Cold Nuclear Effects on Quarkonium Production

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Based on works done with Z.-B. Kang, G. Sterman, P. Sun, J.P. Vary, B.W. Xiao, F. Yuan, X.F. Zhang, …

The 10th International Workshop on Quarkonium Physics (Quarkonium 2014)
CERN, Switzerland, November 10-15, 2014

Outline

- Introduction – heavy quarkonium production

- Nuclear modification for quarkonium production in p+A:

  - Total production rate
  - P_T – spectrum
  - x_F (or y) distribution

- Heavy quarkonium production in polarized p+A collisions

  - Complimentary probe for small-x physics (no time for it)

See Venugopalan's talk on Monday

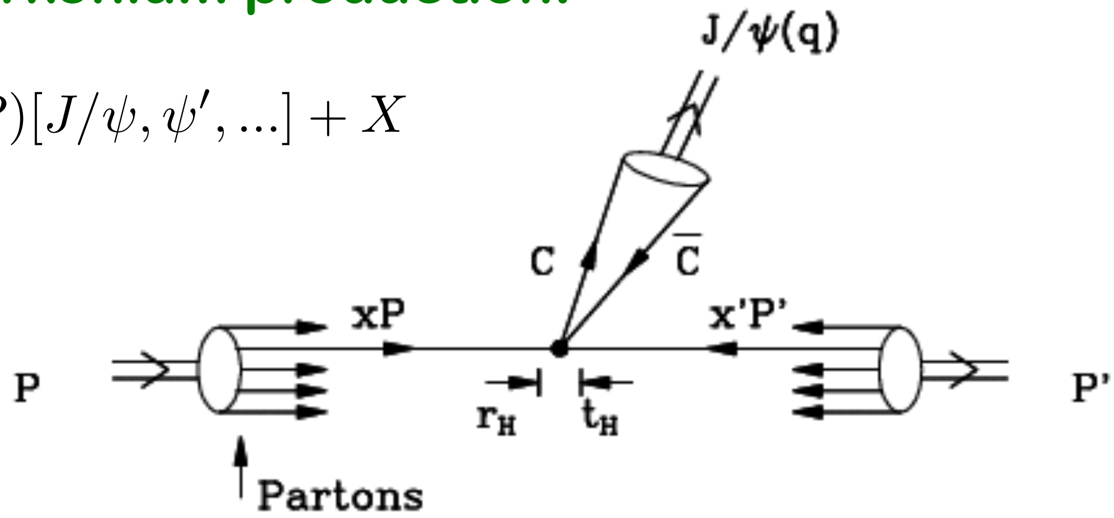
- Summary and outlook

Heavy quarkonium production

❑ **Hadronic heavy quarkonium production:**

$$A(P_1) + B(P_2) \to H(P)[J/\psi, \psi', ...] + X$$

❑ **Partonic picture:**



❑ **Momentum exchange:** $> 2m_c \sim 3.1 \text{ GeV}$

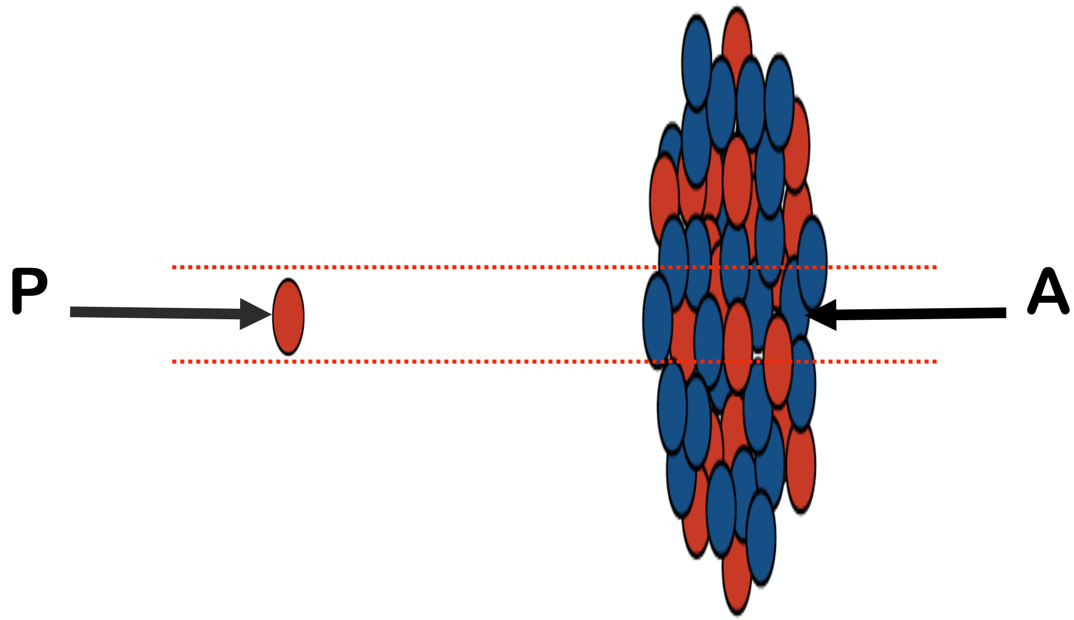
❑ **J/ψ is unlikely to be formed at:** $r_H \leq \frac{1}{2m_c} \sim \frac{1}{15} \text{ fm}$

Production of a heavy quark pair is likely to be perturbative!

It is likely the heavy quarks, not quarkonia that interact with the medium

Heavy quarkonium in p(d)+A collisions

❑ Proton (deuteron) – Nucleus Collisions:



✧ NO QGP (m_Q >> T)! ➡ Cold nuclear effect for the "production"

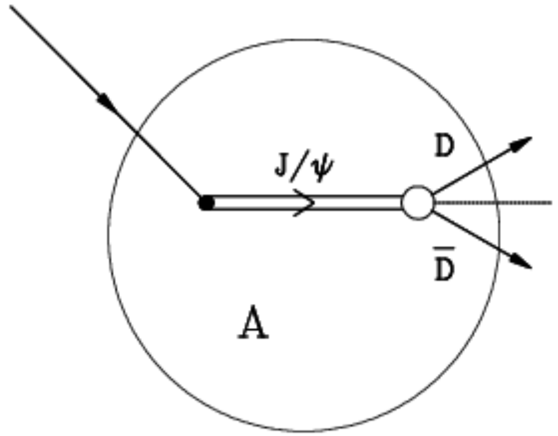
✧ Necessary calibration for AA collisions

✧ Hard probe (m_Q >> 1/fm) ➡ quark-gluon structure of nucleus!

Nucleus is not a simple superposition of nucleons!

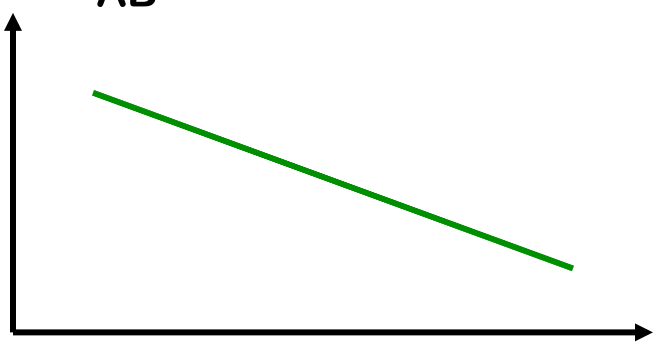
Production in p+A collisions

- If J/ψ were produced at the collision point:
  - Nuclear effect in PDFs
  - Medium dependence from J/ψ-nucleon absorption



- Glauber model:

$$\sigma_{AB} \approx AB\sigma_{NN} e^{-\rho_0 \sigma_{\rm abs}^{J/\psi} L_{AB}}$$



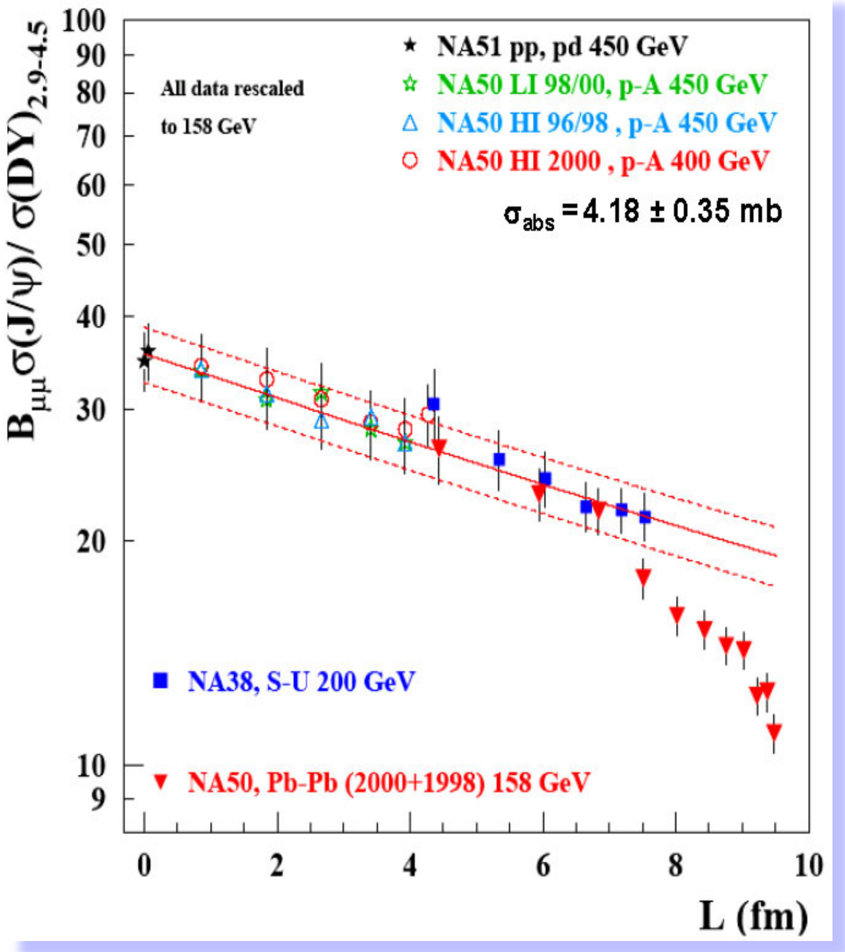
- Expect a straight line on a semi-log plot

