Suppression of Heavy Quarkonium Production in pA Collisions

Jianwei Qiu
Brookhaven National Laboratory

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

INT Program (INT-14-3) – Focused workshop on

"Heavy Flavor and Electromagnetic Probes in Heavy Ion Collisions"

Institute for Nuclear Theory, University of Washington, Seattle, WA 9/15-10/10, 2014

Outline

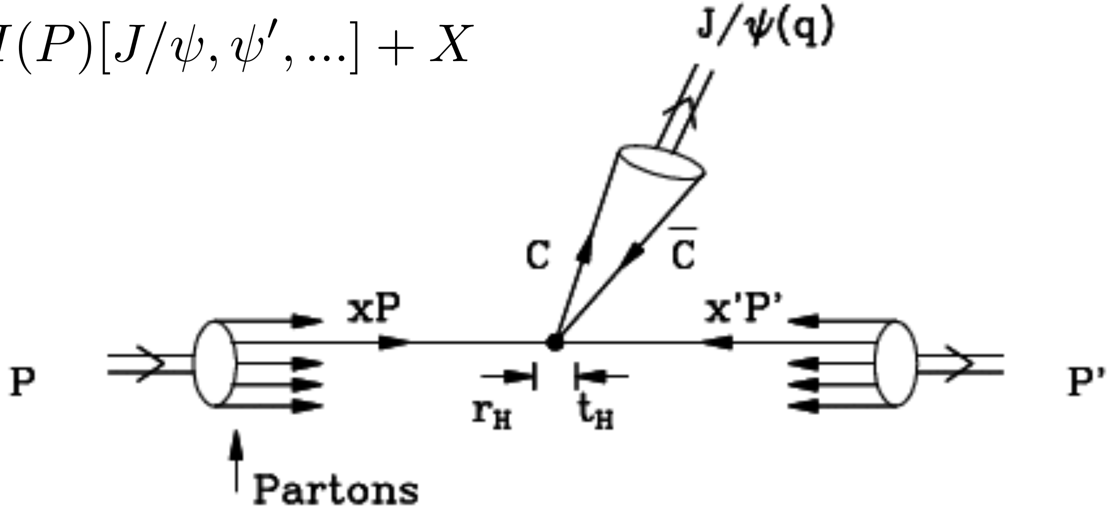
- Introduction – heavy quarkonium production
- Suppression of heavy quarkonium production in p+A:
  - Total production rate
  - pT – spectrum
  - xF (or y) distribution
- Heavy quarkonium production in polarized p+A collisions
  - Transverse single spin asymmetry (or phenomenon)
  - New and complimentary probe of small-x physics
- Summary

Introduction

- **Hadronic heavy quarkonium production:**

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

- **Partonic picture:**



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

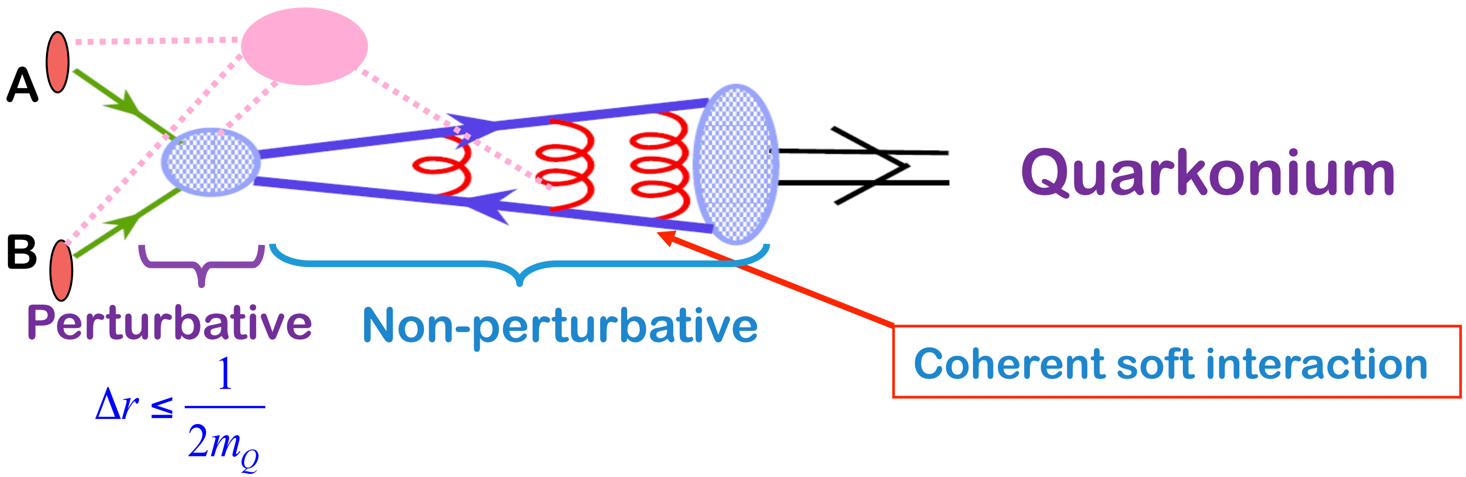
- **J/ψ is unlikely to be formed at:** $r_H \leq \frac{1}{2m_c} \sim \frac{1}{15} \text{ fm}$

