Two Particle Production in Proton-Nucleus Collisions

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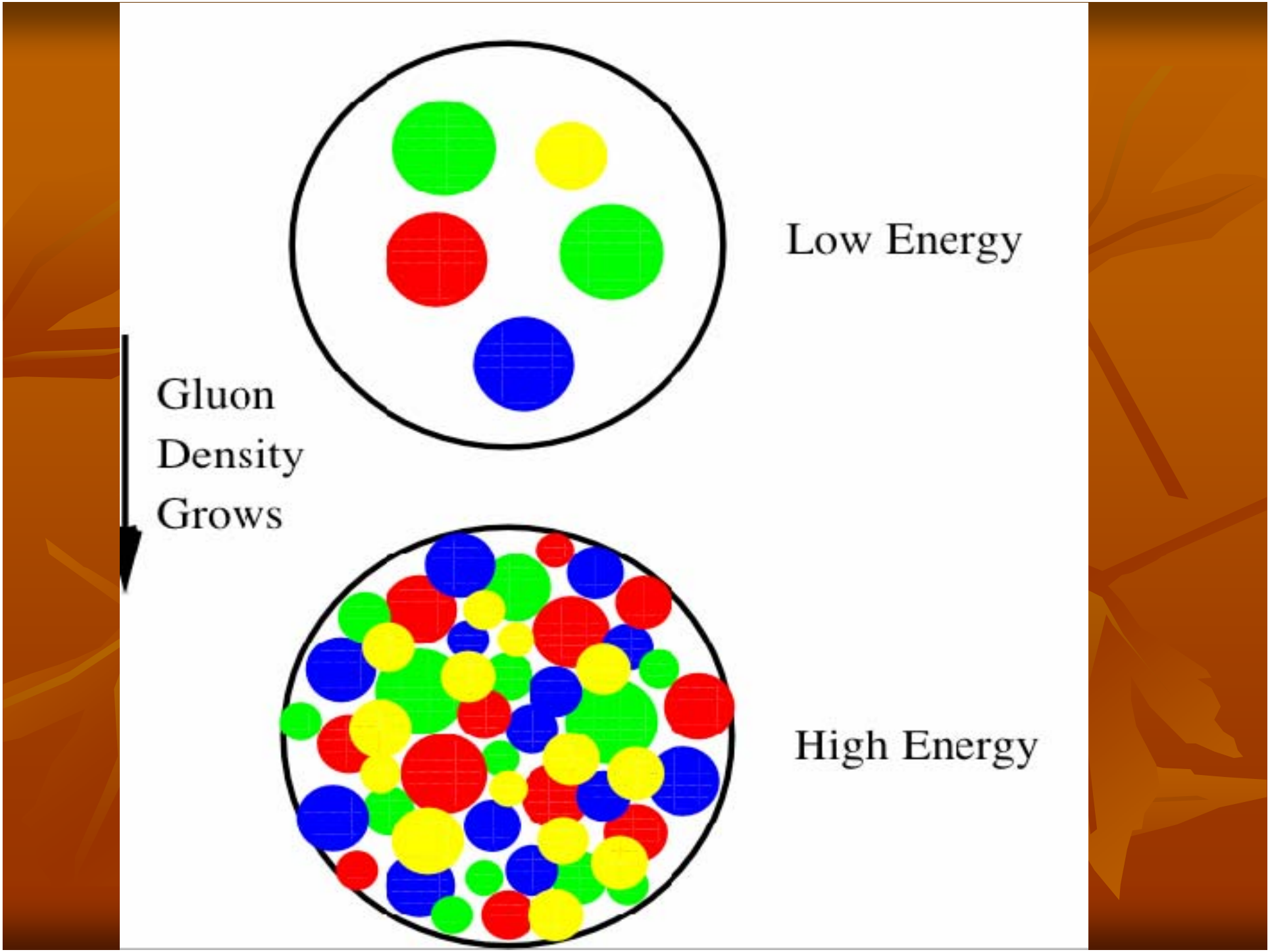
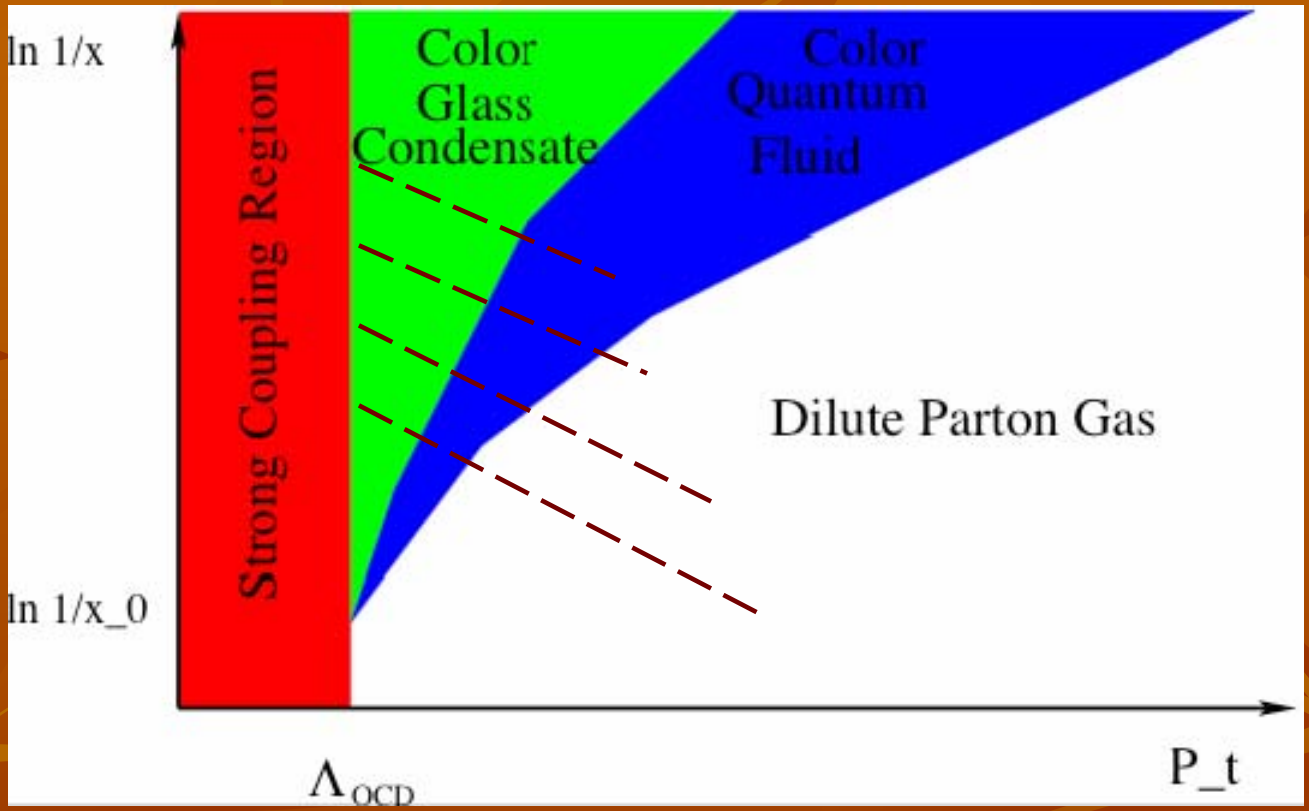