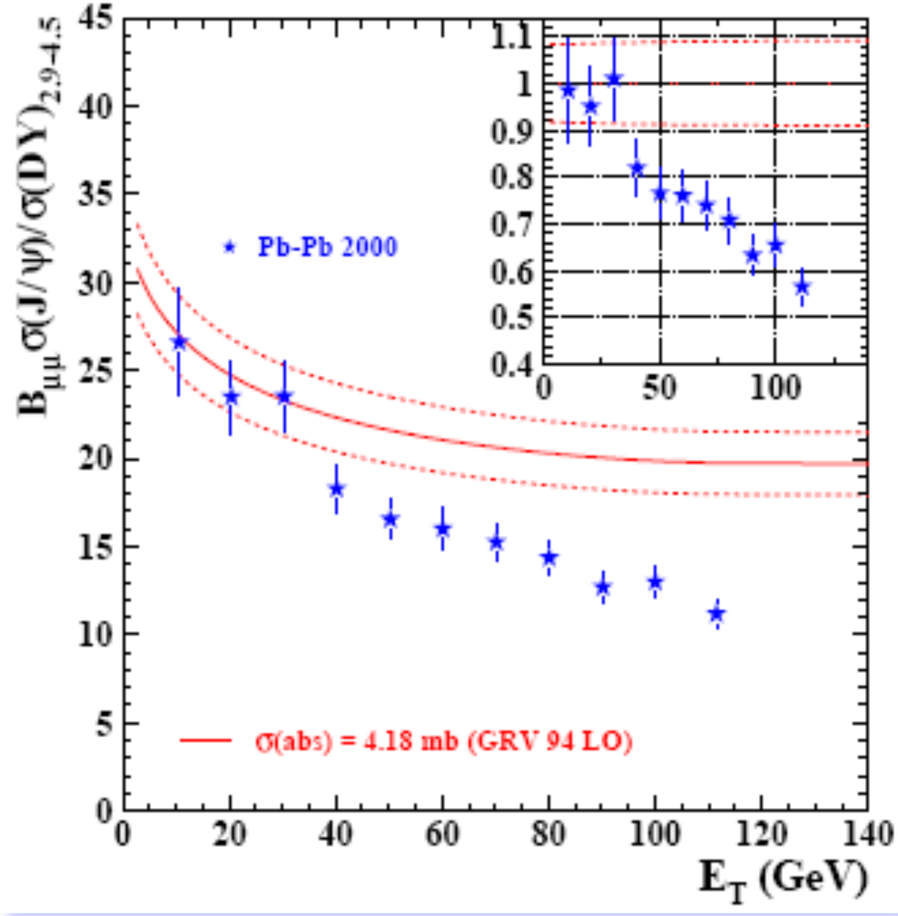
- Need a much too larger σ_{abs} to fit the data

Suppression in total production rate

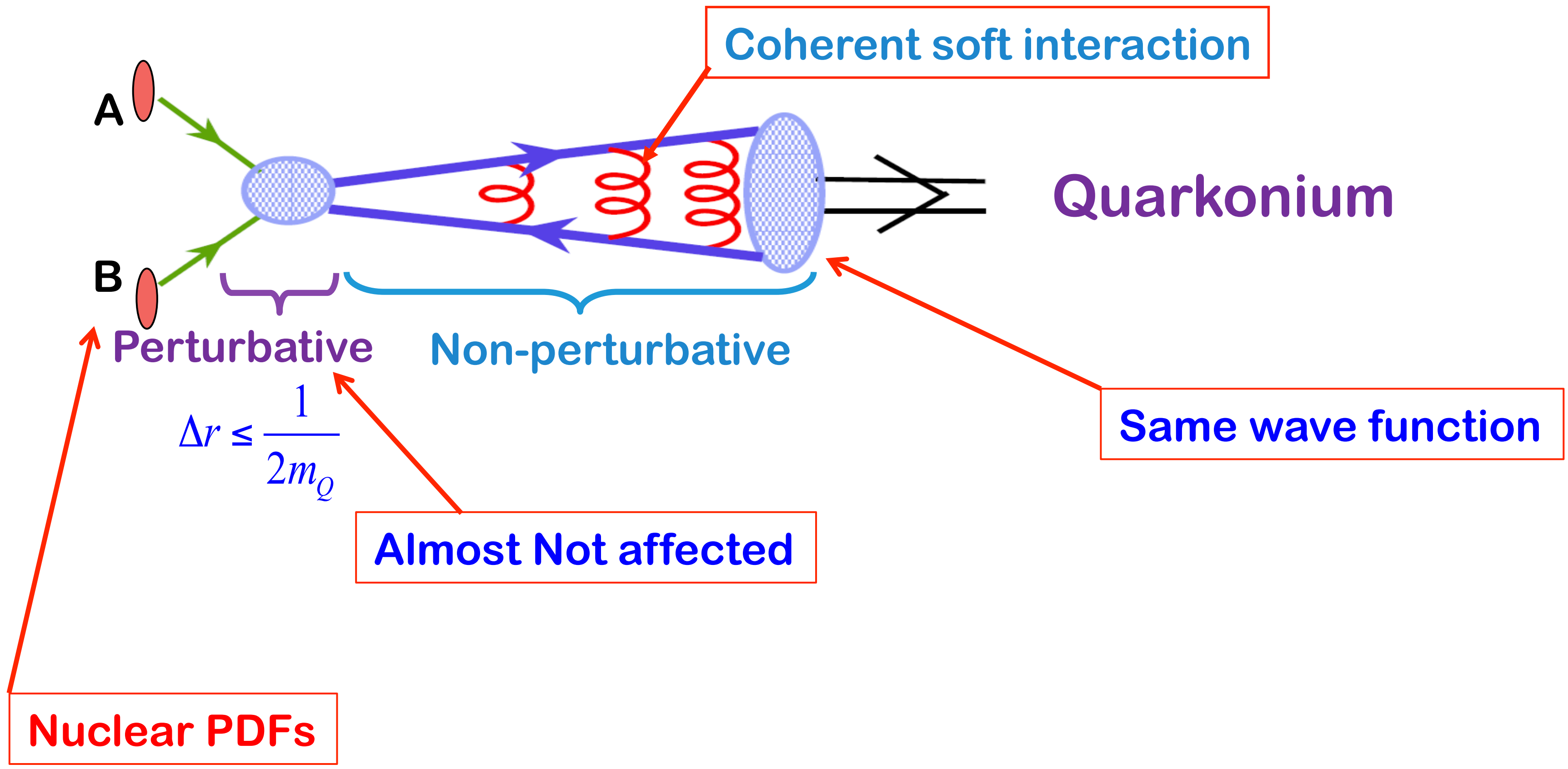
- **Anomalous suppression:**

  Not a straight line on the semi-log plots – additional suppression!

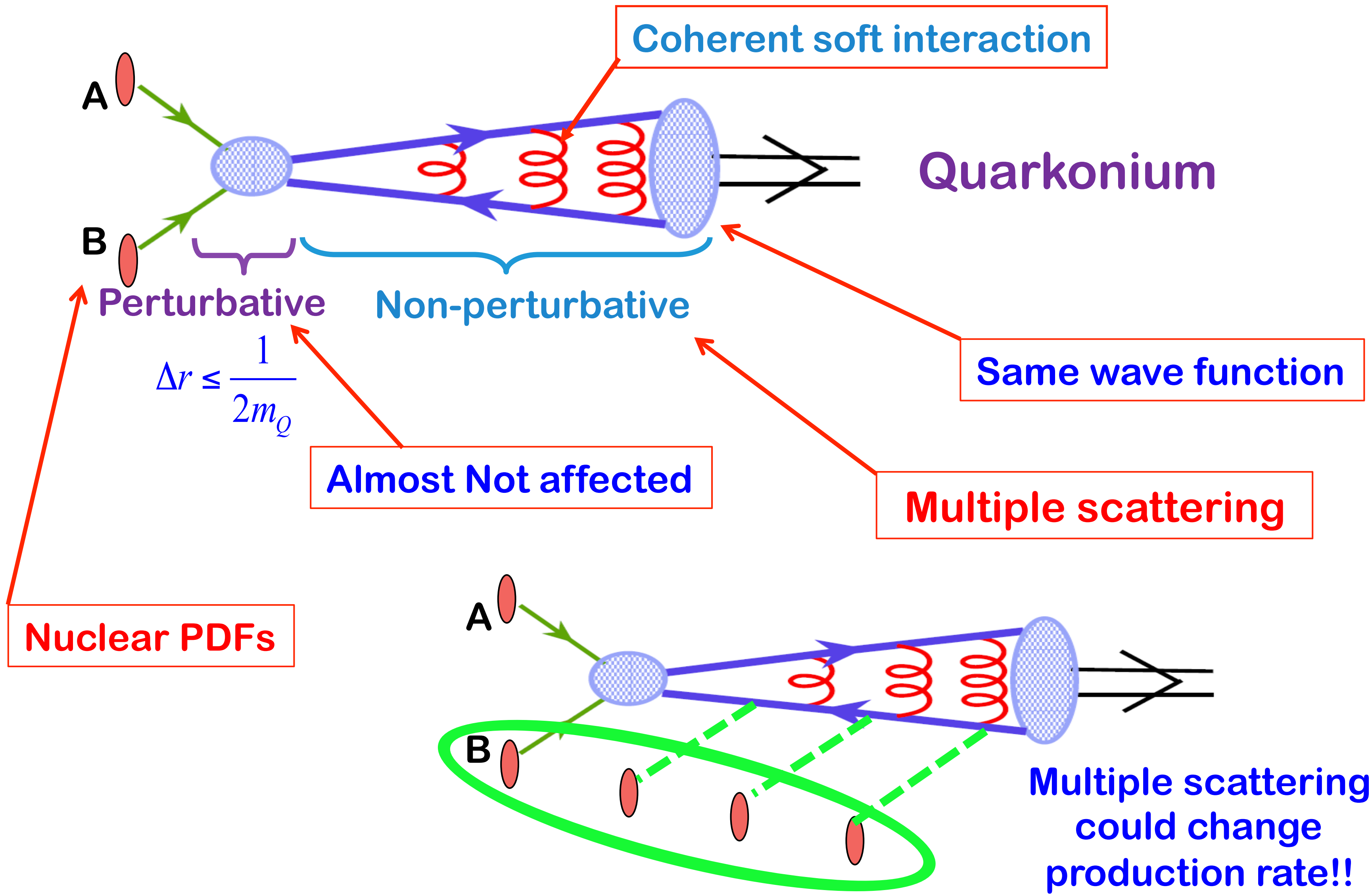




Production in p+A collisions

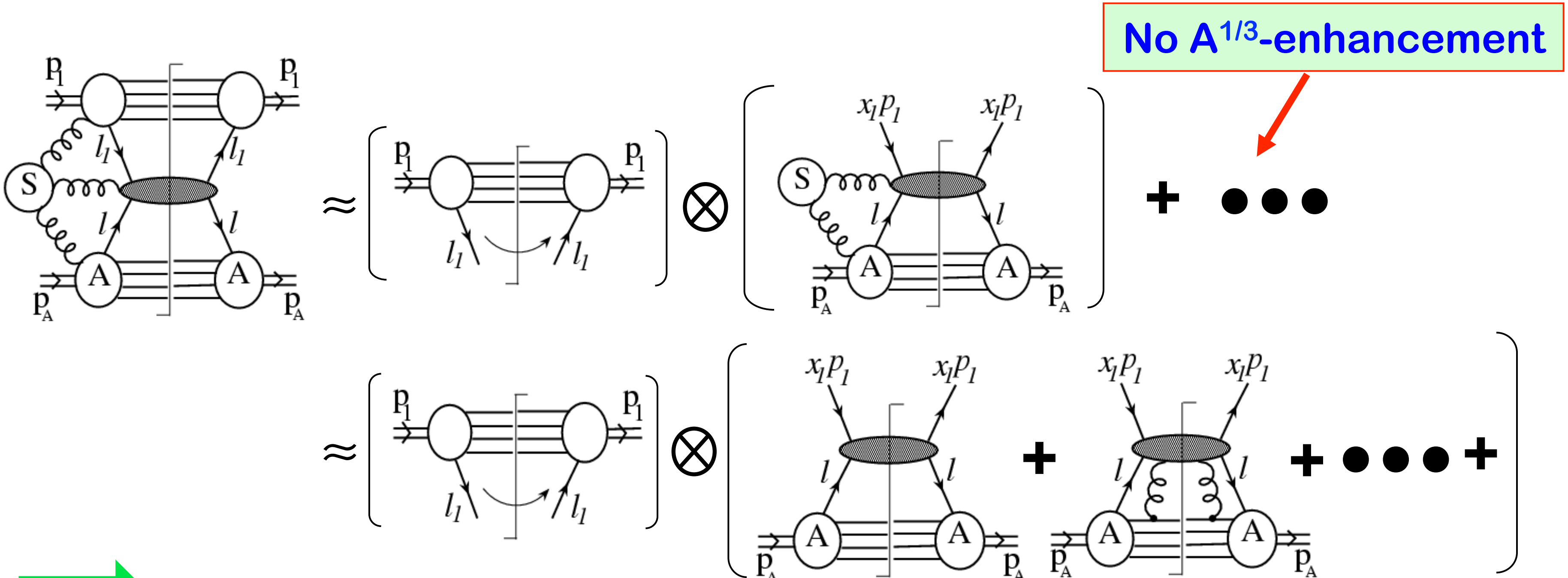


Production in p+A collisions



Factorization in p+A collisions

❑ A-enhanced power corrections, $A^{1/3}/Q^2$, may be factorizable:



✧ Total x-section: Factorization argument similar to DIS

Collinear power expansion – single scale

✧ P_T spectrum: Factorization argument similar to SIDIS

TMD or collinear – low P_T to high P_T

Suppression in total production rate

- **Multiple scattering in A:**
- **Final-state:**

  Increases the relative momentum of the pair

  $\overline{Q}^2 > Q^2$

  $$q^2 \Rightarrow q^2 + \varepsilon L_{AB}$$

  Suppression of J/ψ

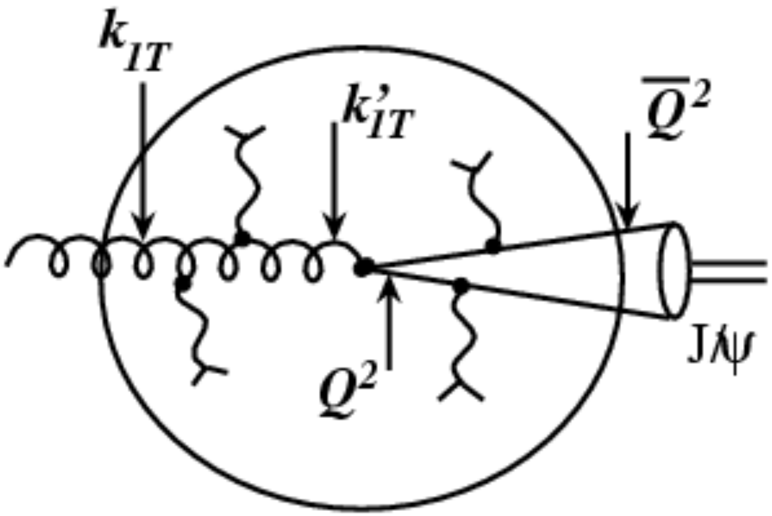
  $$\varepsilon \sim \hat{q} \sim \langle \Delta q_T^2 \rangle$$

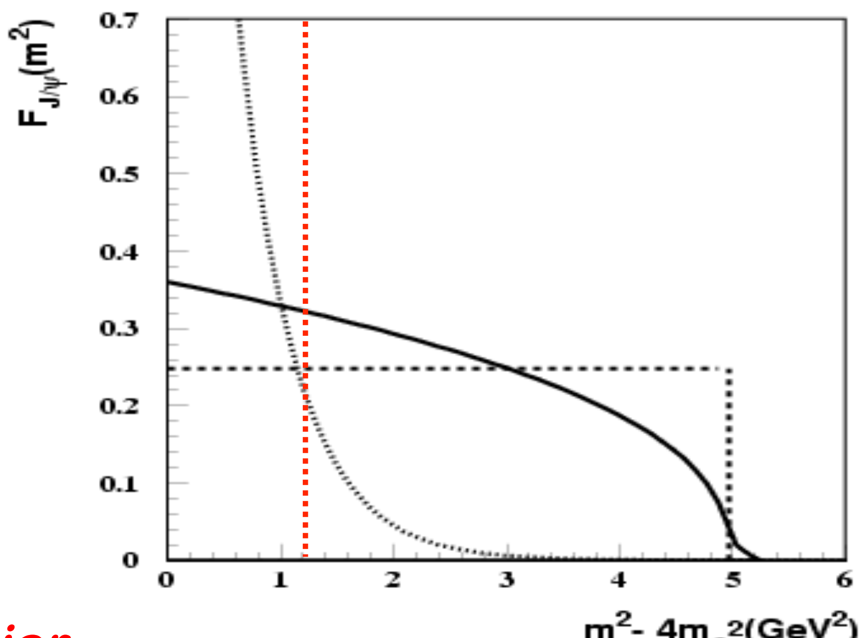
- **Threshold effect leads to different effective σ_{abs}**

  Curved line for R_{pA}

- **Different suppression for ψ'**

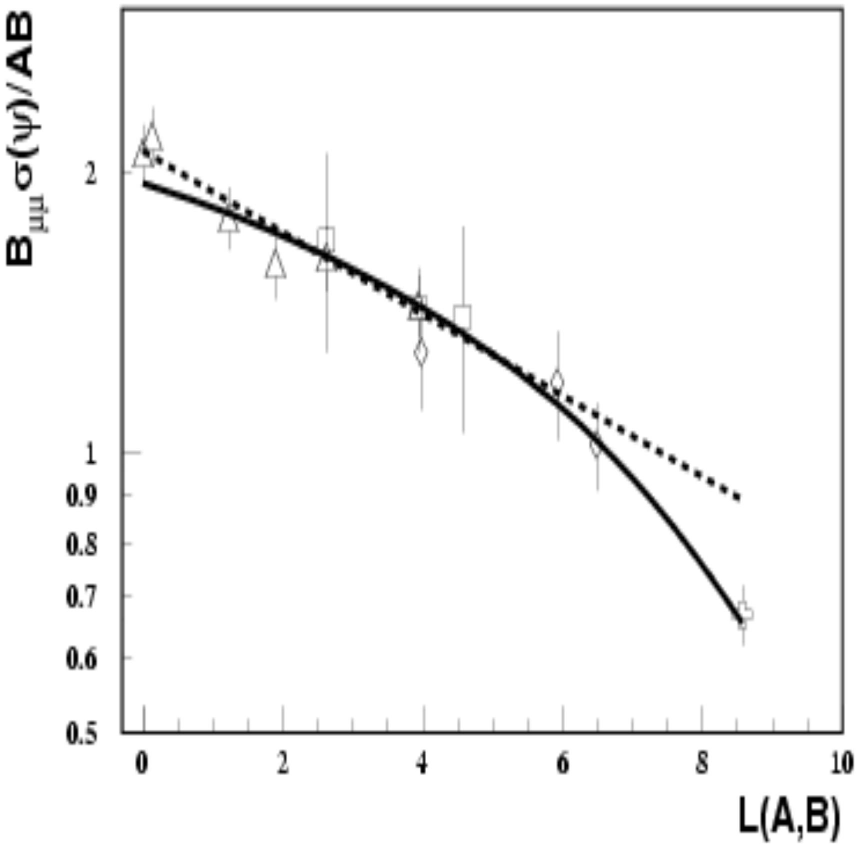
  Difference in threshold behavior

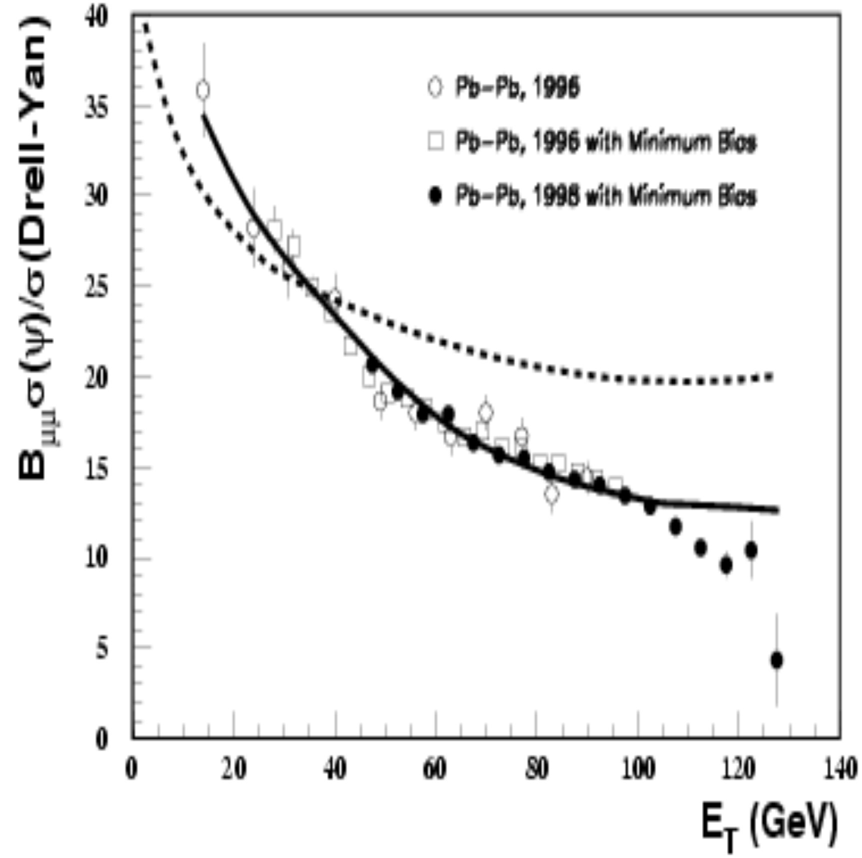




Suppression in total production rate

Qiu, Vary, Zhang, PRL 2002





Single parameter: $\varepsilon \propto \hat{q}$

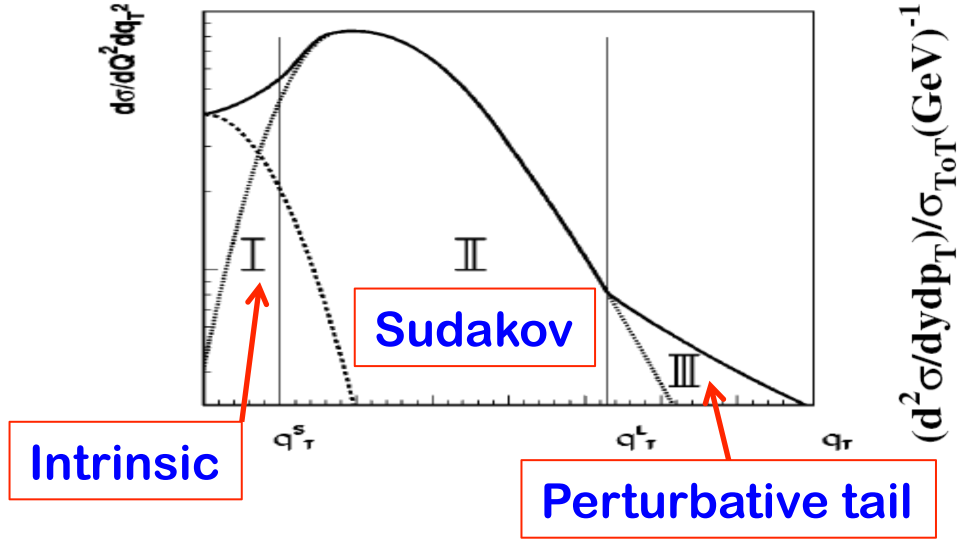
- ✧ **Extract shape of transition distributions?**
- ✧ **Transverse momentum broadening**