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

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



❑ **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?

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

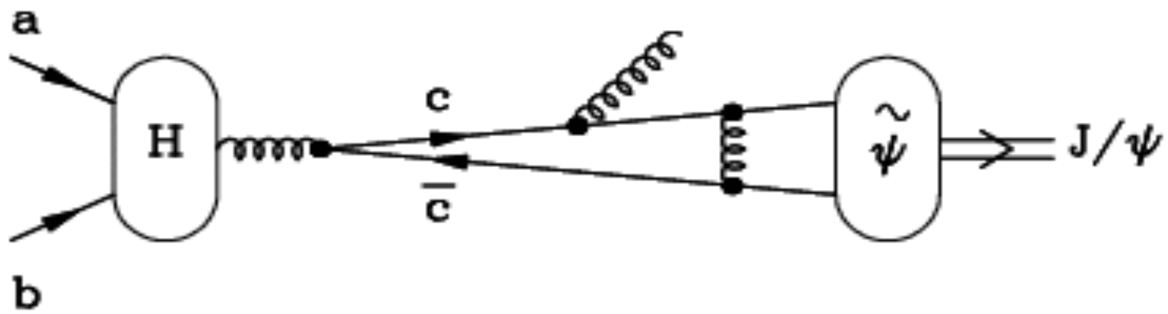
  Unknown, but universal, fragmentation functions – evolution

- Soft-Collinear Effective Theory + NRQCD: 2012 –

  Fleming, Leibovich, Mehen, …

See my talk last week

Transition from the pair to a quarkonium



- **Large phase space available for gluon radiation:**

$$Q^2 - 4M_C^2 \Rightarrow 4M_D^2 - 4M_C^2 \approx 6\ \text{GeV}^2$$

- **Larger heavy quark velocity in production than decay:**

$$v_{\text{decay}} \sim \sqrt{\frac{4M_{J/\psi}^2 - 4m_c^2}{4m_c^2}} \sim 0.48$$

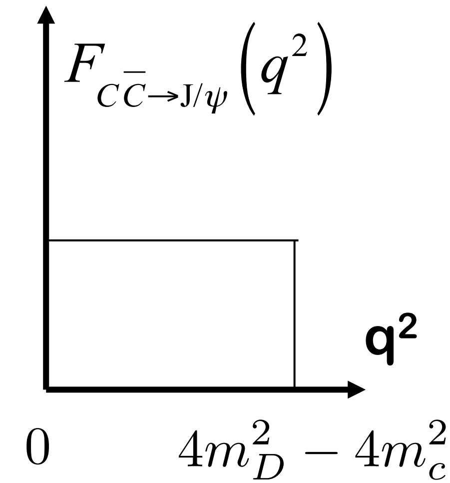
$$v_{\text{prod}} \sim \frac{|q_c|}{m_c} \sim \sqrt{\frac{4m_D^2 - 4m_c^2}{4m_c^2}} \sim 0.88 > v_{\text{decay}}$$

Direct impact the approximation of production models

Color evaporation model (CEM)

❑ Transition distribution:

- ✧ vanishes above the open charm threshold
- ✧ independent of pair's mass and color, and
- ✧ is a constant

