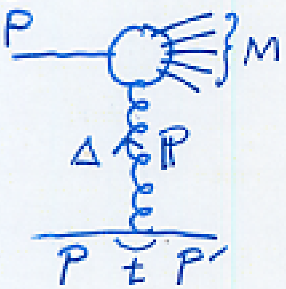
Diffraction and Small-x Physics

1. Diffraction in P-$\bar{P}$ (and P-P) reactions

Big surprise in single diffractive (SD) cross section



$\Delta = x_{\mathbb{P}} P$, $x_{\mathbb{P}} = \xi$

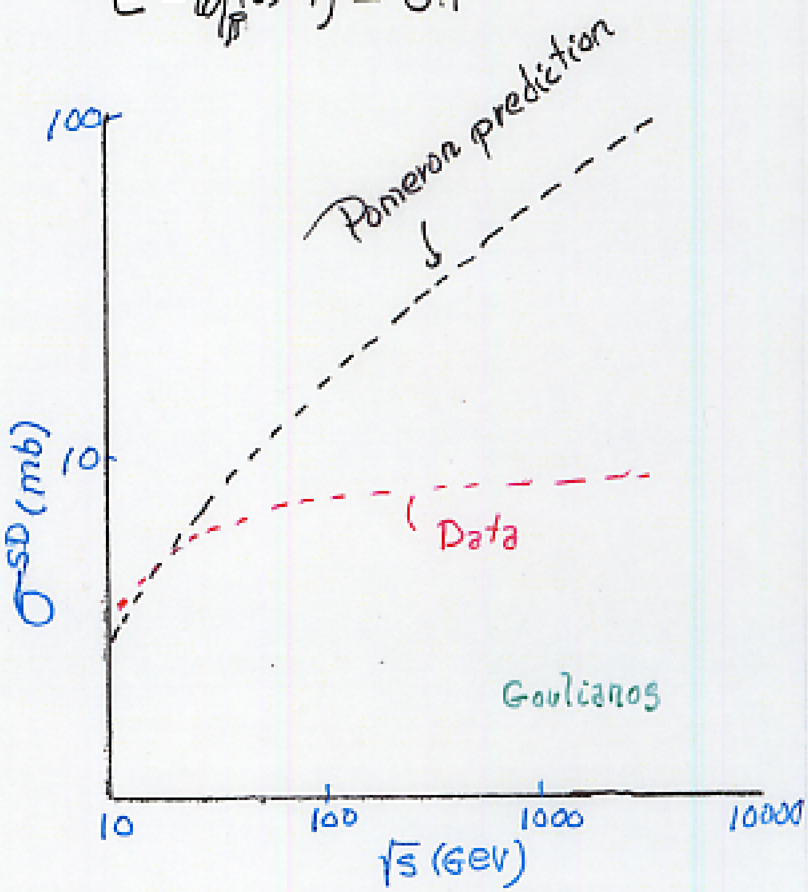
$\xi \simeq \dfrac{M^2}{s}$

$$\sigma^{SD} = 2\int_{\xi<\xi_0} \frac{d\sigma}{dM^2 dt}\, dt\, dM^2$$

Expected $\sigma^{SD} \propto s^{2\epsilon}$ $\qquad \epsilon = (\alpha_{\mathbb{P}}(0)-1) \simeq 0.1$

Pomeron predictoon ok for $\sqrt{s} \lesssim 25\,GeV$

Pomeron prediction much too large for $\sqrt{s}$ in Tevatron regime



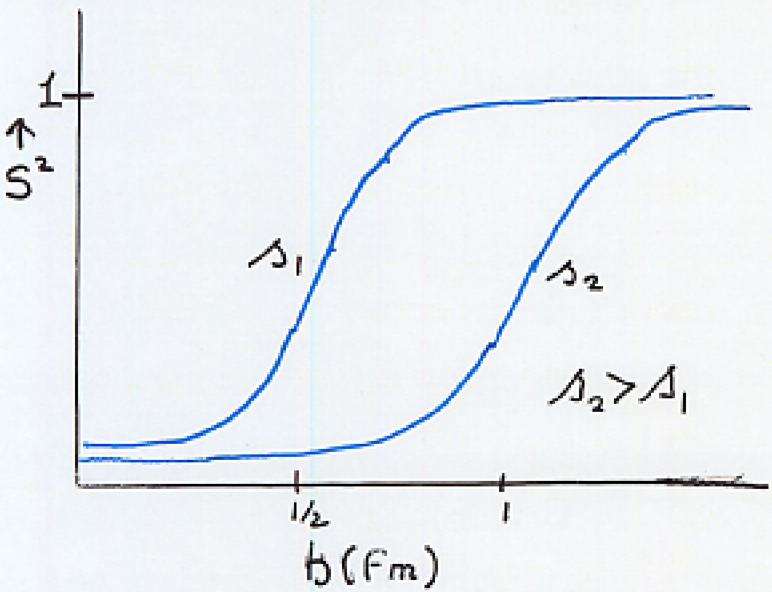
To see what has gone wrong recall Amaldi-Schubert analysis