Low Energy
Gluon
Density
Grows
High Energy

Probing the CGC

- Deep Inelastic Scattering: ep(A) ---> eX
  - Structure functions: F_2, F_L
  - Particle production
- Nucleus - Nucleus Collisions
  - Initial conditions, multiplicities, CGC + ….
- Proton - Nucleus Collisions
  - Multiplicities
  - Single Particle production
    - Hadrons, dileptons, photons
  - Two particle production
    - Hadron + photon
    - Hadron + hadron

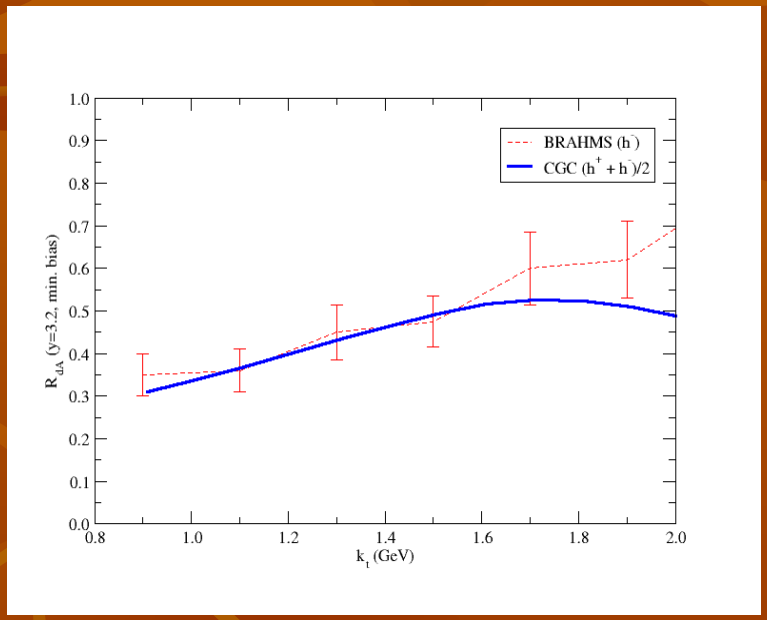
Color Glass Condensate

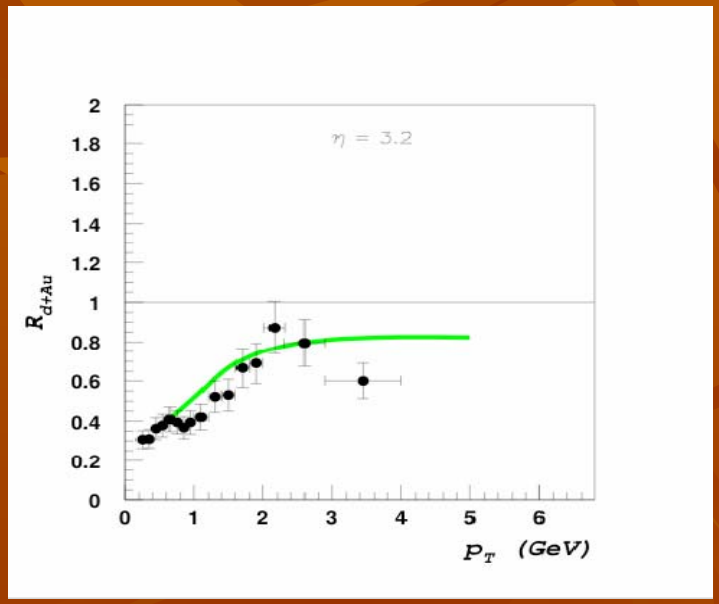


- DPG: high p_t, leading twist, DLA DGLAP
- CQF: anomalous dimension, leading twist, BFKL
- CGC: saturation region, all twist, JIMWLK

Particle production in pA: hadrons

- **Forward rapidity at RHIC: phase space in x_{bj} opens up**
  - Small x_{bj} gluons in nuclei: $x_{bj} < 0.01$
  - Large x_{bj} quarks and gluons in deuteron: $x_{bj} \sim 0.1$





JJM: Nucl-th/0402080

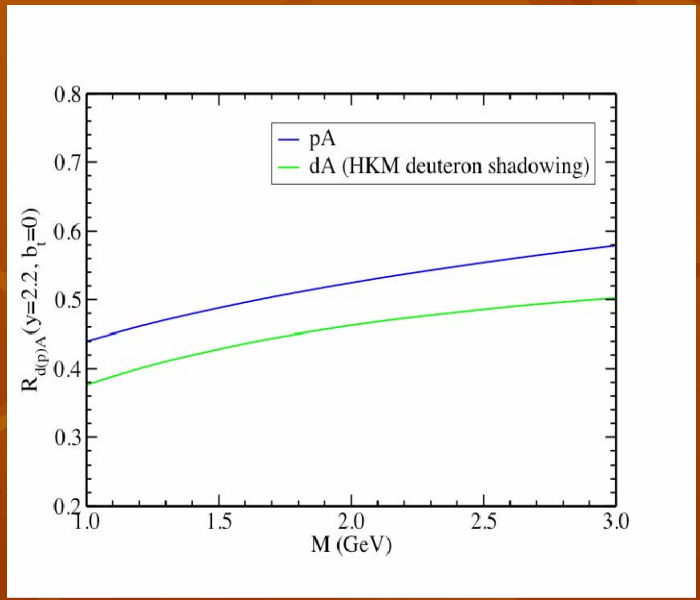
$$\frac{1}{N_c} Tr < 1 - V(x_t)\, V^\dagger(y_t) >$$

