Quarkonium production and attenuation in high energy pA collisions

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1. Introduction
2. Quarkonium attenuation
3. Production w/ attenuation
4. Outlook

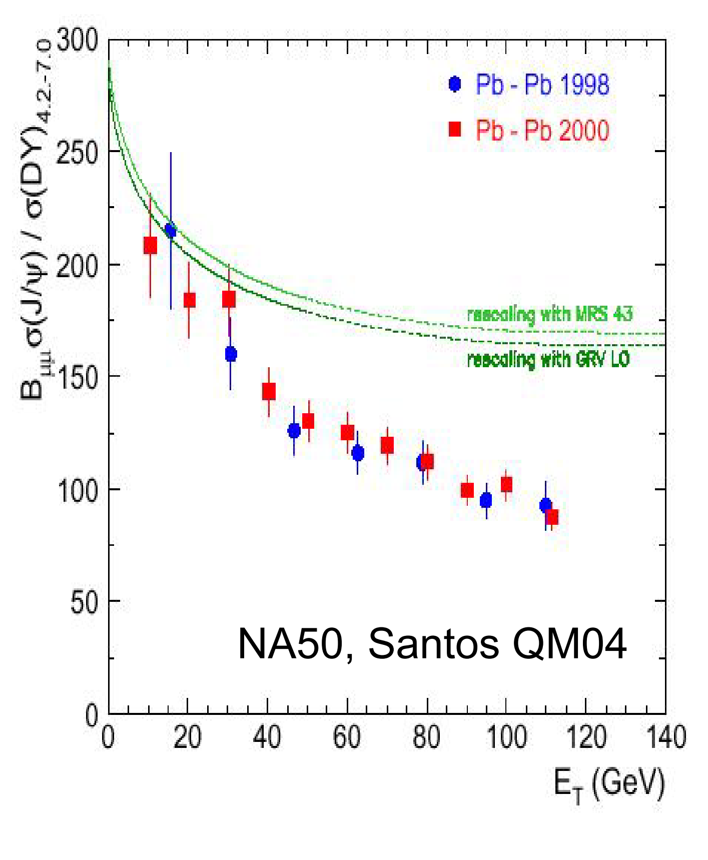
HF, T.Matsui, PLB545, NPA709
HF, F. Gelis, R. Venugopalan, work in progress

Motivations

- ***J/psi suppression*** (Matsui-Satz, 1986)
  - anomaly was found at CERN
  - on top of "Nuclear absorption"

$$\frac{\sigma_{\mathrm{AB}}}{AB\,\sigma_{pp}} = \exp(-\sigma_{\mathrm{abs}}\, n_0 L)$$

- **understood as independent Φ absorption by nucleons**



Motivations

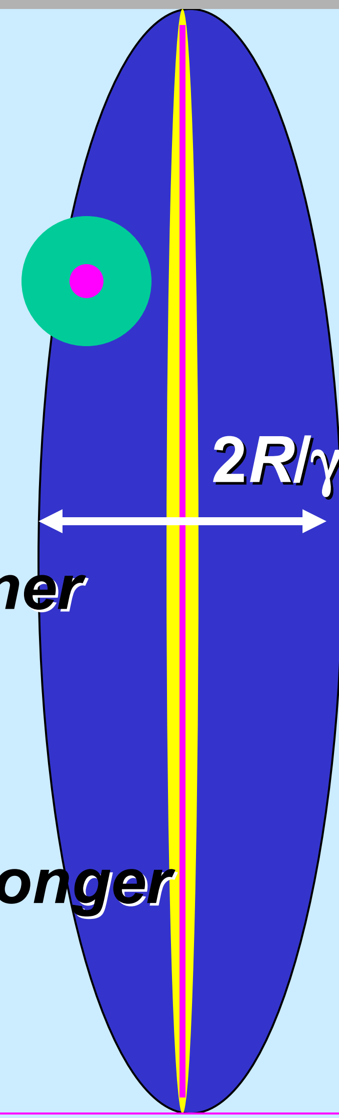
- ***J/psi suppression*** (Matsui-Satz, 1986)
  - anomaly was found at CERN
  - on top of "Nuclear absorption"
- ***Heavy quark production at high energy***
  - info on initial (nuclear) gluon distribution
  - particle production in nuclear medium