For simplicity neglect the (small) real part of the scattering amplitude. Then

$$S(b_\perp, s) = 1 - N\int d^2\Delta_\perp \, e^{-i b_\perp \cdot \Delta_\perp} \sqrt{\frac{d\sigma}{d^2\Delta_\perp}}$$

elastic scattering

Find



$\sigma_{in} = \int d^2b\,(1 - S^2)$

$\sigma_{el} = \int d^2b\,(1 - S)^2$

$\sigma_{tot} = 2\int d^2b\,(1 - S)$

At Fermilab unitarity limit reached

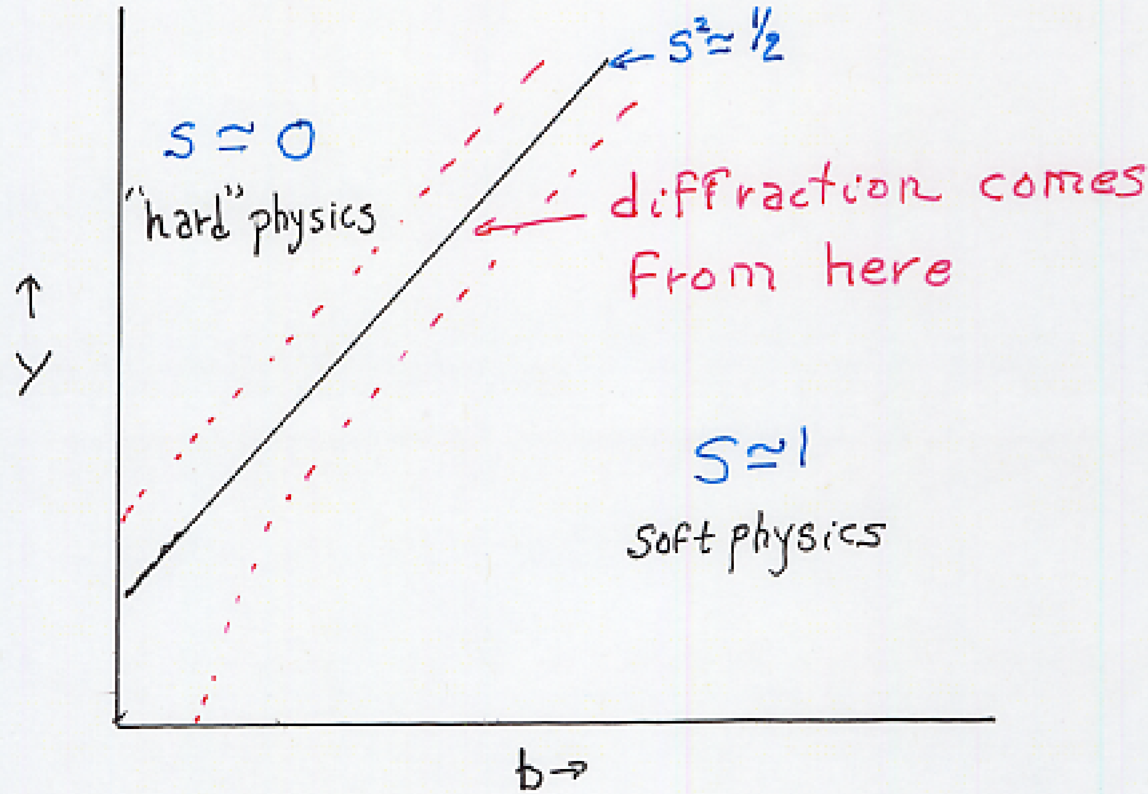
For $b \leq 1\,\mathrm{fm}$.