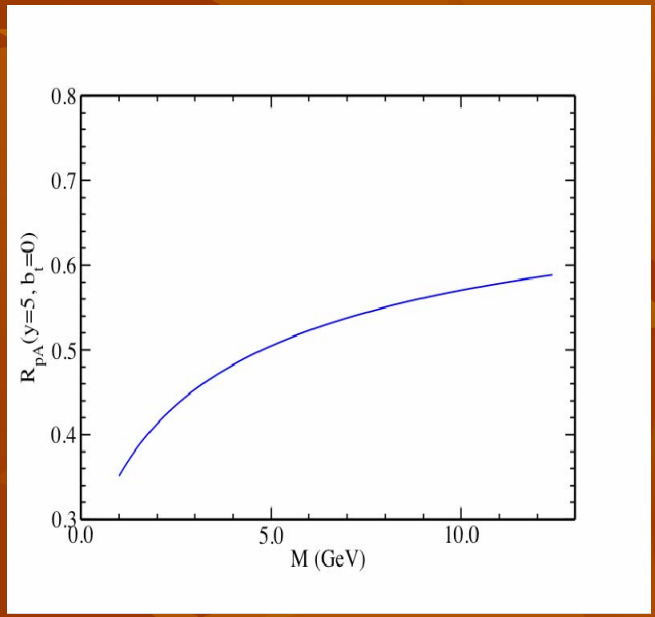
KKT: hep-ph/0405045

$$\frac{1}{N_c^2 - 1} Tr < 1 - U(x_t)\, U^\dagger(y_t) >$$

Particle production in pA

- Electromagnetic probes of CGC: cleaner
  - Photons
  - Dileptons: M is an additional knob
  - Recombination?



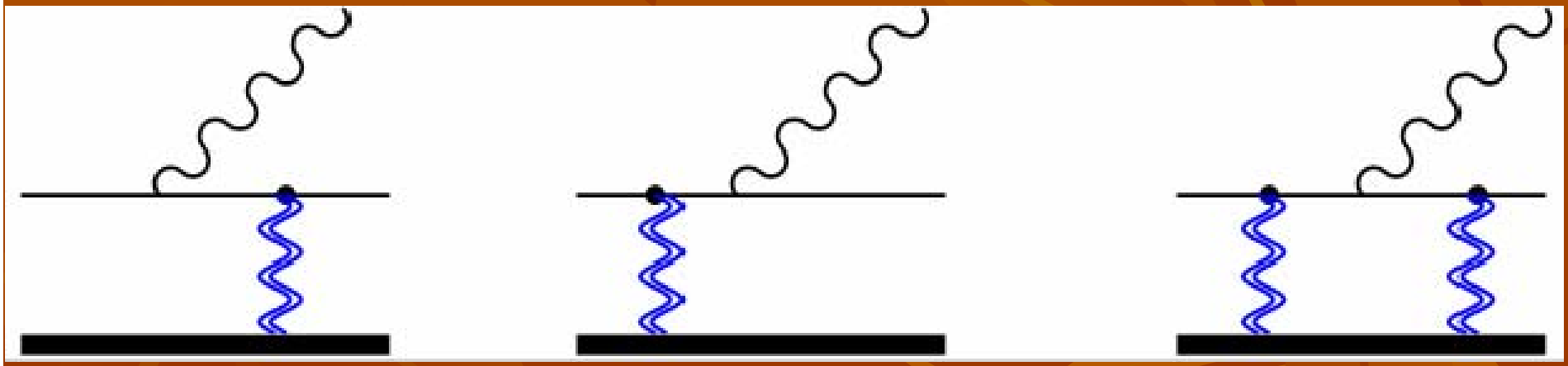


$$\frac{1}{N_c} Tr < 1 - V(x_t)\, V^{\dagger}(y_t) >$$

FG + JJM: PRD66 (2002) 014021
JJM, NPA379 (2004) 319

Two Particle Production in pA

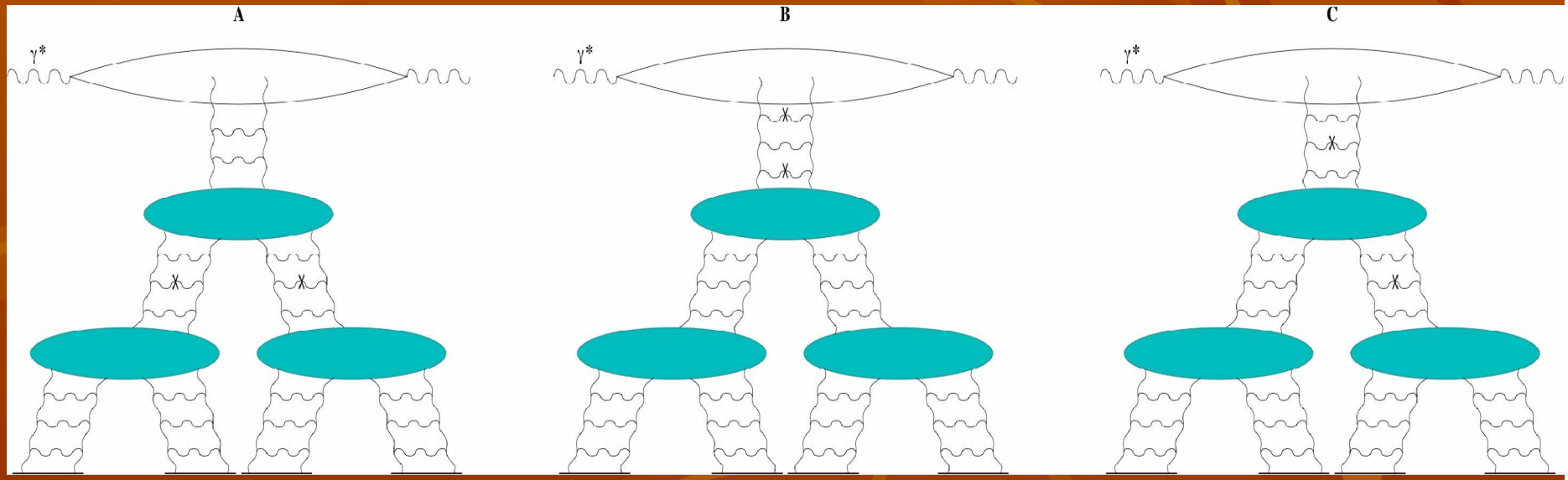
- Photon + hadron
  - Direct probe of the dipole cross section
  - Background for energy loss in AA