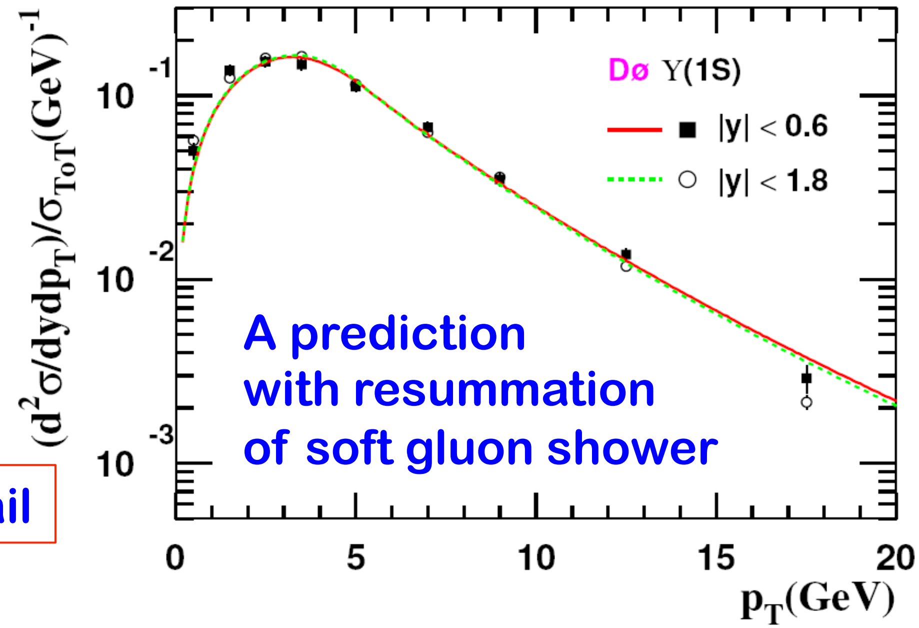
Quarkonium P_T distribution

- P_T spectrum is not completely perturbative:

Guo, Qiu, Zhang, PRD 2002

Berger, Qiu, Wang, PRD 2005





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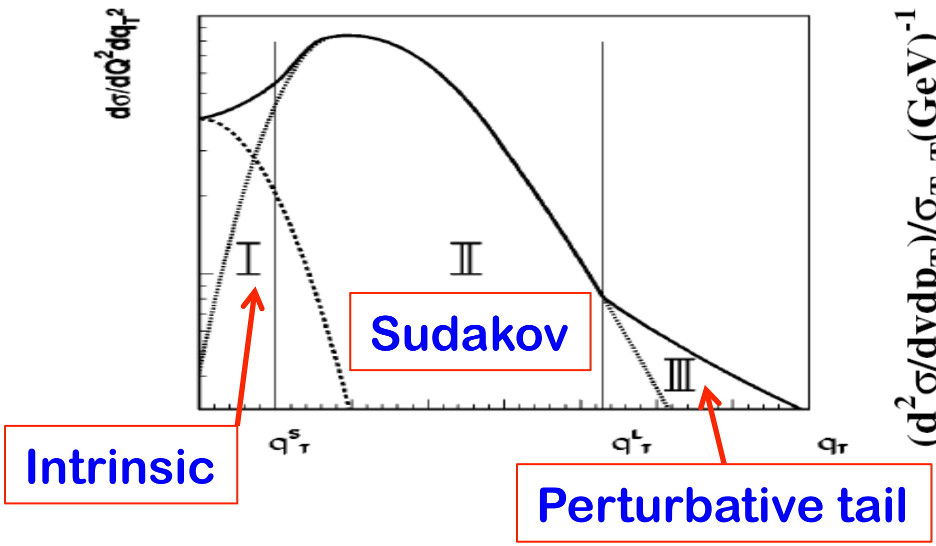
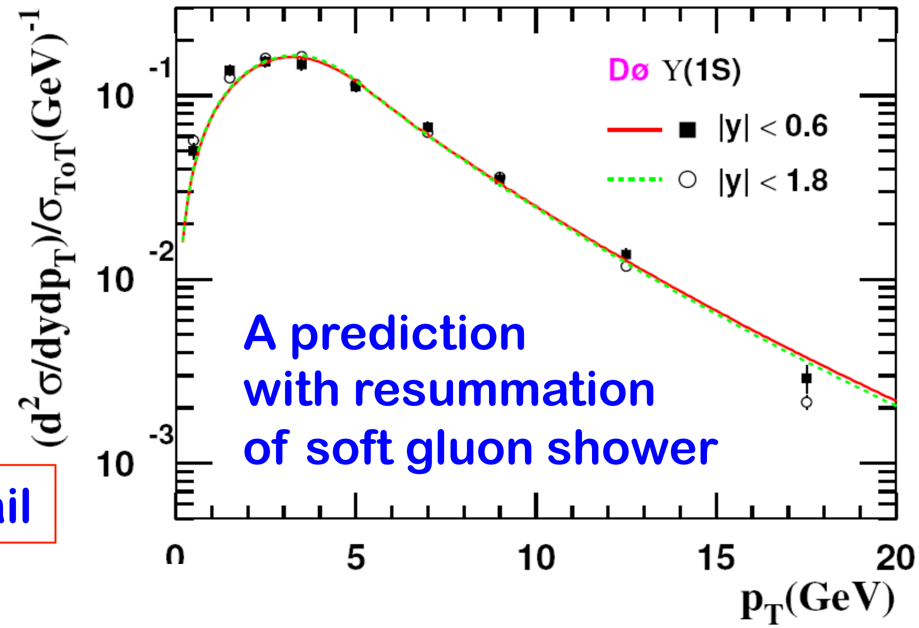
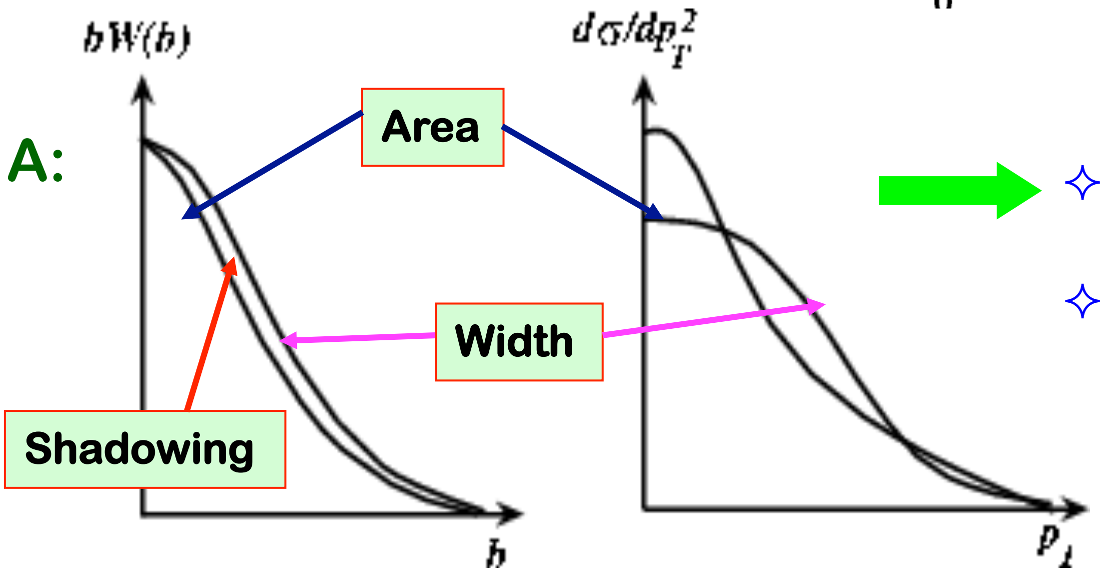




❑ In A:



✧ Suppression in total rate

✧ Broadening in P_T
Shadowing
+ multiple scattering

A-dependence of the P_T distribution

Guo, Qiu, Zhang, PRL, PRD 2002

- Ratio of x-sections:

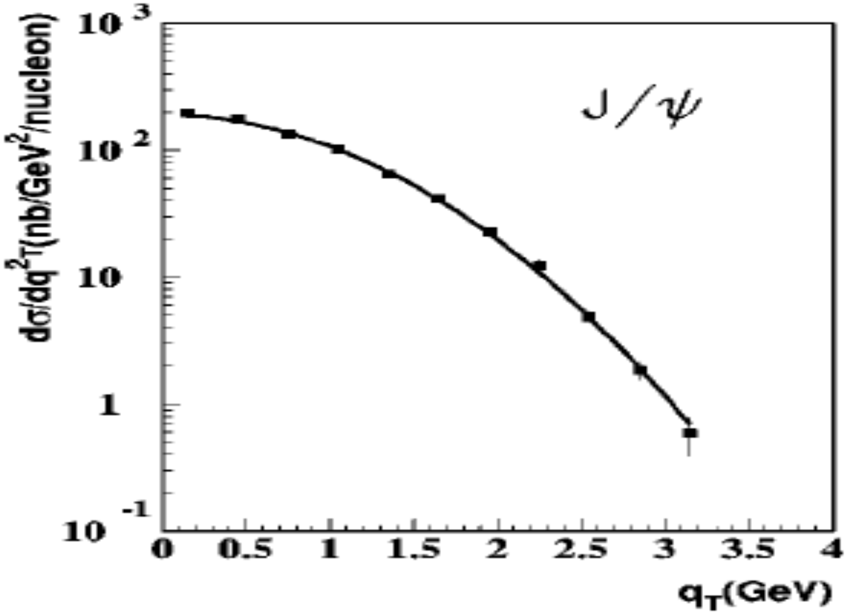
$$R(A,q_T) \equiv \frac{1}{A}\frac{d\sigma^{hA}}{dQ^2\,dq_T^2} \Big/ \frac{d\sigma^{hN}}{dQ^2\,dq_T^2} \equiv A^{\alpha(A,q_T)-1}$$

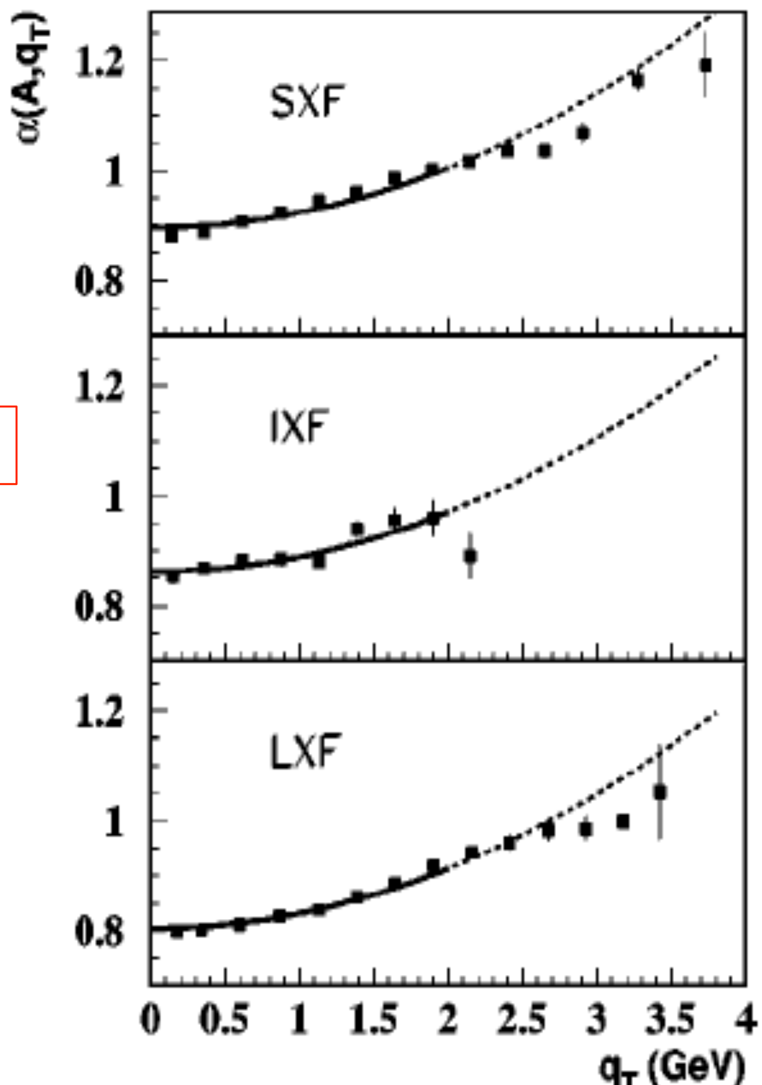
$$\approx 1 + \frac{\Delta\langle q_T^2\rangle}{A^{1/3}\langle q_T^2\rangle_{\rm DY}^{hN}}\left[-1+\frac{q_T^2}{\langle q_T^2\rangle_{\rm DY}^{hN}}\right]$$