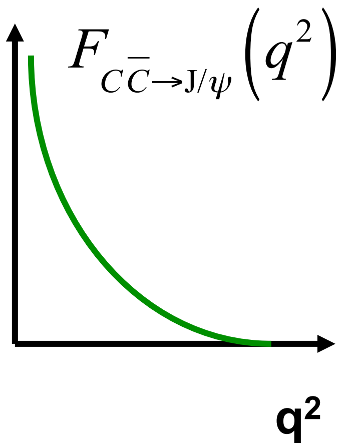


$$\sigma^{\rm CEM}_{AB\to J/\psi}(P_{J/\psi}) \approx F_{c\bar{c}\to J/\psi}\int_0^{4m_D^2-4m_c^2} dq^2\,\left[\sigma_{AB\to c\bar{c}}(q^2)\right]$$

- ✧ One transition constant for each heavy quarkonium state
- ✧ Heavy quark mass Is only another "adjustable" parameter

Non-Relativistic QCD (NRQCD) model

- Transition distribution
  - Narrowly peaked distribution at $q^2 \ll m_c^2$
  - Velocity expansion is a good approximation $v \sim |q|/m_c$
  - Perturbatively defined color singlet and octet states $m_c \gg \Lambda_{\rm QCD}$



$$\sigma_{AB\to[Q\bar{Q}](n)}(q^2) \approx \sum_m \frac{[q^2]^m}{m!}\left[\frac{d}{dq^2}\right]^m \sigma_{AB\to[Q\bar{Q}](n)}(q^2=0)$$

$$\sigma_{AB\to J/\psi}(P_{J/\psi}) \approx \sum_{n,m}\left[\frac{d}{dq^2}\right]^m \sigma_{AB\to[Q\bar{Q}](n)}(q^2=0)$$

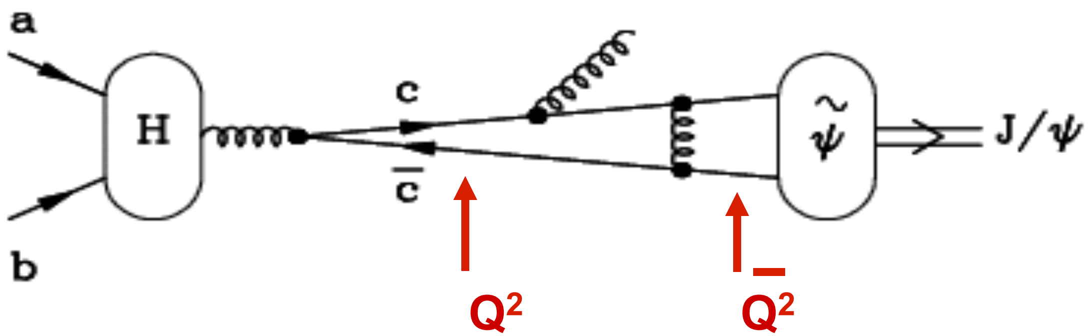
$$\times \int dq^2 \frac{[q^2]^m}{m!} F_{[Q\bar{Q}(n)]\to J/\psi}(q^2)$$

$$\approx \sum_{\mathcal{O}} \sigma_{AB\to\mathcal{O}}(q^2=0)\langle\mathcal{O}^{J/\psi}\rangle$$

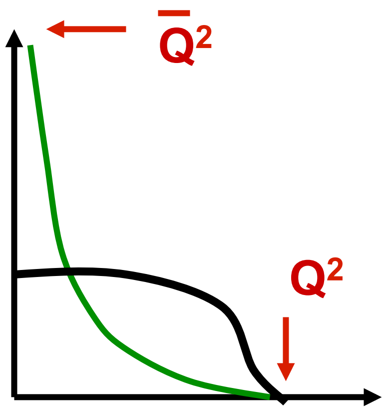
- Velocity expansion might have large corrections:

  v_{prod}~0.88 for m_c=1.4GeV

Role of semihard gluon radiation



- Over 6 GeV^2 phase space for gluon radiation
- Pair with large q^2 has a vanishing chance to become J/ψ in NRQCD Model
- Radiation pays a penalty in coupling
  But, gains a lot on wave function