FG + JJM: PRD66 (2002) 014021

Two Gluon Production in DIS

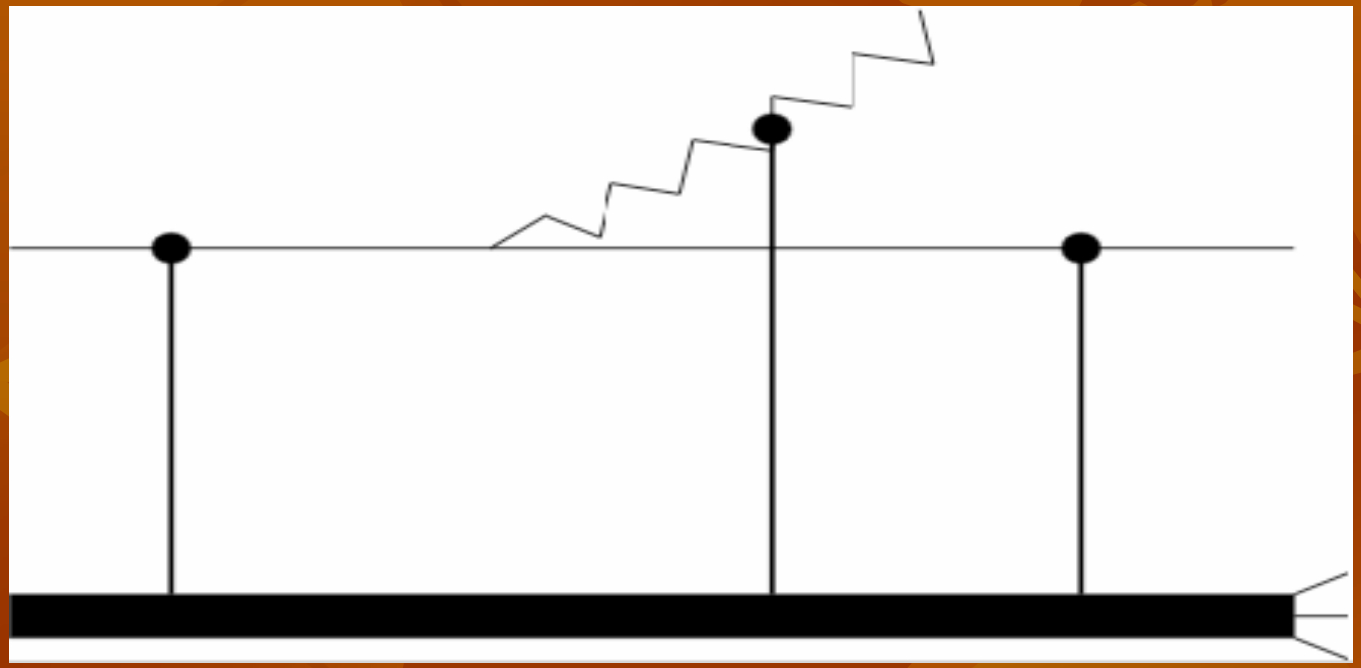
- Two gluon production
  - Classical
  - Quantum
- Violation of k_t factorization
- Breakdown of fan diagrams + AGK approach!!