Similar formula for J/ψ

- Spectrum and ratio:

E772 data

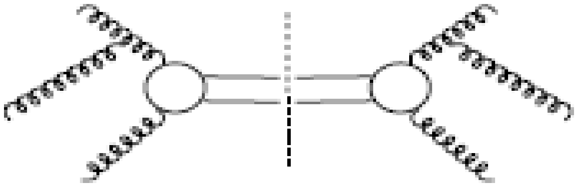




Broadening of heavy quarkonium P_T

Kang, Qiu, PRD77(2008)

- **Initial-state only:**



$$\Delta\langle q_T^2\rangle^{(I)}_{J/\psi} = C_A\left(\frac{8\pi^2\alpha_s}{N_c^2-1}\,\lambda^2\,A^{1/3}\right)$$

$$\Delta\langle q_T^2\rangle_{DY} \approx C_F\left(\frac{8\pi^2\alpha_s}{N_c^2-1}\,\lambda^2\,A^{1/3}\right)$$

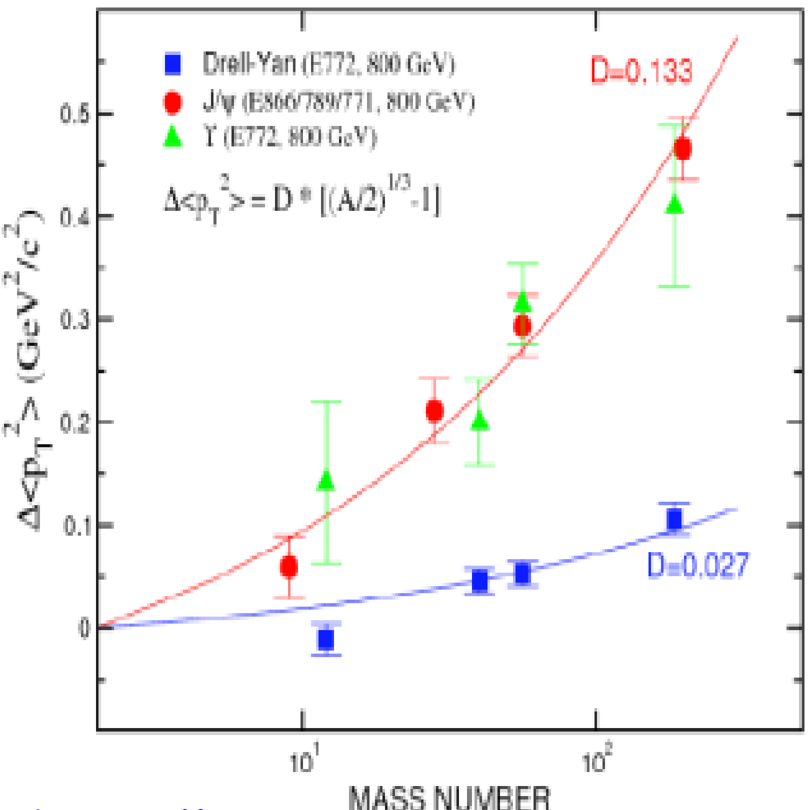
- **Experimental data from d+A:**

Clear $A^{1/3}$ dependence

But, wrong normalization!

$$\Delta\langle q_T^2\rangle^{(I)}_{J/\psi}\Big/\Delta\langle q_T^2\rangle_{DY}\Big|_{thy} = C_A/C_F = 2.25$$

$$\Delta\langle q_T^2\rangle^{(I)}_{J/\psi}\Big/\Delta\langle q_T^2\rangle_{DY}\Big|_{exp} = 0.133/0.027 \approx 4.9$$



J.C.Peng, hep-ph/9912371

Johnson,et al, 2007

Final-state effect – octet channel dominated!

Only depend on observed quarkonia

Final-state multiple scattering - CEM

Kang, Qiu, PRD77(2008)

- **Double scattering – $A^{1/3}$ dependence:**

$$\Delta\langle q_T^2\rangle_{\rm HQ}^{\rm CEM} \approx \int dq_T^2 q_T^2 \int_{4m_Q^2}^{4M_Q^2} dQ^2 \frac{d\sigma^D_{hA\to Q\bar{Q}}}{dQ^2 dq_T^2} \Big/ \int_{4m_Q^2}^{4M_Q^2} dQ^2 \frac{d\sigma_{hA\to Q\bar{Q}}}{dQ^2}$$

- **Multiparton correlation:**

$$T_{g/A}^{(F)}(x) = T_{g/A}^{(I)}(x) = \int \frac{dy^-}{2\pi} e^{ixp^+y^-} \int \frac{dy_1^- dy_2^-}{2\pi} \theta(y^- - y_1^-)\theta(-y_2^-) \times \frac{1}{xp^+} \langle p_A | F_\alpha{}^+(y_2^-) F^{\sigma+}(0) F^+{}_\sigma(y^-) F^{+\alpha}(y_1^-) | p_A\rangle$$

$$= \lambda^2 A^{4/3} \phi_{g/A}(x)$$

- **Broadening – twice of initial-state effect:**

$$\Delta\langle q_T^2\rangle_{\rm HQ}^{\rm CEM} = \left(\frac{8\pi^2\alpha_s}{N_c^2-1}\lambda^2 A^{1/3}\right) \frac{(C_F + C_A)\sigma_{q\bar{q}} + 2C_A\sigma_{gg}}{\sigma_{q\bar{q}} + \sigma_{gg}}$$

$$\approx 2C_A\left(\frac{8\pi^2\alpha_s}{N_c^2-1}\lambda^2 A^{1/3}\right)$$

if gluon-gluon dominates, and if $r_F > R_A$

Final-state multiple scattering - NRQCD

Kang, Qiu, PRD77(2008)

- Cross section:

$$\sigma_{hA\to H}^{\rm NRQCD} = A\sum_{a,b}\int dx'\,\phi_{a/h}(x')\int dx\,\phi_{b/A}(x)\Big[\sum_n H_{ab\to Q\bar{Q}[n]}\langle \mathcal{O}^H(n)\rangle\Big]$$

- Broadening:

$$\Delta\langle q_T^2\rangle_{\rm HQ}^{\rm NRQCD} = \left(\frac{8\pi^2\alpha_s}{N_c^2-1}\lambda^2 A^{1/3}\right)\frac{(C_F+C_A)\sigma_{q\bar{q}}^{(0)} + 2C_A\sigma_{gg}^{(0)} + \sigma_{q\bar{q}}^{(1)}}{\sigma_{q\bar{q}}^{(0)}+\sigma_{gg}^{(0)}}$$

Hard parts:

$$\hat{\sigma}_{q\bar{q}}^{(0)} = \frac{\pi^3\alpha_s^2}{M^3}\frac{16}{27}\delta(\hat{s}-M^2)\langle\mathcal{O}^H({}^3S_1^{(8)})\rangle$$

$$\hat{\sigma}_{q\bar{q}}^{(1)} = \frac{\pi^3\alpha_s^2}{M^3}\frac{80}{27}\delta(\hat{s}-M^2)\langle\mathcal{O}^H({}^3P_0^{(8)})\rangle$$

$$\hat{\sigma}_{gg}^{(0)} \equiv \frac{\pi^3\alpha_s^2}{M^3}\frac{5}{12}\delta(\hat{s}-M^2)\Big[\langle\mathcal{O}^H({}^1S_0^{(8)})\rangle + \frac{7}{m_Q^2}\langle\mathcal{O}^H({}^3P_0^{(8)})\rangle\Big]$$

Only color octet channel contributes

- Leading features:

$$\Delta\langle q_T^2\rangle_{\rm HQ}^{\rm NRQCD} \approx \Delta\langle q_T^2\rangle_{\rm HQ}^{\rm CEM} \approx (2C_A/C_F)\Delta\langle q_T^2\rangle_{\rm DY}$$

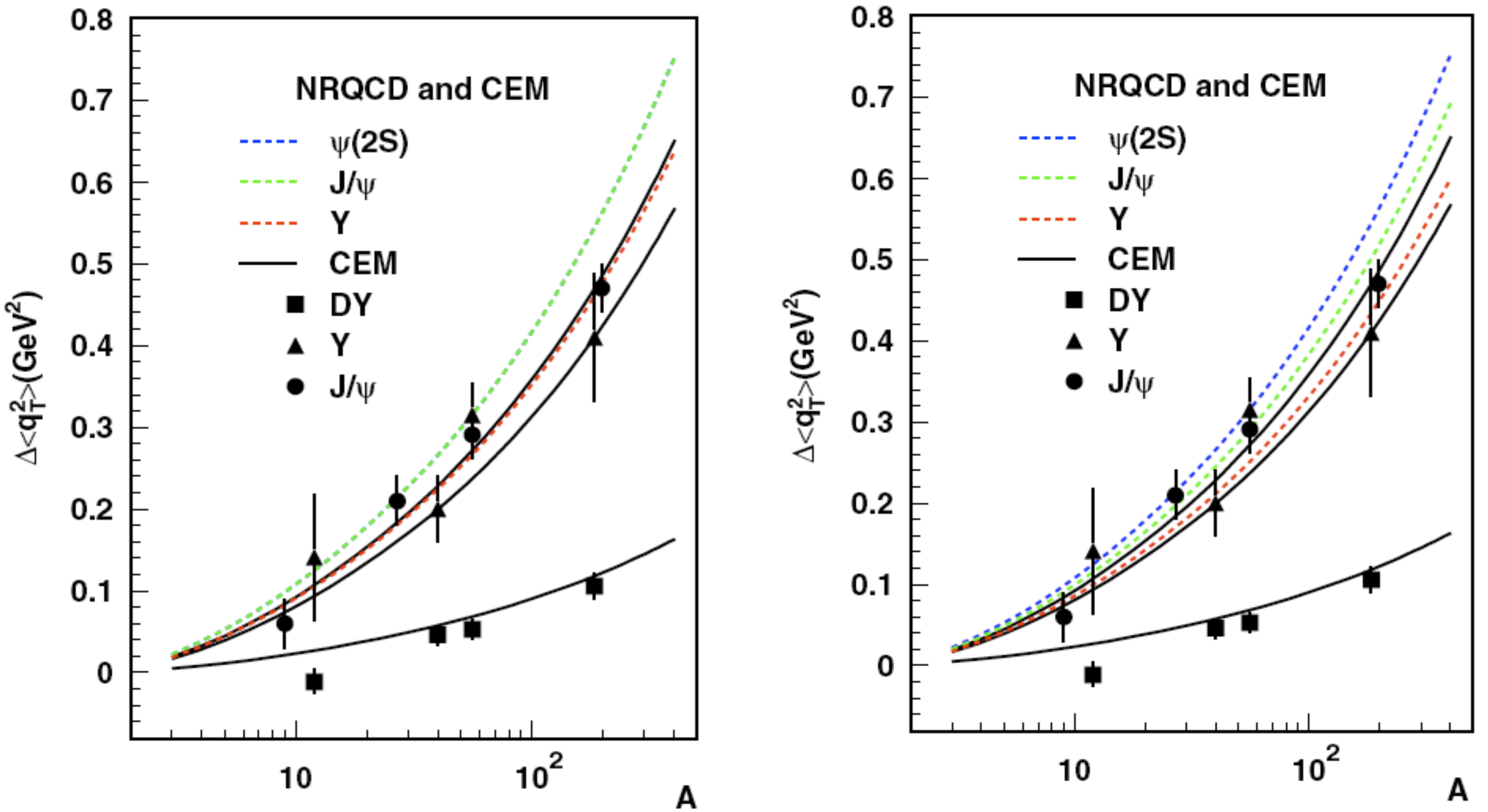
Broadening of heavy quarkonia in p(d)+A

Kang, Qiu, PRD77(2008)