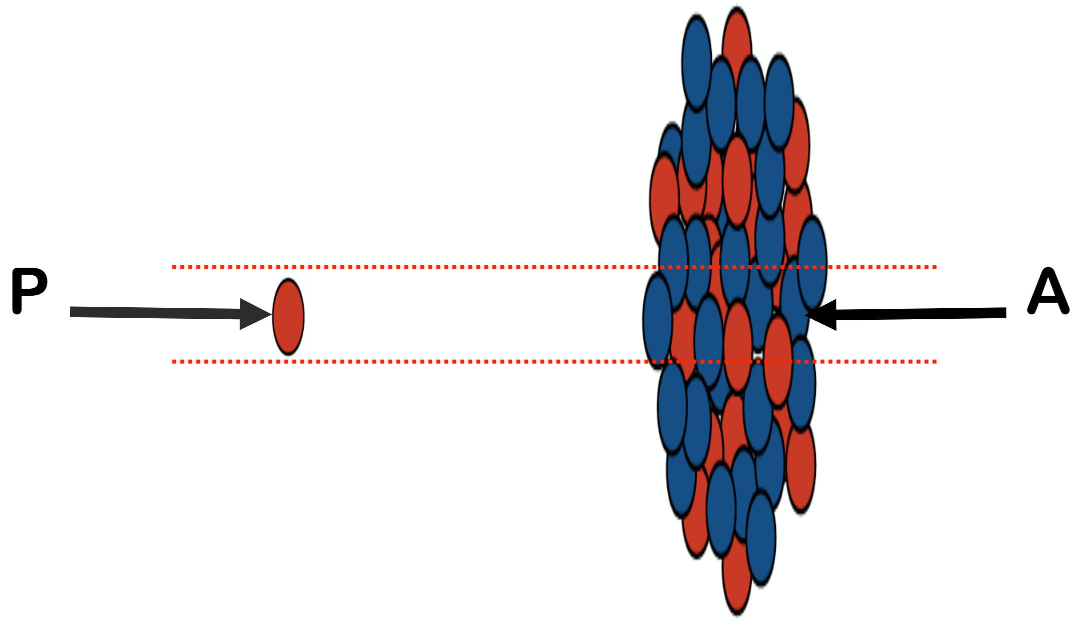


$$a_s(Q^2)\ \ln(Q^2/4M_c^2)\ F(4M_c^2)$$

Threshold behavior for the transition distribution!

Heavy quarkonium in p(d)-A collisions

❑ Proton (deuteron) – Nucleus Collisions:



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

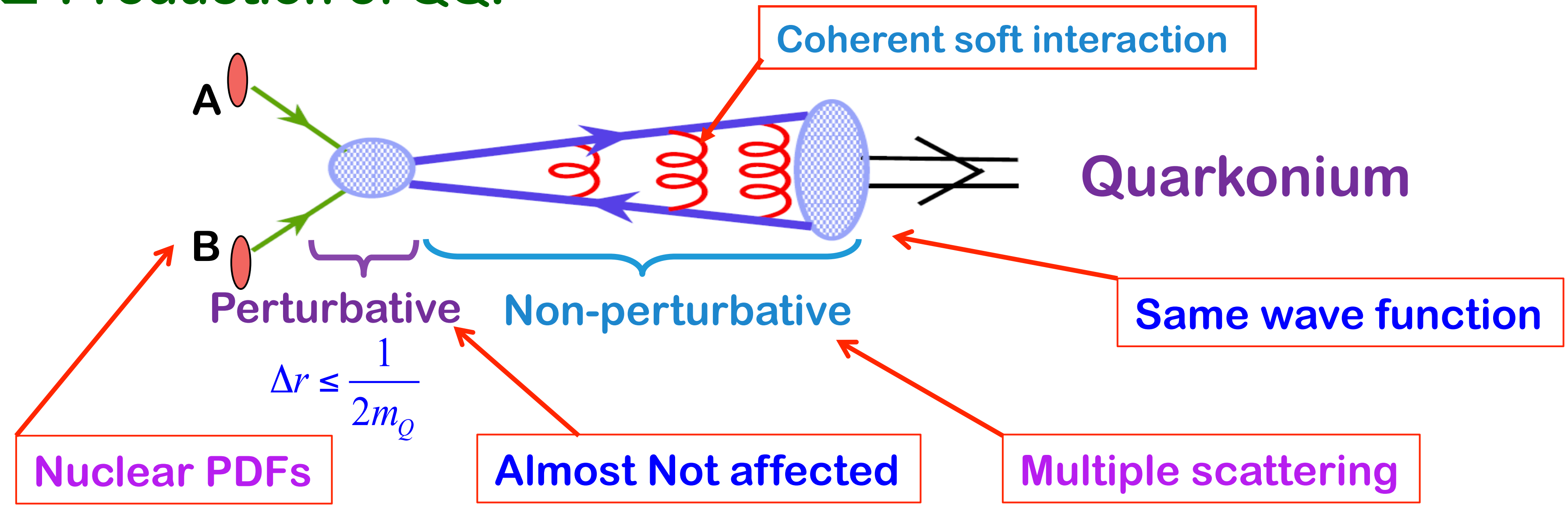
✧ Necessary calibration for AA collisions