JJM + YK: hep-ph/0405266

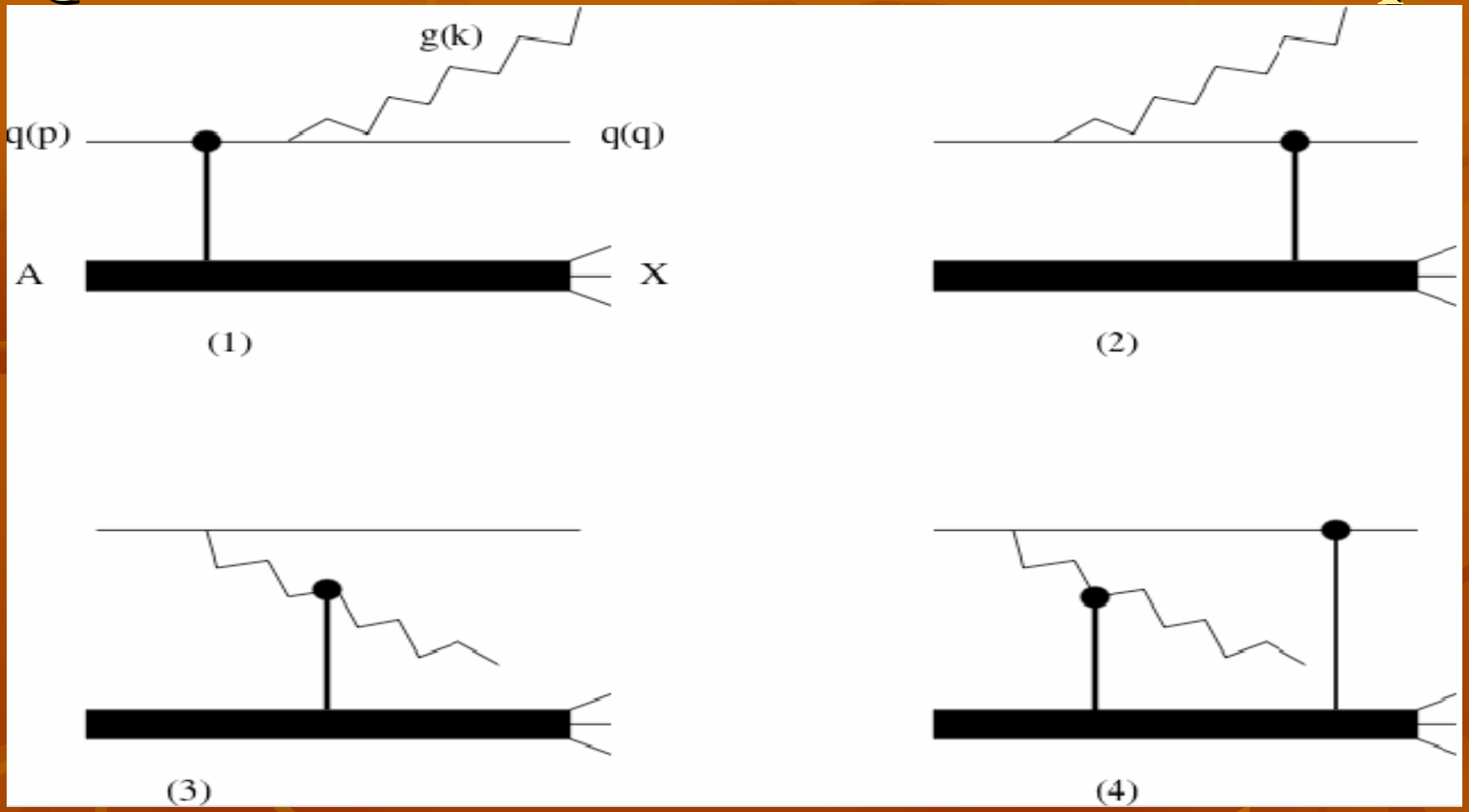
Two particle production in pA

- Two hadron production in the forward region
  - Quark + gluon



JJM + YK: hep-ph/0405266

Quark and Gluon Production in pA



Quark and Gluon Production in pA

Quark and gluon propagators

$$S_F(q,p) \equiv (2\pi)^4\delta^4(p-q)\,S_F^0(p) + S_F^0(q)\,\tau_f(q,p)\,S_F^0(p)$$

$$G^{\mu\nu}(q,p) \equiv (2\pi)^4\delta^4(p-q)\,G^{0\mu\nu}(p) + G_\rho^{0\mu}(q)\,\tau_g(q,p)\,G^{0\rho\nu}(p)$$

$$\tau_f(q,p) \equiv (2\pi)\delta(p^- - q^-)\,\gamma^- \int d^2x_t\, e^{i(q_t-p_t)\cdot x_t}\,[V(x_t)-1]$$

$$\tau_g(q,p) \equiv 2p^-\,(2\pi)\delta(p^- - q^-) \int d^2x_t\, e^{i(q_t-p_t)\cdot x_t}\,[U(x_t)-1]$$