- ❑ Final-state effect is important:

$$\Delta\langle q_T^2\rangle_{\mathrm{J}/\psi}^{(I+F)} \Big/ \Delta\langle q_T^2\rangle_{\mathrm{DY}}\Big|_{\mathrm{thy}} \approx 2C_A/C_F = 4.5$$

in both CEM and NRQCD



- ❑ Mass – independence, not very sensitive to the feeddown

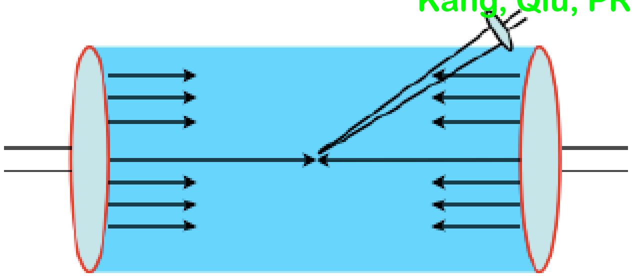
Broadening of heavy quarkonia in A+A

- If no hot medium was formed:

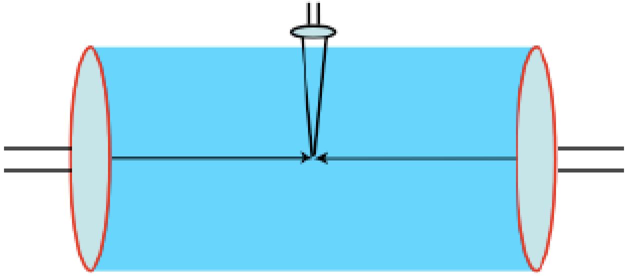
$$\Delta\langle q_T^2\rangle_{AB} \approx C_F\left(\frac{8\pi^2\alpha_s}{N_c^2-1}\,\lambda^2(Q)[A^{1/3}+B^{1/3}]\right)$$

Superposition of pA

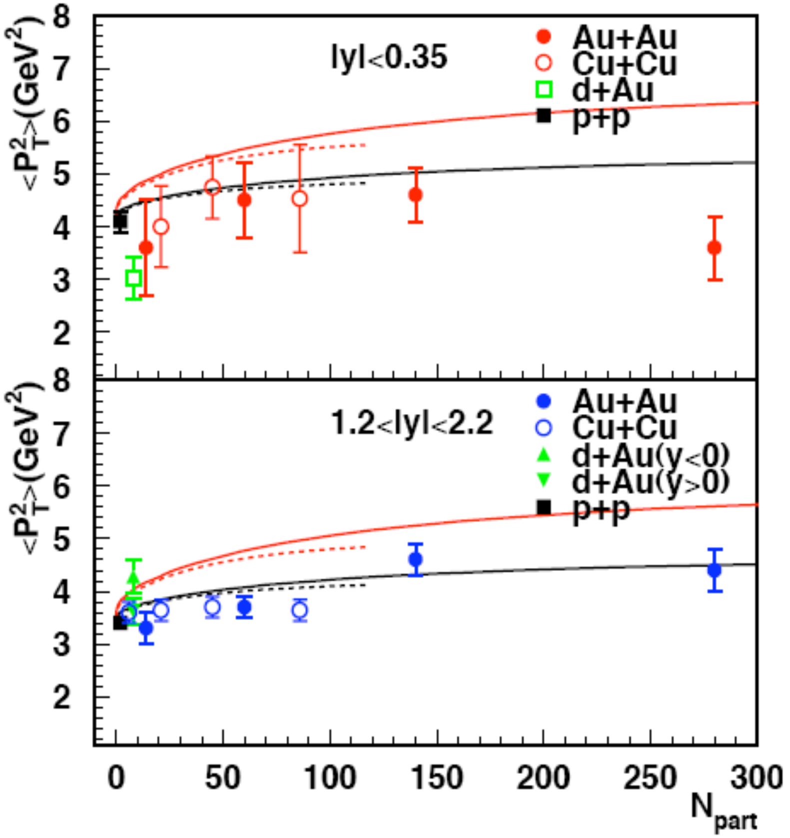
Kang, Qiu, PRD77(2008)



- If hot medium is formed:



- $\Delta\langle p_T^2\rangle_{final} \sim 0$
- $\Delta\langle p_T^2\rangle_{initial} \lesssim \text{superposition of } \Delta\langle p_T^2\rangle_{pA}$



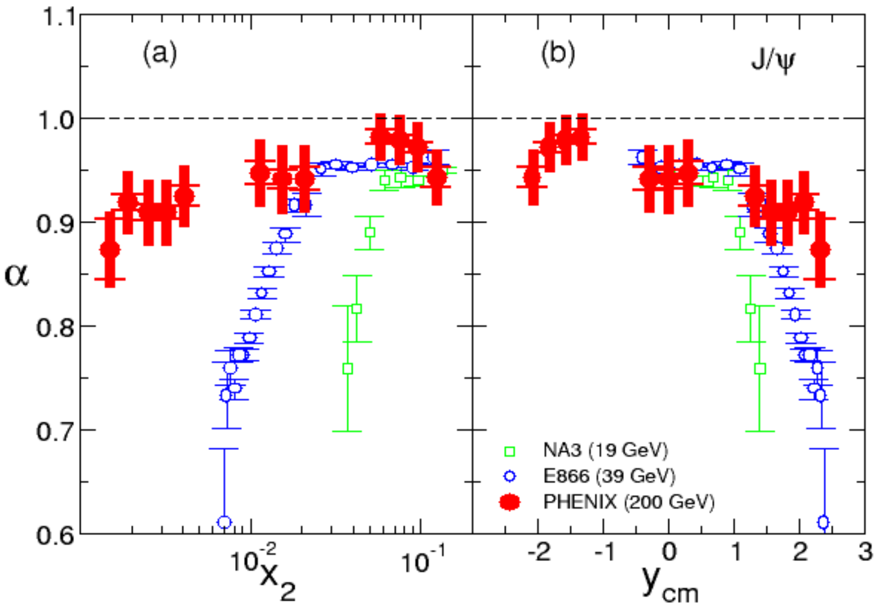
"Slow" expanding hot & dense medium at RHIC and the LHC!

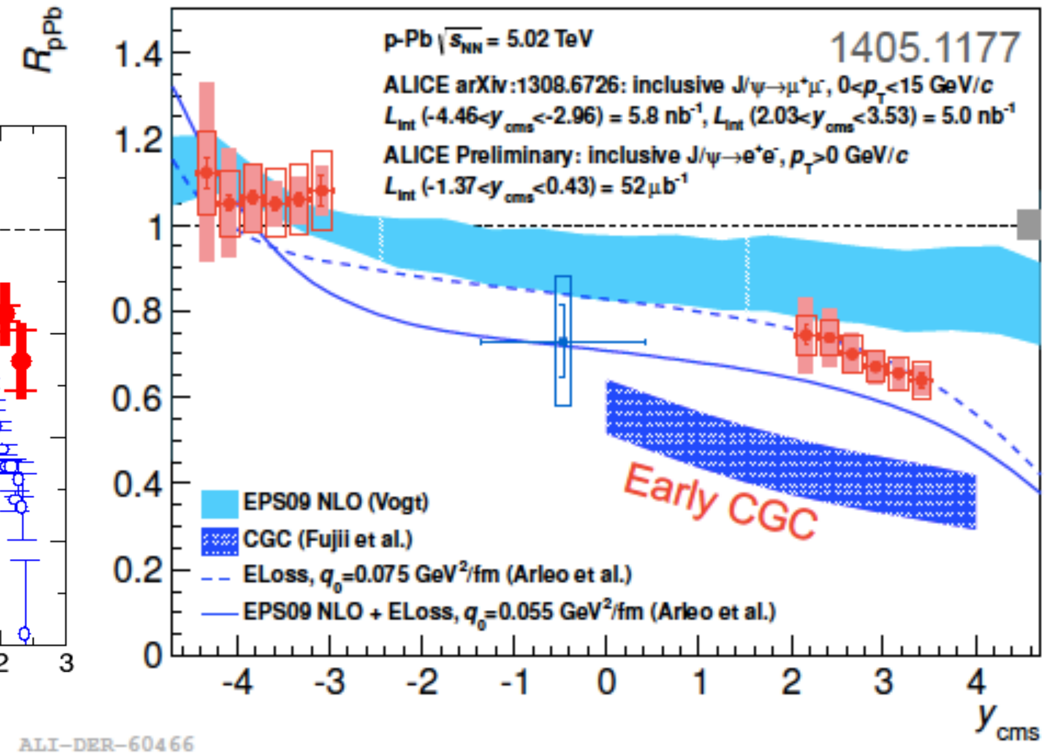
$\Delta\langle q_T^2\rangle_{AA}$ **could be less than 0!**

final-state energy loss, initial-state thermal medium?

