collisions at RHIC

Gluons $k_\perp \lesssim Q_s$ in condensate $f_g \sim 1/\alpha$

Gluons not shadowed. Gluons are classical.

Quarks are quantum and shadowed. No leading twist shadowing.

M-V + BFKL

BRAMS data suggests BFKL evolutoon importany at forward rapidity regions

Now leading twist gluon (and quark) shadowing in scaling region, intimately related to saturation.