Scales in the problem

- ***heavy quark creation***
  - $\tau_p \sim 1/(2m_c) \sim 0.1$ fm
- ***quarkonium binding***
  - $\tau_c \sim 1/\Delta E \sim 1/(\alpha_s m_c) \sim 0.3$ fm
- ***nucleus*** $2R \sim 10$ fm, ***inter-nucleon*** ~ 2 fm

- ***in n-n CM frame, nucleus becomes thinner***
  - $2R/\gamma \sim 1$fm(SPS), 0.1fm(RHIC), 0.01fm(LHC)
  - NB wee partons ignored

- ***in A-rest frame, coherence length gets longer***
  - $\tau_c\gamma \sim 3$fm(SPS), 30fm(RHIC), 600fm(LHC)



Coherence becomes more important at higher energies

Attenuation of a pair bound state

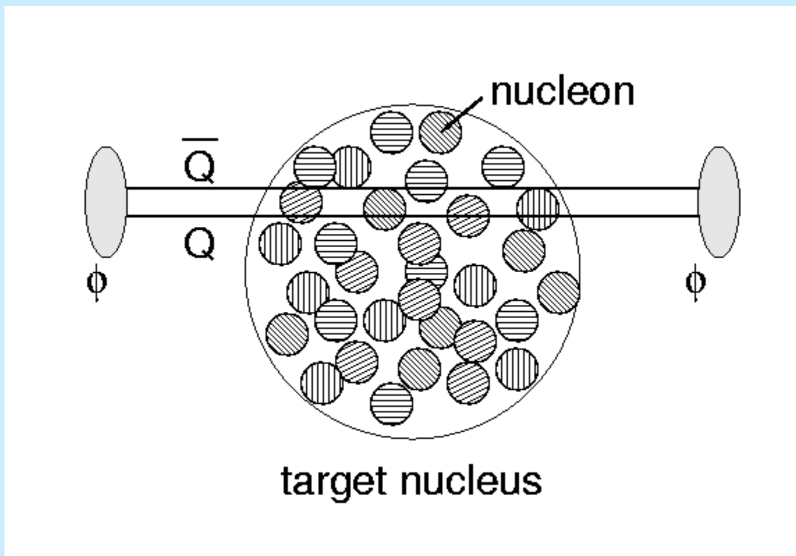
- **Simple model of coherent scattering effect**
  - **Non-abeian analog of 'superpenetration'**

HF, T. Matsui, '02

  - **Eikonal propagation of a bound quark-pair**

$$S = \langle \varphi_0 | \mathrm{Tr}[\widetilde{U}(\mathbf{r}_1)\, \widetilde{U}^+(\mathbf{r}_2)] | \varphi_0 \rangle$$

$$\widetilde{U}(\mathbf{r}) = \mathrm{P} e^{ig\int_{-\infty}^{\infty} dx^+ A^{a-}(\mathbf{r}) t^a}$$



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  - **Target; Random Gaussian gauge field**

$$\overline{A^a(\mathbf{x}, z_i) A^b(\mathbf{y}, z_j)} = \delta^{ab}\delta_{ij} C(\mathbf{x}-\mathbf{y}, z_i)$$

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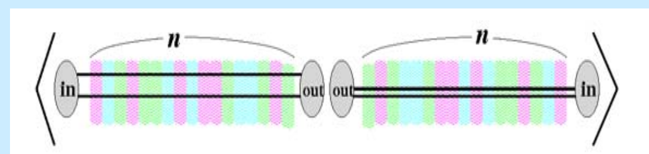
  - **Target; Random Gaussian gauge field**

$$\overline{A^a(\mathbf{x}, z_i) A^b(\mathbf{y}, z_j)} = \delta^{ab}\delta_{ij} L(\mathbf{x}-\mathbf{y}, z_i)$$

  - **Survival probability, roughly,**



$$\overline{|S|^2} \approx \int d\mathbf{r} d\mathbf{r}' \varphi_0{}^2(\mathbf{r}) \varphi_0{}^2(\mathbf{r}') \exp(-K(\mathbf{r},\mathbf{r}')L)$$

$$\approx \int d\mathbf{q} d\mathbf{q}'\, \widetilde{\varphi}_0{}^2(\mathbf{q}) \widetilde{\varphi}_0{}^2(\mathbf{q}') \Phi(\mathbf{q},\mathbf{q}')$$