Quark and Gluon Production in pA

$$M_1^a = -ig\frac{1}{2q\cdot k}\bar{u}(q)\not{\epsilon}(\not{q}+\not{k})\gamma^- u(p)\,t^a\,[V(q_t+k_t)-(2\pi)^2\delta^2(q_t+k_t)]$$

$$M_2^a = ig\frac{1}{2p\cdot k}\bar{u}(q)\gamma^-(\not{p}-\not{k})\not{\epsilon}\,u(p)\,[V(q_t+k_t)-(2\pi)^2\delta^2(q_t+k_t)]\,t^a$$

$$M_3^a = ig\frac{k^-}{p\cdot q}\bar{u}(q)\gamma_\nu u(p)\,d^{\nu\mu}(p-q)\,\epsilon_\mu(k)\,t^b\,[U^{ba}(q_t+k_t)-\delta^{ba}(2\pi)^2\delta^2(q_t+k_t)]$$

$$M_4^a = ig\frac{k^-}{p^-}\int\frac{d^2l_t}{(2\pi)^2}\bar{u}(q)\gamma^-(\not{p}-\not{l})\gamma_\nu u(p)\,\frac{d^{\nu\mu}(l)}{l_t^2}\,\epsilon_\mu(k)$$
$$[V(q_t+l_t)-(2\pi)^2\delta^2(q_t+l_t)]t^b[U^{ba}(k_t-l_t)-\delta^{ba}(2\pi)^2\delta^2(k_t-l_t)]$$

with

$$d^{\mu\nu}(k) \equiv -i\,k^2\,G_0^{\mu\nu}(k)$$

$$G^0_{\mu\nu}(k) = \frac{i}{k^2}\left[-g_{\mu\nu}+\frac{\eta_\mu k_\nu+\eta_\nu k_\mu}{\eta\cdot k}\right]$$

$$V(x_t) \equiv \hat{P}\,e^{ig\int dx^-\,A_a^+(x_t,x^-)\,t_a}$$

$$U(x_t) \equiv \hat{P}\,e^{ig\int dx^-\,A_a^+(x_t,x^-)\,T_a}$$

Quark and Gluon Production in pA

$$
\begin{aligned}
|M_1+M_2|^2 &= 16p^-p^-\left\{\frac{z(1-z)^2}{[zk_t-(1-z)q_t]^2}\right. \\
Tr[V^\dagger(q_t &+ k_t)-(2\pi)^2\delta^2(q_t+k_t)]t^a\,t^a[V(q_t+k_t)-(2\pi)^2\delta^2(q_t+k_t)] \\
+\frac{z(1-z)^2}{k_t^2}\,Tr[V(q_t &+ k_t)-(2\pi)^2\delta^2(q_t+k_t)]t^a\,t^a[V^\dagger(q_t+k_t)-(2\pi)^2\delta^2(q_t+k_t)] \\
+\left[(1-z)^2(1 &+ z^2)\frac{q_t^2}{k_t^2[zk_t-(1-z)q_t]^2}+\frac{z^2(1-z^2)}{[zk_t-(1-z)q_t]^2}-\frac{1-z^2}{k_t^2}\right] \\
Tr\,t^a[V^\dagger(q_t &+ k_t)-(2\pi)^2\delta^2(q_t+k_t)]t^a[V(q_t+k_t)-(2\pi)^2\delta^2(q_t+k_t)]\Big\} \\
&+ 32\,p^-p^-z^2(1-z)\left[[V^\dagger(q_t+k_t)-(2\pi)^2\delta^2(q_t+k_t)],t^a\right] \\
\left[\frac{1}{[zk_t-(1-z)q_t]^2}t^a[V(q_t\right. &+ k_t)-(2\pi)^2\delta^2(q_t+k_t)]-\frac{1}{k_t^2}[V(q_t+k_t)-(2\pi)^2\delta^2(q_t+k_t)]t^a
\end{aligned}
$$