Regge pole: $S = 1 - c\left(\frac{s}{s_0}\right)^{\alpha(0)-1} e^{-\frac{b^2}{R^2(s)}}$

OK when S close to one

When $S \simeq 0$ shadow of inelastic reactions is purely elastic. Regge pole not applicable.

View in $y = \ln s/s_0$ and b plane



Detailed pictures by

Goulianos

Gotsman, Levin and Maor

Kaidalov, Khoze, Martin, Ryskin

⋮

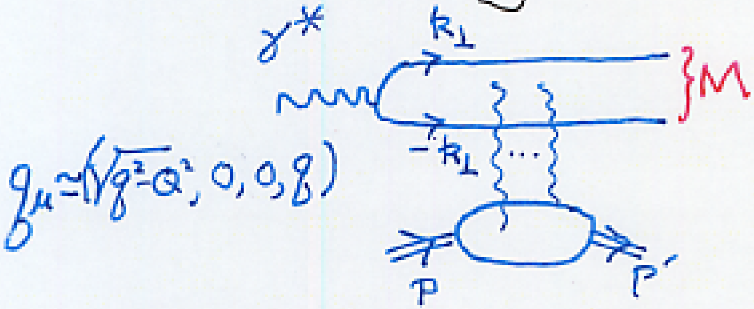
Picture "clear"; still struggling for quantitative control

Diffraction, in PP at beginning of transition between soft and hard physics

t-dependence would be very useful!

2. Diffraction in deep inelastic scattering

Useful to use frame where all diffraction fragments are left-moving



+ terms with additional gluons in γ^*-wavefunction

Diffraction corresponds to <u>elastic</u> dipole proton scattering.

$$dF_2^D \propto \underbrace{dP_r(\gamma^* \to q\bar{q}(k_\perp))}_{\frac{dk_\perp^2}{Q^2}} \cdot (1 - S(x, k_\perp))^2$$

$1 - S \propto \left(\frac{1}{k_\perp^2}\right)^2$ in perturbation theory

At very high energy the proton has strong color fields and S becomes small when $k_\perp^2/\Lambda_{QCD}^2 \gg 1$. If $Q_s^2(x)$ is scale at which $S = 1/2$, say. Then

$$F_2^D(x, Q^2) \sim Q_s^2(x) R_p^2$$

$Q_s^2(x) \sim (1/x)^{0.3}$

└ saturation momentum

Faster than hard Pomeron; and more reliable

↓

$$Q_s^2 \sim e^{\frac{2\alpha(Q_s^2) N_c}{\pi} \frac{\chi(\lambda_0)}{1-\lambda_0} \ln\frac{1}{x}}$$

Gribov, Levin, Ryskin

Triantafyllopoulos

So in comparison to $P\bar{P}$ collisions, diffraction in inelastic scattering is:

the shadow of events where the proton breaks up

central impact parameter dominated

a "hard" process; on scale Q_s^2

3. Saturation of partons

Recall that $x(q_F(x,Q^2) + \bar{q}_F(x,Q^2))$ and $xG(x,Q^2)$ grow strongly with $1/x$ for moderate values of Q^2. Also, for example, $xG(x,Q^2)$ has the interpretation of the number of gluons of "size" $\Delta x_\perp \sim 1/Q$, in a unit of rapidity, in the high energy wavefunction of the proton.

How big can xG get?

Useful to view in terms of occupation numbers.

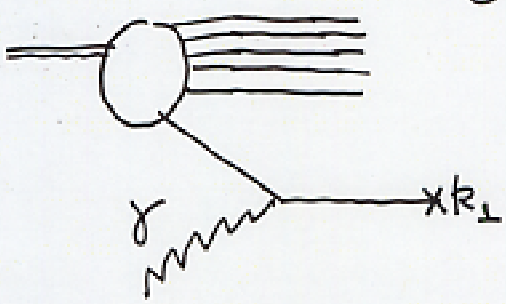
$$f_g = \frac{(2\pi)^3}{2\cdot(N_c^2-1)} \frac{dxG}{d^2b\, d^2k_\perp}$$

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

particle -antiparticle spin

(Rough, have used $dy = \frac{dk_z}{k_z} \simeq dz \cdot dk_z$)