Attenuation of a pair bound state

- **Simple model of coherent scattering effect**
  - **Non-abeian analog of ‘superpenetration’**
  - **Survival probability, asymptotically**

$$\exp[-K(\mathbf{r},\mathbf{r}')L] \rightarrow \begin{cases} 1-K(\mathbf{r},\mathbf{r}')L & \text{small } L \\ a\delta(\mathbf{r}-\mathbf{r}')/L & \text{large } L \end{cases}$$

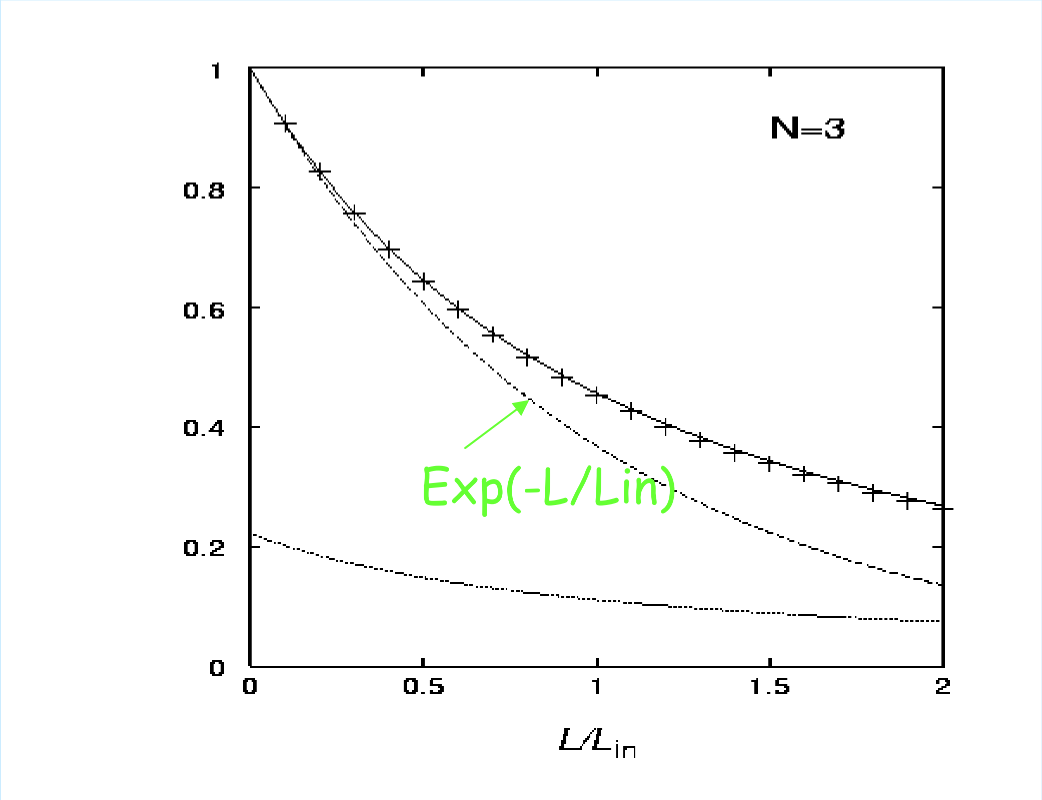
$$\overline{|S|^2} \approx \int d\mathbf{r}d\mathbf{r}'\varphi_0{}^2(\mathbf{r})\varphi_0{}^2(\mathbf{r}')\exp[-K(\mathbf{r},\mathbf{r}')L]$$

$$\rightarrow \begin{cases} 1-L/L_{\text{in}} \approx \exp(-L/L_{\text{in}}) \\ \text{const}/L \end{cases}$$

Attenuation of a pair bound state

- **Simple model of coherent scattering effect**
  - **Non-abeian analog of 'superpenetration'**