P(d)+A collision at forward rapidity

❑ Puzzling rapidity dependence:





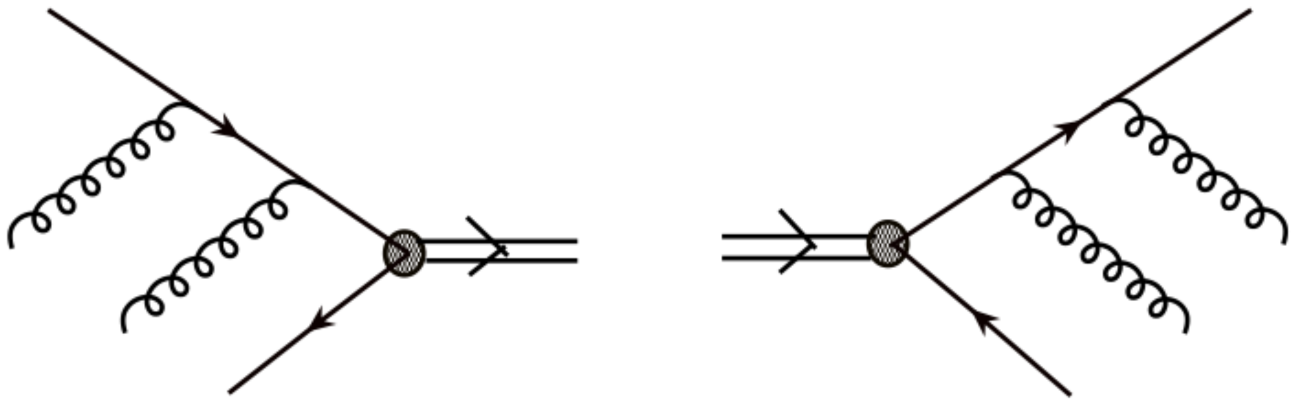
LHCb has similar forward rapidity result

✧ x_F – scaling (not x_2-scaling) in low energy data

✧ Less suppression from LHC data
(early CGC calculation does not work)

Heavy quarkonium y distribution in p+A

- Resummed multiple scattering:



$$\sigma_{PA}(p_T, x_F) \propto \sum_{a,b} \xi_g^2 \, x \frac{d}{dx} \left[f_{a/p}(x_F + x) f_{b/A}(x) \right]_{x = x_2(x_F, Q)}$$

In the forward region,

$$\frac{d}{dx} \left[f_{a/p}(x_F + x) \right]_{x = x_2(x_F, Q)} \gg \frac{d}{dx} \left[f_{b/A}(x) \right]_{x = x_2(x_F, Q)}$$

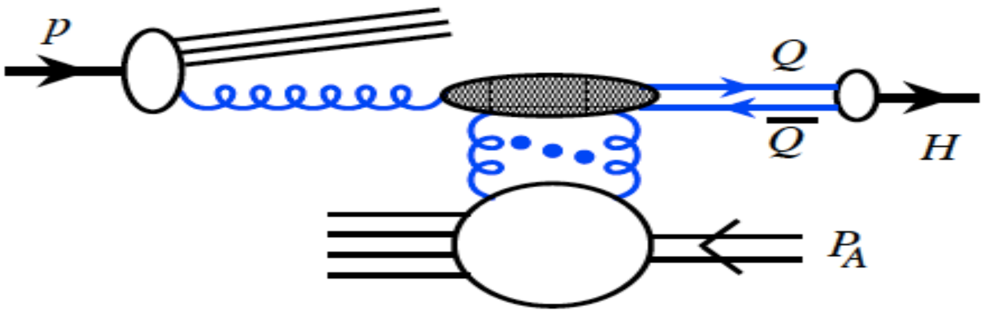
$$x_1 = x_F + x_2 \qquad\qquad x_2 = \frac{1}{2} \left[\sqrt{x_F^2 + 4Q^2/s} - x_F \right]$$

➡ Close to x_F scaling!

Heavy quarkonium y distribution in p+A

Qiu, Sun, Xiao, Yuan PRD89 (2014)

- QCD factorization for $A^{1/3}$ enhanced contribution:



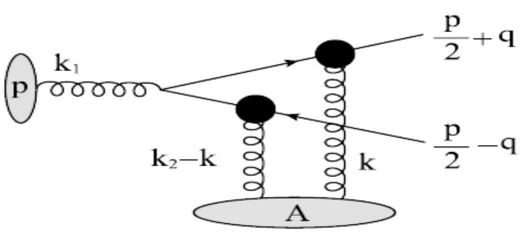
Time dilation factor:

$$\frac{1}{mv}\left(\frac{P_{\|}}{M}\right) \gg \frac{1}{P_{\perp}} \sim \frac{1}{Q_s(A)}$$

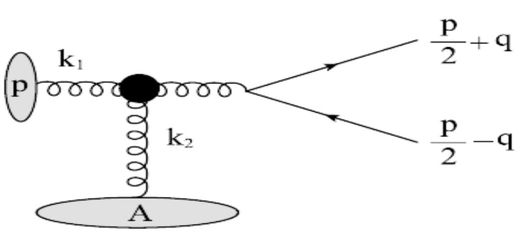
$$\Leftrightarrow \quad y \gg \ln\left(\frac{2mv}{P_T}\right) \sim \ln\left(\frac{Mv}{Q_s(A)}\right)$$

Condition for multiple scattering not to interfere with hadronization

- Heavy quarkonium production in pA collisions:



(a)



(b)

Coherent multiple Scattering → Suppression at large y

✧ Kang et al.: 1309.7337 — NRQCD, CEM, $P_T \sim Q_s >> M$, … – small-x evolution + CGC multiple scattering

✧ Qiu et al.: 1310.2230 — NRQCD, CEM, $P_T \sim Q_s << M$ – Coherent multiple scatteing + Sudakov resummation

No numerical prediction yet

Summary

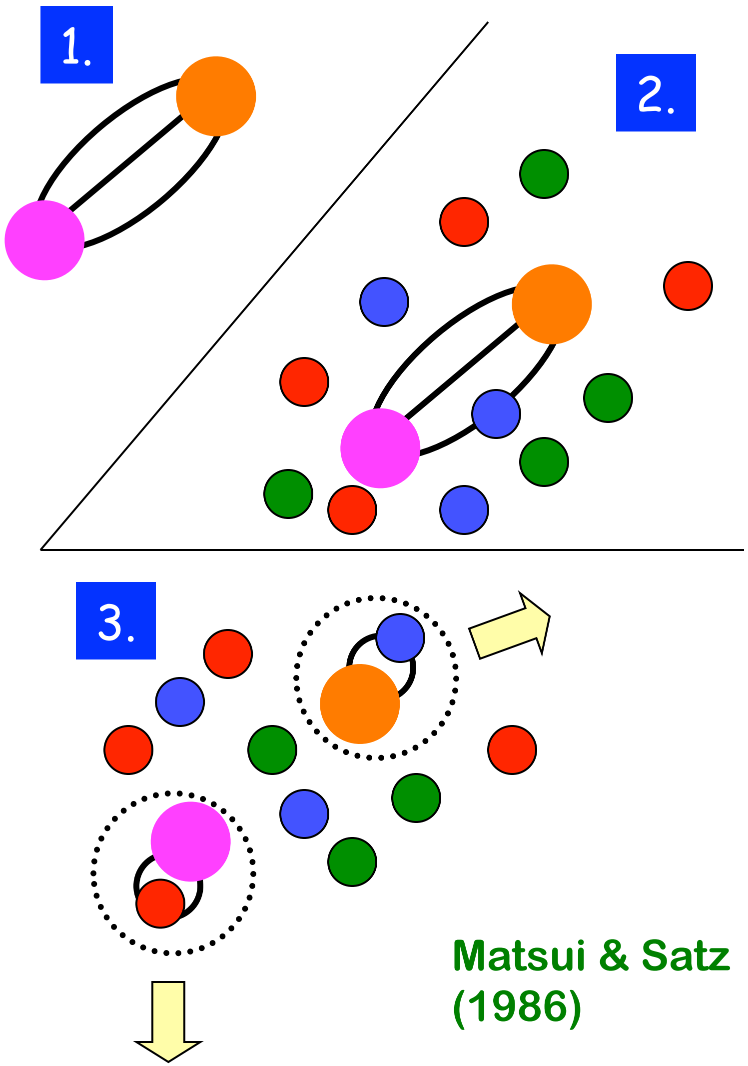
- Heavy quarkonium production has been a powerful tool to test and challenge our understanding of strong interaction and QCD
- Both initial-state and final-state multiple scattering are relevant for nuclear dependence of Quarkonium production – could redistribute the p_T- & y-dependence
- Final-state multiple scattering could be an effective source of J/ψ suppression because of the sharp threshold behavior
- Polarized p+A at RHIC could provide new and exciting opportunities
- More discussion and work on QCD factorization is needed for p+A collision. A weaker factorization might be true for A-dependence in p+A, but, certainly not for A+A collisions

Thank you!

Backup slides

Melting a quarkonium in QGP

- Start with a J/ψ
  - ✧ This works with other charmonium states as well
  - ✧ The J/ψ is easiest to observe
- Put it in a sea of color charges
- The color lines attach themselves to other quarks
  - – This forms a pair of charmed mesons
- These charmed mesons "wander off" from each other
- When the system cools, the charmed particles are too far apart to recombine
  - – Essentially, the J/ψ has melted



Matsui & Satz (1986)

A long history for the production

- **Color singlet model: 1975 –**

  Einhorn, Ellis (1975),
  Chang (1980),
  Berger and Jone (1981), …

  Only the pair with right quantum numbers

  Effectively No free parameter!

- **Color evaporation model: 1977 –**

  Fritsch (1977), Halzen (1977), …

  All pairs with mass less than open flavor heavy meson threshold

  One parameter per quarkonium state

- **NRQCD model: 1986 –**

  Caswell, Lapage (1986)
  Bodwin, Braaten, Lepage (1995)
  QWG review: 2004, 2010

  All pairs with various probabilities – NRQCD matrix elements

  Infinite parameters – organized in powers of v and α_s

- **QCD factorization approach: 2005 –**

  Nayak, Qiu, Sterman (2005), …
  Kang, Qiu, Sterman (2010), …

  $P_T >> M_H$: M_H/P_T power expansion + α_s – expansion

  Unknown, but universal, fragmentation functions – evolution

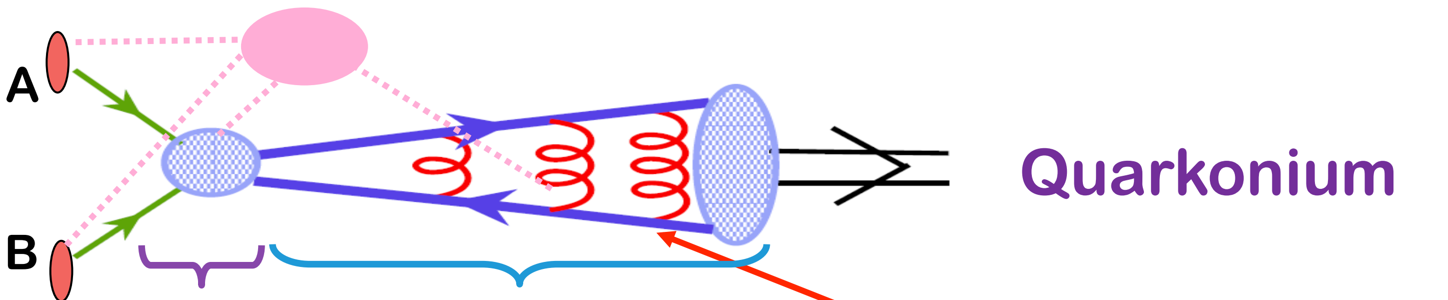
- **Soft-Collinear Effective Theory + NRQCD: 2012 –**

See my talk last week

Fleming, Leibovich, Mehen, …

Basic production mechanism

- ❑ **QCD factorization is likely to be valid for producing the pairs:**
  - ✧ **Momentum exchange is much larger than 1/fm**
  - ✧ **Spectators from colliding beams are "frozen" during the hard collision**



$$\Delta r \leq \frac{1}{2m_Q}$$

- ❑ **Approximation: on-shell pair + hadronization**

$$\sigma_{AB\to J/\psi}(P_{J/\psi}) \approx \sum_n \int dq^2 \left[\sigma_{AB\to[Q\bar{Q}](n)}(q^2)\right] F_{[Q\bar{Q}(n)]\to J/\psi}(P_{J/\psi}, q^2)$$