In Bjorken-type frame, in "good" light-cone gauge



$$= \frac{dxG}{d^2k_\perp} = \frac{dN_g}{dy\, d^2k_\perp}$$

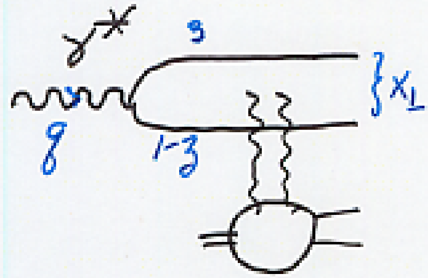
$$f_q \simeq \frac{1}{\pi} \qquad k_\perp^2 \ll \bar{Q}_s^2(Y)$$

$$f_g \simeq \frac{c_1}{\alpha_s N_c}\left[\ln Q_s^2/k_\perp^2 + c_2\right] \qquad k_\perp^2 \ll Q_s^2(Y)$$

$$Q_s^2 = \frac{N_c}{C_F}\bar{Q}_s^2 = \frac{2N_c^2}{N_c^2-1}\bar{Q}_s^2$$

Dipole of size $\Delta x_\perp \simeq 1/Q_s$ interacts strongly with target having saturation momentum Q_s.

Golec-Biernat and Wüsthoff model



$$F_2 = \frac{Q^2}{8\pi^2 \alpha_{em}} \int d^2x_\perp \int_0^1 dz \sum_f e_f^2 \left| \psi_{T}(x_\perp, z, Q) \right|^2 \sigma_0 \; 2(1-S)$$

$$F_2^D = \quad '' \qquad\qquad '' \quad (1-S)^2 + q\bar{q}g \text{ term}$$

$$S = e^{-x_\perp^2 \bar{Q}_s^2/4} \qquad \bar{Q}_s^2(x) = 1\,\text{GeV}^2 \left(\frac{3\cdot 10^{-4}}{x}\right)^\lambda$$

$\lambda = 0.3 \qquad \sigma_0 \simeq 23$ mb

λ too large by factor of 2.

Essential Feature

$S \simeq 1 \qquad x_\perp \ll 2/Q_s$

$S \simeq 0 \qquad x_\perp \gg 2/Q_s$

Major weaknesses

impact parameter blind
no scaling violations

<u>Many</u> improved models of the G-B+W type

Frankfurt, Guzey, McDermott, Strikman
Bartels, Golec-Biernat, Kowalski
Gotsman, Levin, Lublinsky
Kowalski, Teaney

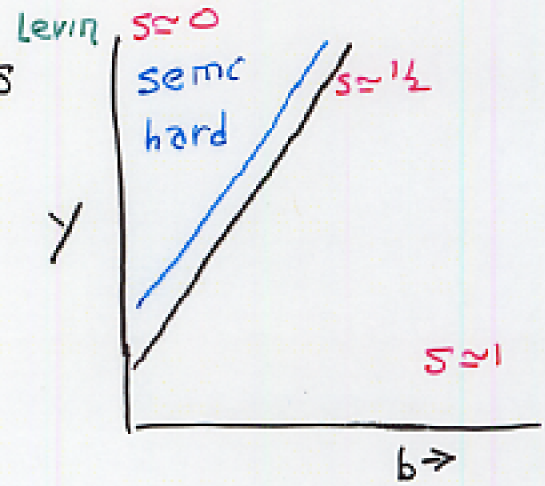
4. $p\text{-}\bar{p}$ collisions

At Fermilab energies $p\text{-}\bar{p}$ (central) collisions dominated by semi-hard collisions

eg

$$\frac{d\langle k_\perp^2\rangle}{dy} \sim \frac{1}{\alpha_s} Q_s^2(Y) \qquad \cancel{AKG}$$