  - **Coherent scattering results in**
    non-exp, power-law suppression

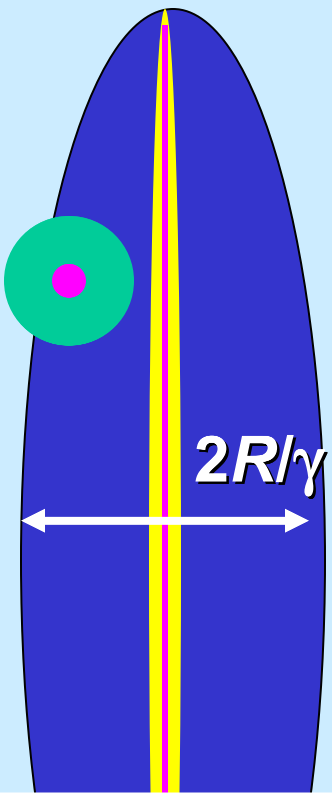


Production: pair mom modified

- **$1/2m_c \ll 2R/\gamma < 1/\Delta E$ case**

  - produced pair is scattered within the target before resonance formation
  - rescattering changes pair momentum

Qiu-Vary-Zhang, PRL '02



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$$\sigma_{AB\to J/\psi X} = K_{J/\psi} \sum_{a,b} \int dq^2 \left(\frac{\hat{\sigma}_{ab\to c\bar{c}}(Q^2)}{Q^2} \right) \times \int dx_F \phi_{a/A}(x_a) \phi_{b/B}(x_b) \frac{x_a x_b}{x_a + x_b} F_{c\bar{c}\to J/\psi}(q^2)$$

Formation probability w/ threshold (cf. color evaporation model)

$$F_{c\bar{c}\to J/\psi}(\bar{q}^2) = F_{c\bar{c}\to J/\psi}(q^2 + \varepsilon^2 L)$$

sums leading *A*-enhanced terms

NB. For a certain L, $\varepsilon^2 L > M_{th}^2$

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$$\bar{F}_{c\bar{c}\to J/\psi}(q^2) \equiv \frac{1}{(2\pi\varepsilon^2 L)^{3/2}} \int d^3q' e^{-\frac{(q'-q)^2}{2\varepsilon^2 L}} F_{c\bar{c}\to J/\psi}(q'^2)$$