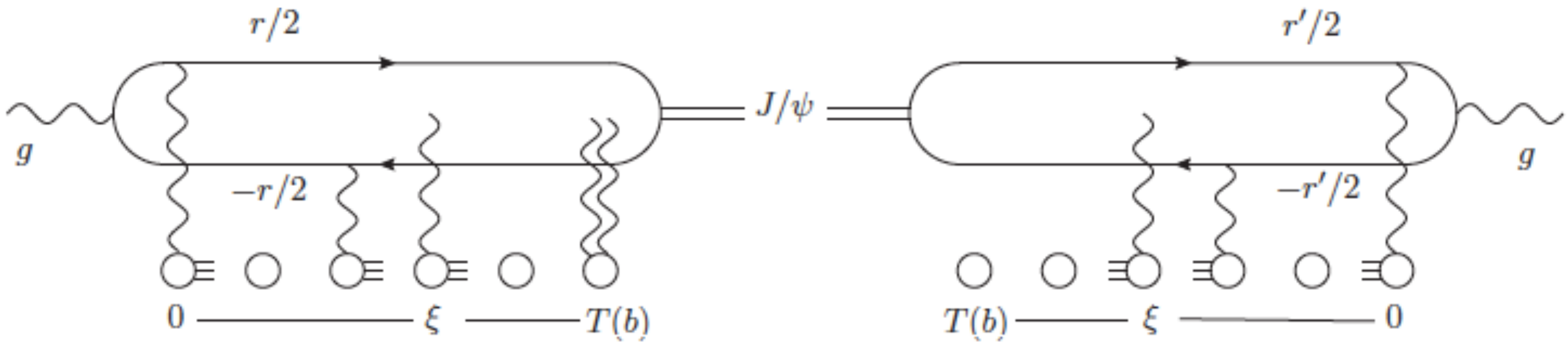
Models & Debates

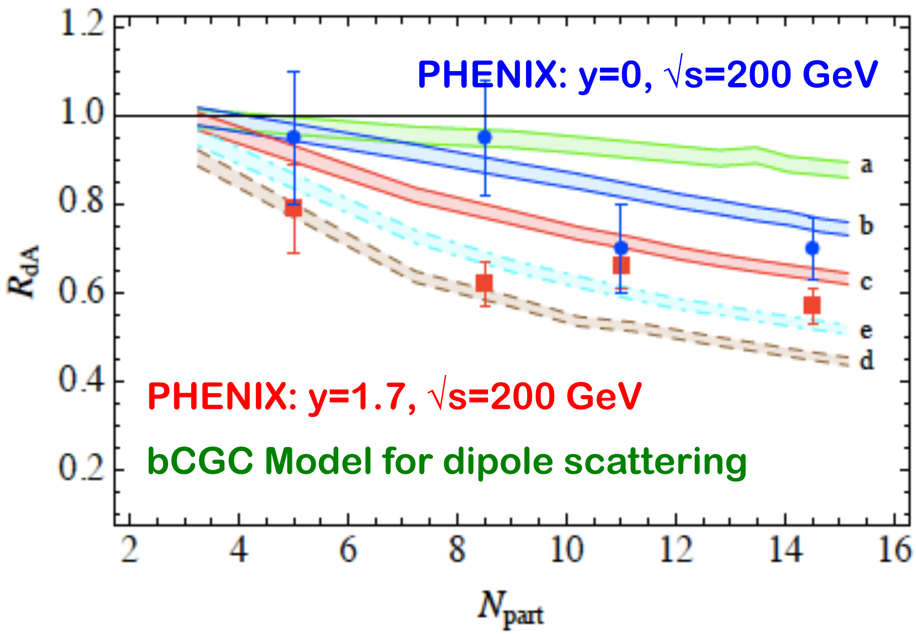
⇔ **Different assumptions/treatments on** $F_{[Q\bar{Q}(n)]\to J/\psi}(P_{J/\psi}, q^2)$
how the heavy quark pair becomes a quarkonium?

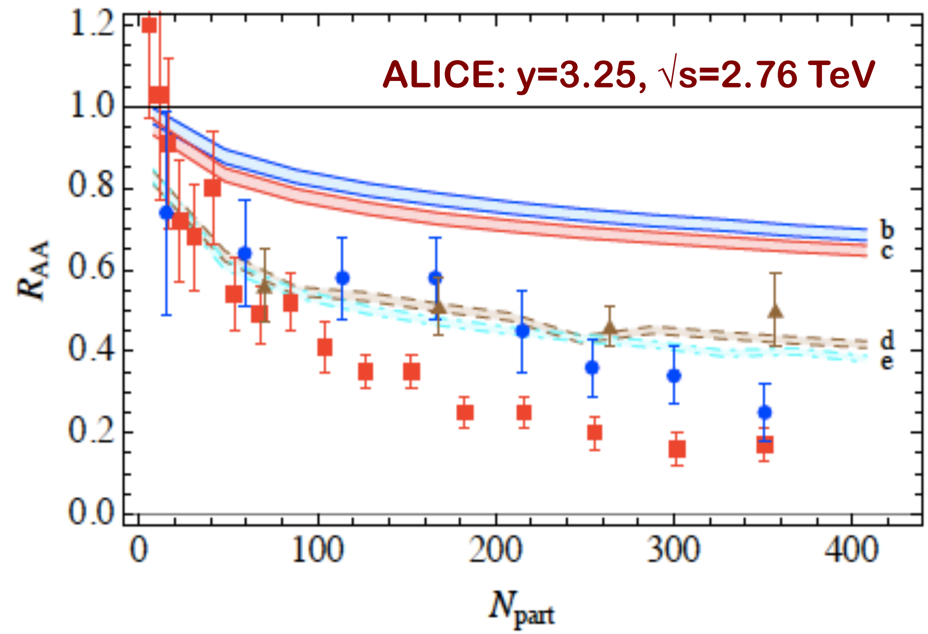
Multiple scattering in cold nuclear matter

Dominguez, Kharzeev, Levin, Mueller, and Tuchin, 2011

$$\frac{d\sigma_{pA\to J/\psi X}}{d^2b\,dy} = x_1 G(x_1, m_c^2)\frac{d\sigma_{gA\to J/\psi X}}{d^2b}$$



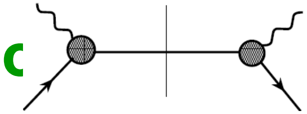




OK for pA, but, far off for AA – J/ψ melting in QGP (MS 1986)?

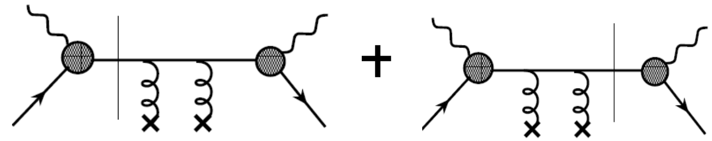
Multiple coherent scattering to DIS

❑ **LO contribution to DIS cross sectic**



$\Rightarrow$ $\delta(x - x_B)$

❑ **NLO contribution:**

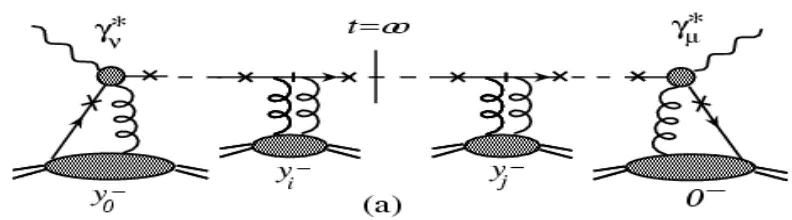


$$\Rightarrow \frac{g^2}{Q^2}\left(\frac{1}{2N_c}\right)\left[2\pi^2\tilde{F}^2(0)\right] x_B \lim_{x_1\to x}\left[\frac{1}{x-x_1}\delta(x_1-x_B)+\frac{1}{x_1-x}\delta(x-x_B)\right]$$

$$\left[2\pi^2\tilde{F}^2(0)\right] = \int \frac{dy_2^- dy_1^-}{(2\pi)^2}\left[F^{+\alpha}(y_2^-)F_\alpha{}^+(y_1^-)\right]\theta(y_2^-)$$

$$x_B \lim_{x_1\to x}\left[\cdots\right] = x_B\left[-\frac{d}{dx}\delta(x-x_B)\right]$$

❑ **Nth order contribution:**



$$\Rightarrow \left[\frac{g^2}{Q^2}\left(\frac{1}{2N_c}\right)\left[2\pi^2\tilde{F}^2(0)\right]\right]^N x_B^N \lim_{x_i\to x}\sum_{m=0}^{N}\delta(x_m-x_B)\left[\prod_{i=1}^{m}\left(\frac{1}{x_{i-1}-x_m}\right)\right]\left[\prod_{j=1}^{N-m}\left(\frac{1}{x_{m+j}-x_m}\right)\right]$$

$$= x_B^N\left[(-1)^N\frac{1}{N!}\frac{d^N}{dx^N}\delta(x-x_B)\right]$$

Infrared safe!

Resummed contribution to structure functions

- **Transverse structure function:**

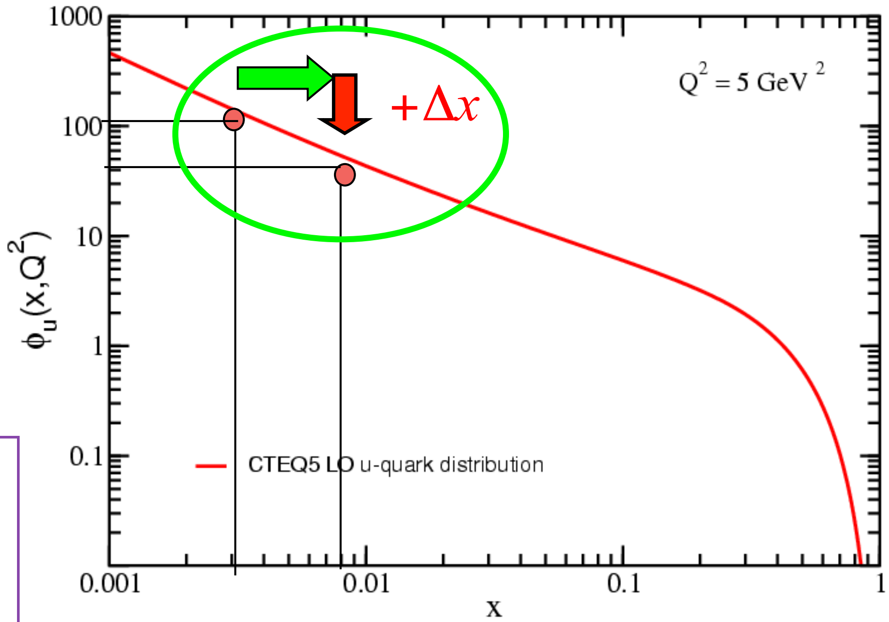
Qiu and Vitev, PRL (2004)

$$F_T(x_B, Q^2) = \sum_{n=0}^{N} \frac{1}{n!} \left[\frac{\xi^2}{Q^2} \left(A^{1/3} - 1\right) \right]^n x_B^n \frac{d^n}{dx_B^n} F_T^{(0)}(x_B, Q^2)$$

$$\approx F_T^{(0)}(x_B(1+\Delta), Q^2)$$

$$\Delta \equiv \frac{\xi^2}{Q^2} \left(A^{1/3} - 1\right)$$

$$\xi^2 = \frac{3\pi\alpha_s}{8R^2} \langle F^{+\alpha} F_\alpha^{\ +} \rangle$$



Single parameter for the power correction, and is proportional to the same characteristic scale

- **Similar result for longitudinal structure function**

Neglect LT shadowing upper limit of ξ^2

ξ^2 :   0.09 - 0.12 GeV^2