Quark and Gluon Production in pA

$$
\begin{aligned}
|M_3^\dagger M_1| &= 16\,p^- p^-\, z(1+z^2)\frac{q_t^2 - z q_t\cdot(q_t+k_t)}{q_t^2[zk_t-(1-z)q_t]^2} \\
&\quad [U^{\dagger ab}(q_t+k_t) - \delta^{ab}(2\pi)^2\delta^2(q_t+k_t)] \\
&\quad Tr\, t^b\, t^a [V(q_t+k_t) - (2\pi)^2\delta^2(q_t+k_t)] \\
|M_3^\dagger M_2| &= 16\,p^- p^- z(1+z^2)\frac{q_t\cdot k_t}{q_t^2 k_t^2} \\
&\quad [U^{\dagger ab}(q_t+k_t) - \delta^{ab}(2\pi)^2\delta^2(q_t+k_t)] \\
&\quad Tr\, t^b [V(q_t+k_t) - (2\pi)^2\delta^2(q_t+k_t)]\, t^a \\
|M_3|^2 &= 16 p^- p^- \frac{z(1+z^2)}{q_t^2}[U^{\dagger ab}(q_t+k_t) - \delta^{ab}(2\pi)^2\delta^2(q_t+k_t)] \\
&\quad [U^{ca}(q_t+k_t) - \delta^{ca}(2\pi)^2\delta^2(q_t+k_t)] Tr\, t^b\, t^c \\
|M_3^\dagger M_4| &= -16\,p^- p^- z(1+z^2)\int \frac{d^2 l_t}{(2\pi)^2}\frac{q_t\cdot l_t}{q_t^2 l_t^2} \\
&\quad [U^{\dagger ab}(q_t+k_t) - \delta^{ab}(2\pi)^2\delta^2(q_t+k_t)] \\
&\quad [U^{ca}(k_t-l_t) - \delta^{ca}(2\pi)^2\delta^2(k_t-l_t)] \\
&\quad Tr\, t^b [V(q_t+l_t) - (2\pi)^2\delta^2(q_t+l_t)] t^c
\end{aligned}
$$

Quark and Gluon Production in pA

$$
\begin{aligned}
|M_4^\dagger M_1| &= -16p^-p^-z(1+z^2)\int \frac{d^2l_t}{(2\pi)^2}\frac{(1-z)q_t\cdot l_t - zk_t\cdot l_t}{l_t^2[zk_t-(1-z)q_t]^2} \\
&\quad [U^{\dagger ab}(k_t-l_t)-\delta^{ab}(2\pi)^2\delta^2(k_t-l_t)] \\
&\quad Tr\, t^b[V^\dagger(q_t+l_t)-(2\pi)^2\delta^2(q_t+l_t)] \\
&\quad t^a[V(q_t+k_t)-(2\pi)^2\delta^2(q_t+k_t)] \\
|M_4^\dagger M_2| &= -16p^-p^-(1+z^2)\int \frac{d^2l_t}{(2\pi)^2}\frac{(1-z)l_t^2+zk_t\cdot l_t}{l_t^2k_t^2} \\
&\quad [U^{\dagger ac}(k_t-l_t)-\delta^{ac}(2\pi)^2\delta^2(k_t-l_t)] \\
&\quad Tr\, t^c[V^\dagger(q_t+l_t)-(2\pi)^2\delta^2(q_t+l_t)] \\
&\quad [V(q_t+k_t)-(2\pi)^2\delta^2(q_t+k_t)]t^a \\
|M_4|^2 &= 16p^-p^-z(1+z^2)\int \frac{d^2l_t}{(2\pi)^2}\frac{d^2\bar{l}_t}{(2\pi)^2}\frac{l_t\cdot\bar{l}_t}{l_t^2\bar{l}_t^2} \\
&\quad [U^{\dagger ac}(k_t-\bar{l}_t)-\delta^{ac}(2\pi)^2\delta^2(k_t-\bar{l}_t)] \\
&\quad [U^{ab}(k_t-l_t)-\delta^{ab}(2\pi)^2\delta^2(k_t-l_t)] \\
&\quad Tr\, t^ct^b[V^\dagger(q_t+l_t)-(2\pi)^2\delta^2(q_t+l_t)] \\
&\quad [V(q_t+\bar{l}_t)-(2\pi)^2\delta^2(q_t+\bar{l}_t)]
\end{aligned}
$$

Two Hadron Production in pA

$$q^- \, k^- \frac{d\sigma^{qA\to qgX}}{d^3q\, d^3k} = \frac{1}{16p^-}\frac{1}{(2\pi)^6}(2\pi)\delta(p^- - q^- - k^-)\, g^2\, |M|^2$$

$$E_{h1}E_{h2}\frac{d\sigma^{pA\to h1\, h2\, X}}{d^3q_{h1}d^3k_{h2}} = q_p(x_q) \otimes q^- \, k^- \frac{d\sigma^{qA\to qgX}}{d^3q\, d^3k} \otimes D^{q,g}_{h1,h2}(z_1, z_2)$$

Mid rapidity RHIC:classical

Forward rapidity RHIC, LHC:quantum evolution

Evolution equation for product of V's, U's

(single inclusive production ~ two V's or U's)

Summary

- QCD at small x_{bj} ⟶ CGC
- CGC at RHIC
  - AA
    - Initial conditions, multiplicities
  - pA
    - Multiplicities
    - Single particle spectra
    - Two particle correlations