smears mom dist

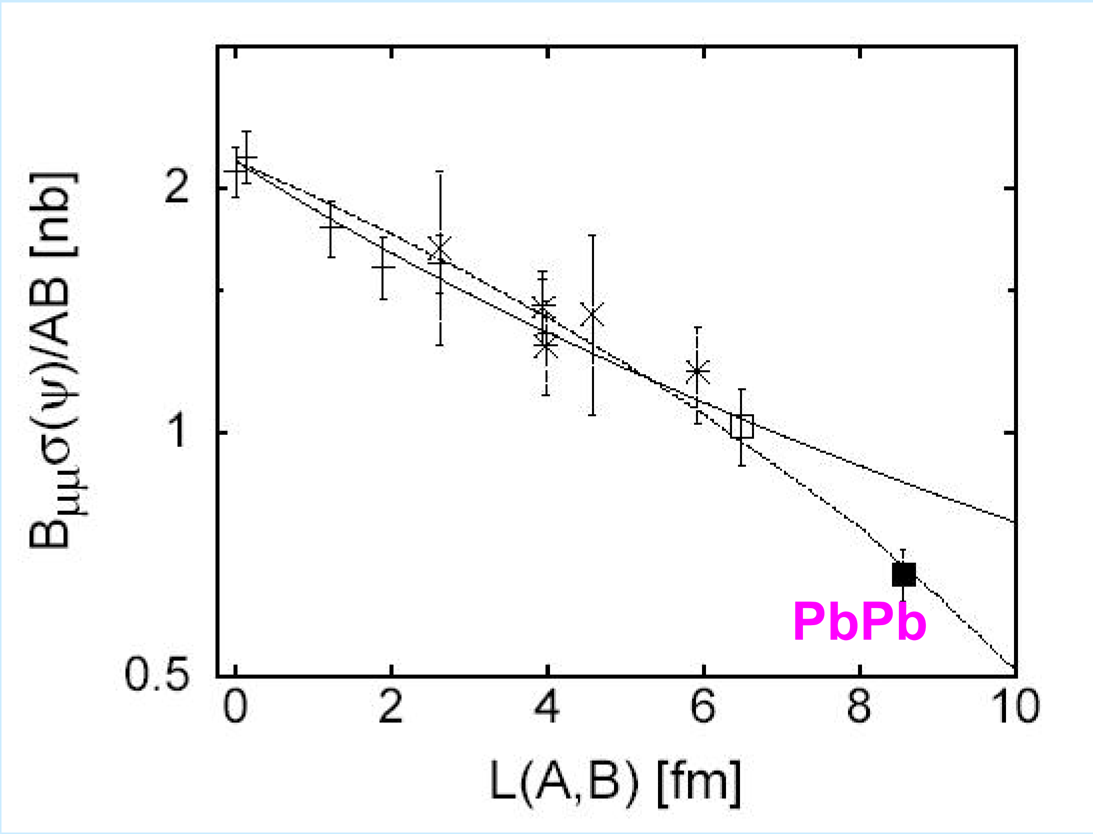
HF, '03

→ ***different behavior at large L***

higher order terms need to be studied

Production: pair mom modified

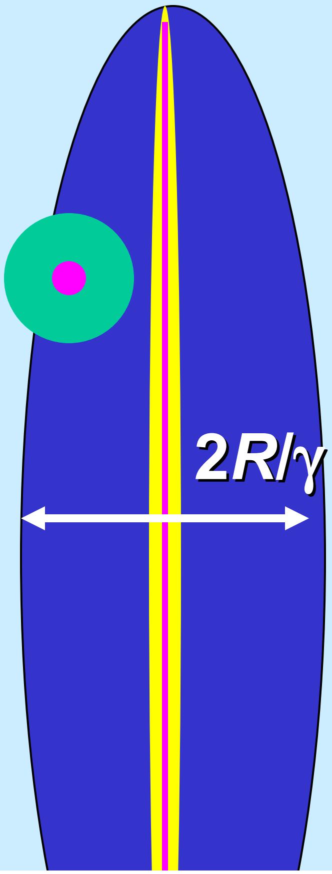
- **$1/2m_c << 2R/\gamma < 1/\Delta E$ case**
  - applied to AA collision by adjusting '*L*'



Production: the MV model

- **$2R/\gamma$ <~ $1/2m_c$ case**

  - all nucleons along the path acts on simultaneously in heavy quark production



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  - in the MV model, ‘wee’ partons (~ classical fields) of nucleus interact and create hadrons

  - quark production in classical field

  - known analytically to $O(\rho_p \rho_A^{infty})$ in Lorentz gauge

Blaizot-Gelis-Venugopalan, ’04

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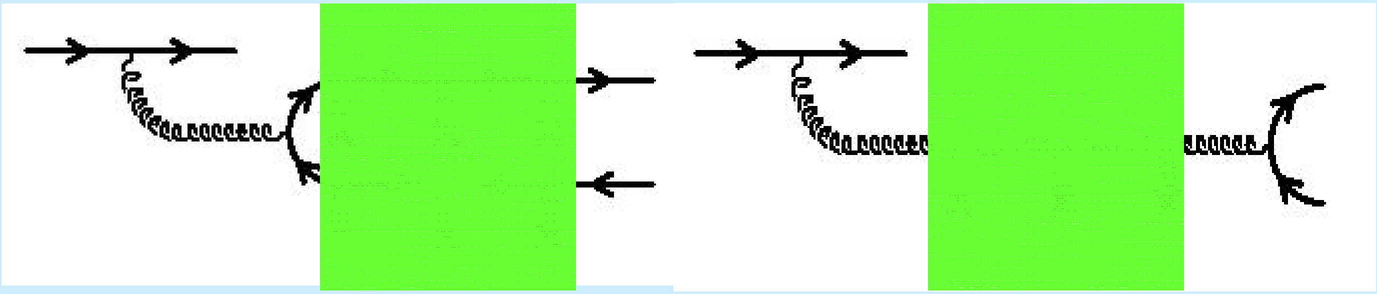
Schematically



Production: the MV model

- **Quark pair production cross section**
  - kT kick on the quarks during production breaks kT factorization