$$Q_s^2 \simeq 5\,\mathrm{GeV}^2$$

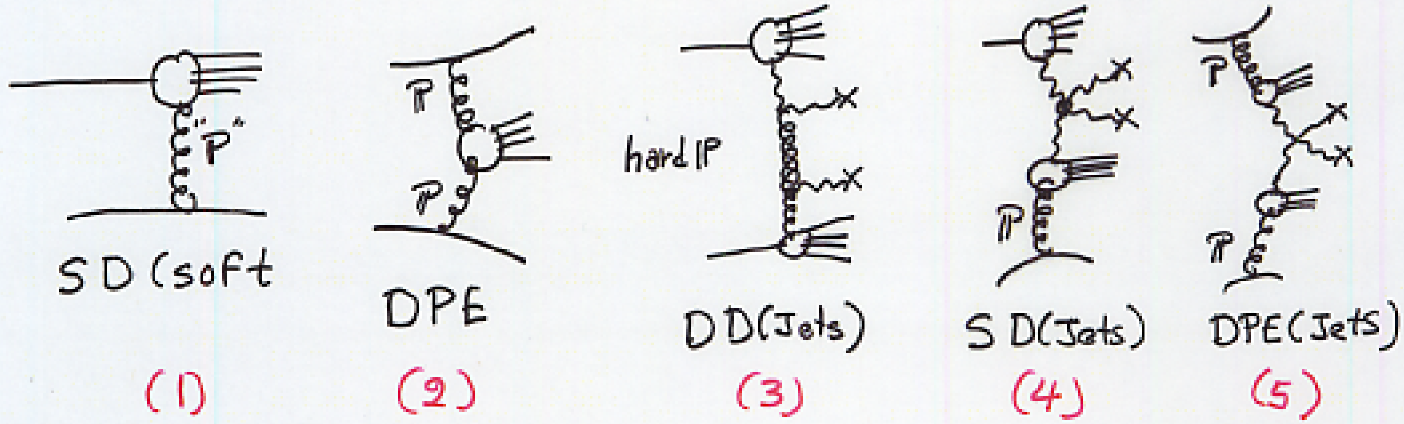


For $S \simeq \frac{1}{2}$ regime soft physics understanding is necessary. But $\alpha_{\mathbb{P}}(0)-1$ cannot be expected to appear.

Central collision produces dense gluonic system. Much denser than RHIC! System will not(?) equilibrate before falling apart.

5. Hard reactions and diffraction at Fermilab

Wide variety of processes now being studied



All these processes occur at large impact parameter <u>or</u> involve rare fluctuations of the proton state.

eg:

$$S \simeq 1 - c\left(s/s_0\right)^{\alpha_P(0)-1} e^{-\frac{b^2}{c_1 + 4\alpha' \ln(s/s_0)}}$$

$$S \simeq \tfrac{1}{2} \quad \text{when} \quad b_c^2 \simeq [\alpha_P(0)-1][c_1 + 4\alpha' \ln s/s_0] \ln s/s_0$$

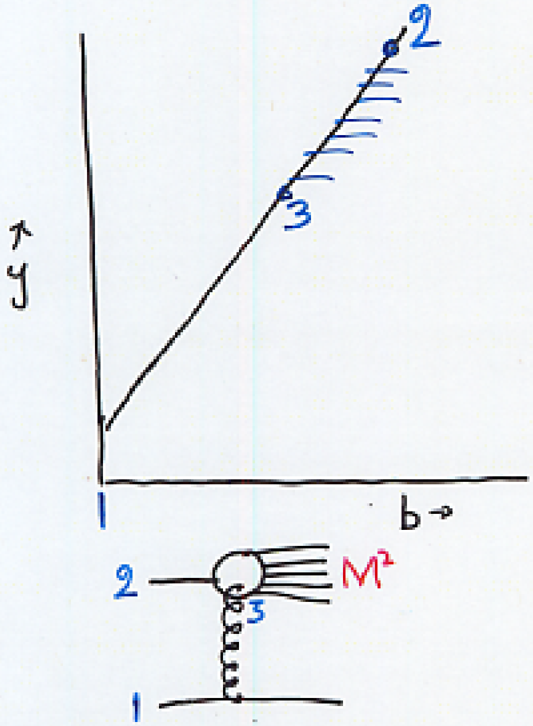
At such large impact parameters, Pomeron growth is lost.