Blaizot-Gelis-Venugopalan, '04

$$\frac{d\sigma}{d^2\boldsymbol{p}_\perp d^2\boldsymbol{q}_\perp dy_p dy_q} = \frac{\alpha_s^2 N}{8\pi^4 d_A} \int_{\boldsymbol{k}_{1\perp},\boldsymbol{k}_{2\perp}} \frac{\delta(\boldsymbol{p}_\perp + \boldsymbol{q}_\perp - \boldsymbol{k}_{1\perp} - \boldsymbol{k}_{2\perp})}{\boldsymbol{k}_{1\perp}^2 \boldsymbol{k}_{2\perp}^2}$$

$$\times \Big\{ \int_{\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp} \mathrm{tr_d}\Big[(\not{q}+m)T_{q\bar{q}}(\not{p}-m)\gamma^0 T'^{\dagger}_{q\bar{q}}\gamma^0\Big] \underline{\varphi_A^{q\bar{q},q\bar{q}}(\boldsymbol{k}_\perp, \boldsymbol{k}_{2\perp}-\boldsymbol{k}_\perp; \boldsymbol{k}'_\perp, \boldsymbol{k}_{2\perp}-\boldsymbol{k}'_\perp)}$$

$$+ \int_{\boldsymbol{k}_\perp} \mathrm{tr_d}\Big[(\not{q}+m)T_{q\bar{q}}(\not{p}-m)\gamma^0 T^{\dagger}_{g}\gamma^0\Big] \underline{\varphi_A^{q\bar{q},g}(\boldsymbol{k}_\perp, \boldsymbol{k}_{2\perp}-\boldsymbol{k}_\perp; \boldsymbol{k}_{2\perp})}$$

$$+ \int_{\boldsymbol{k}_\perp} \mathrm{tr_d}\Big[(\not{q}+m)T_{g}(\not{p}-m)\gamma^0 T^{\dagger}_{q\bar{q}}\gamma^0\Big] \underline{\varphi_A^{q\bar{q},g}(\boldsymbol{k}_\perp, \boldsymbol{k}_{2\perp}-\boldsymbol{k}_\perp; \boldsymbol{k}_{2\perp})}$$

$$+ \mathrm{tr_d}\Big[(\not{q}+m)T_{g}(\not{p}-m)\gamma^0 T^{\dagger}_{g}\gamma^0\Big] \varphi_A^{g,g}(\boldsymbol{k}_{2\perp}) \Big\} \varphi_p(\boldsymbol{k}_{1\perp})$$

Production: the MV model

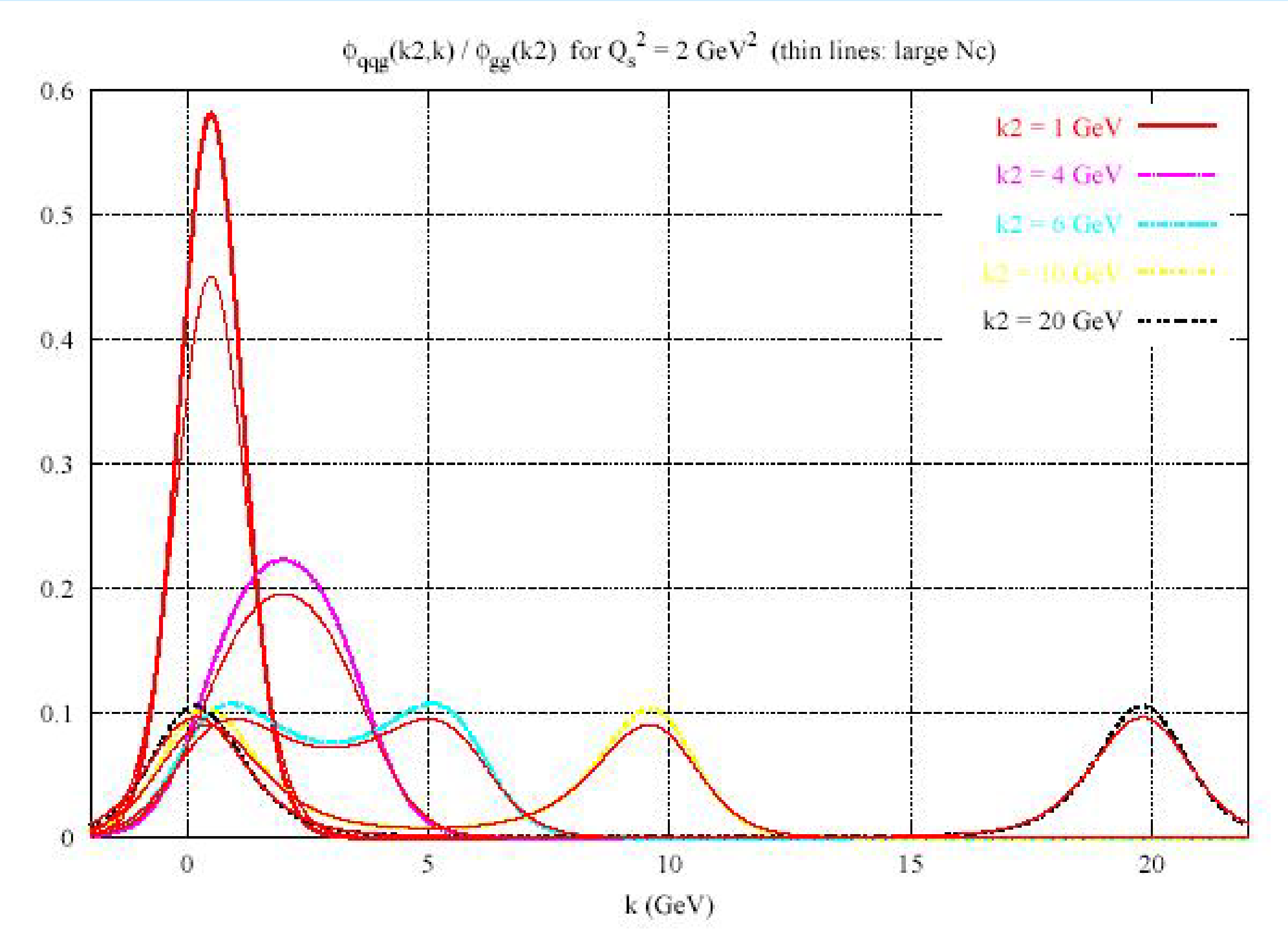
- **large Nc limit for nucleus (collinear form for proton)**
  - 4-, 3-point funcs reduce to a product of 2-point function, *C*
  - *C* expresses Glauber's multiple scattering of each quark

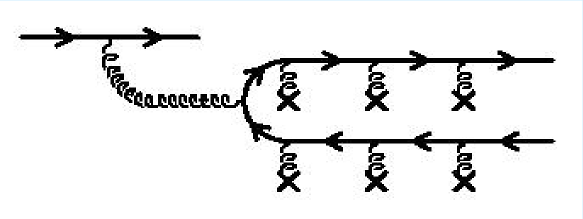
$$\frac{d\sigma}{d^2\mathbf{p}_\perp d^2\mathbf{q}_\perp dy_p dy_q} = \frac{\alpha_s^2 N}{8\pi^4 d_A}\,\pi R^2\,\frac{N}{4\alpha_s} G_p$$
$$\times\Big\{\int_{\mathbf{k}_\perp}\left[\Sigma^{q\bar{q};q\bar{q}}(\mathbf{k}_\perp,\mathbf{k}_\perp;\mathbf{q}_\perp,\mathbf{p}_\perp) + 2\Sigma^{q\bar{q};g}(\mathbf{k}_\perp;\mathbf{q}_\perp,\mathbf{p}_\perp)\right]\ C(\mathbf{k}_\perp;\frac{\mu_A^2}{2})C(\mathbf{p}_\perp+\mathbf{q}_\perp-\mathbf{k}_\perp;\frac{\mu_A^2}{2})$$
$$+\Sigma^{g;g}(\mathbf{q}_\perp,\mathbf{p}_\perp)\ C(\mathbf{p}_\perp+\mathbf{q}_\perp;\mu_A^2)\Big\}$$

- **Implications to quarkonium**
  - kT kicks on quarks smear out the relative pair mom distribution
  - naturally change the formation of the bound state

Production: the MV model

3-point function, ϕ_{qqg}





Outlook

- High energy quarkonium, scattering coherently with nuclear target, attenuates by power-law falling
- In pA colls at RHIC energy or higher, coherent interaction becomes important even for charm quark production, which also will modify quarkonium production rate.
- The MV model will provide a natural framework to study this problem.
- study both of quarkonium and heavy quarks will be interesting and on-going.