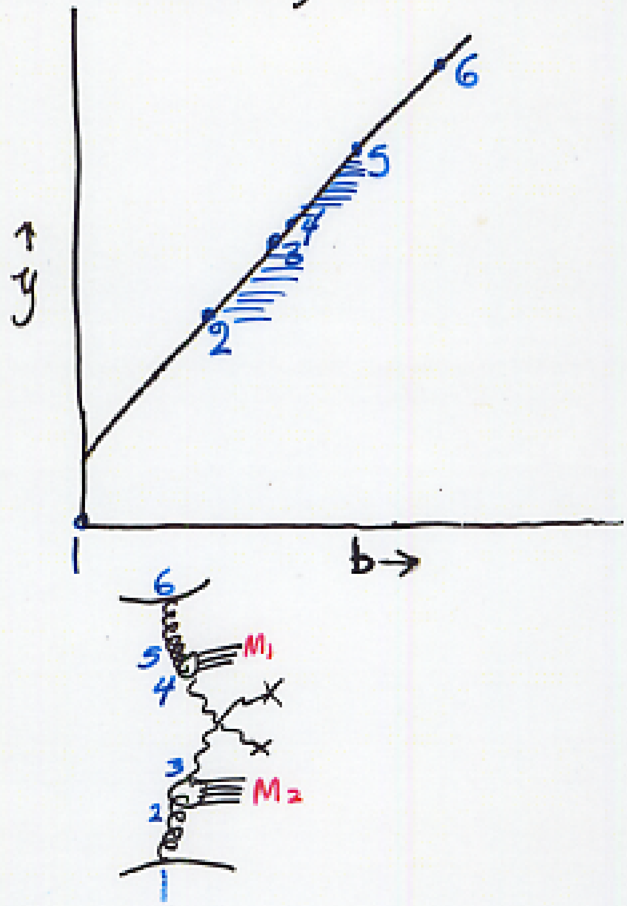
Phenomenology beginning to emerge

Goulianos

Kaidalov, Khoze, Martin, Ryskin

Survival probability factors for all these processes should be related, but not identical.





Simplified picture but, maybe coherent picture can emerge tied (partially) to QCD

Goulianos

(i) Can $(M^2)^{-\alpha(0)}$ emerge, or something similar

(ii) Particles in M, M_1, M_2 should be much softer than in typical $p\bar{p}$ collisions

(iii)* Fits to b-dependence here should be compatible with Amaldi-Schubert.

(iv) Brave phenomenology might relate (crudely). the b-dependence Q_s with the $S=\frac{1}{2}$ line above.

6 Heavy ion collisions

The saturation momentum is the scale below which the gluon occupation number becomes $\gtrsim 1/\alpha_s$. Q_s governs the energy dependence of diffraction in DIS

$$F_2^D \propto Q_s^2(x) R_p^2 .$$

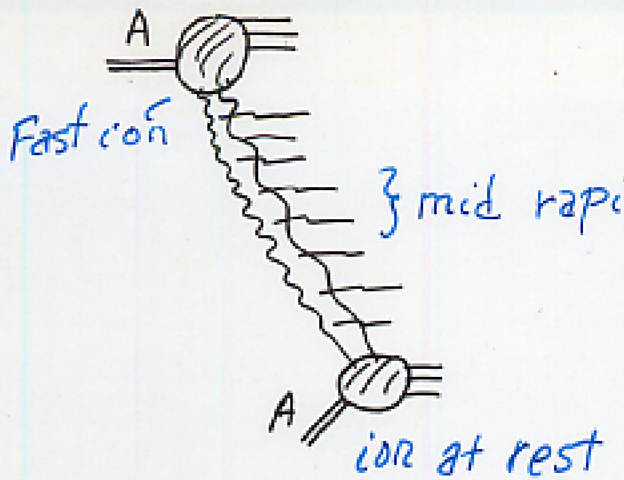
Q_s is also the basic parameter appearing in the early stages of a heavy ion collision.

Illustrate in McLerran-Venugopalan model

$$\frac{dxG_A}{d^2b\, d^2k_\perp} = \frac{N_c^2-1}{4\pi^3 \alpha N_c}\left[\ln Q_s^2/k_\perp^2 + \text{const}\right] \qquad k_\perp \lesssim Q_s$$

$$Q_s^2 = \frac{4\pi^2 \alpha N_c}{N_c^2-1}\, 2\sqrt{R_A^2-b^2}\, xG_N$$

$$\frac{dxG_A}{d^2b} = 2\sqrt{R^2-b^2}\,\rho\, xG_N(x, Q_s^2)$$



Collision, roughly, just frees gluons at or below Q_s.

$$\frac{dN_g}{d^2b} = c\,\frac{N_c^2-1}{4\pi^2\alpha N_c}\,Q_s^2(b)$$

is initial density of gluons. c is freeing parameter. Classical Yang-Mills Field theory calculation gives (numerically) $c \simeq \frac{1}{2}$. Krasnitz, Nara Venugopalan

High density (predominately) gluon system interacts and equilibrates to give QGP.