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

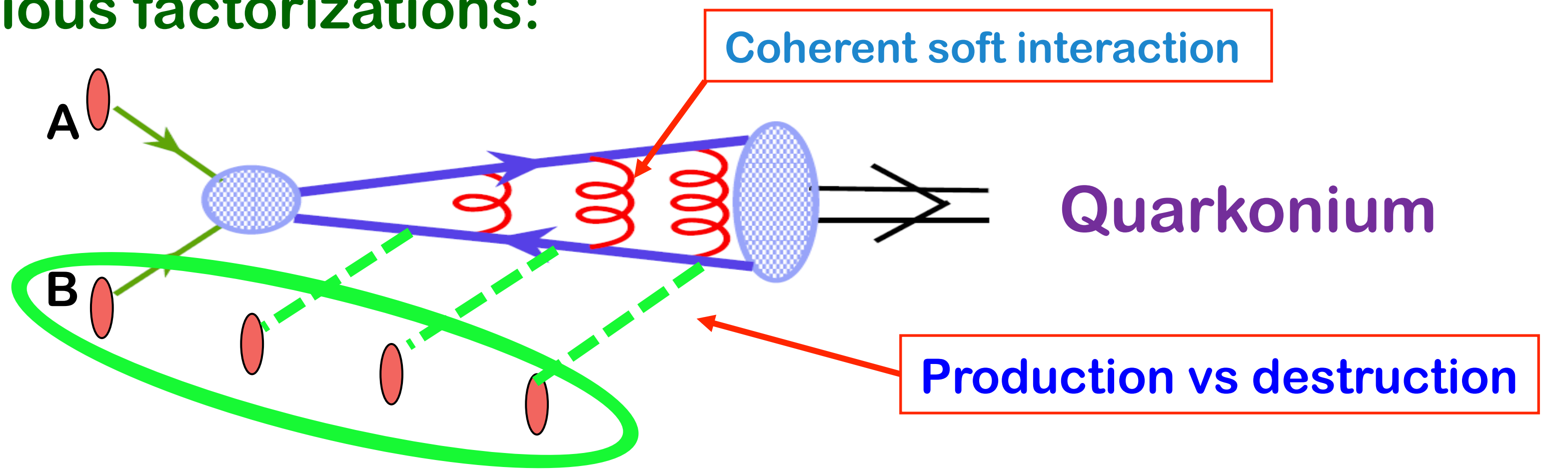
Nucleus is not a simple superposition of nucleons!

Production in pA collisions

- Production of $Q\bar{Q}$:



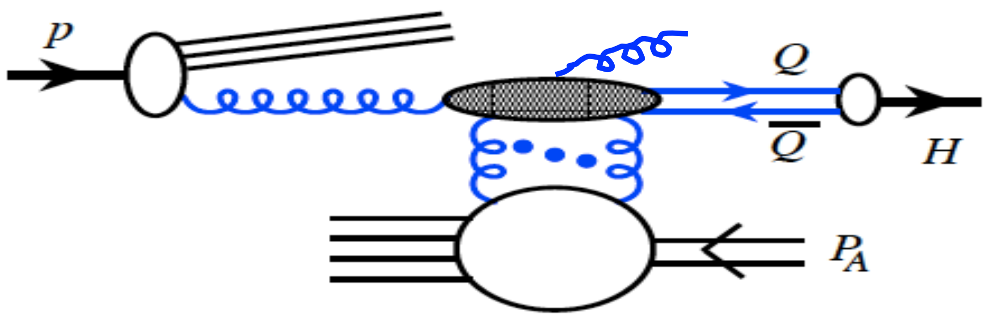
- Various factorizations:



Production in pA collisions

See Arleo's talk on Friday

- Incoherent multiple scattering on a "gluon":

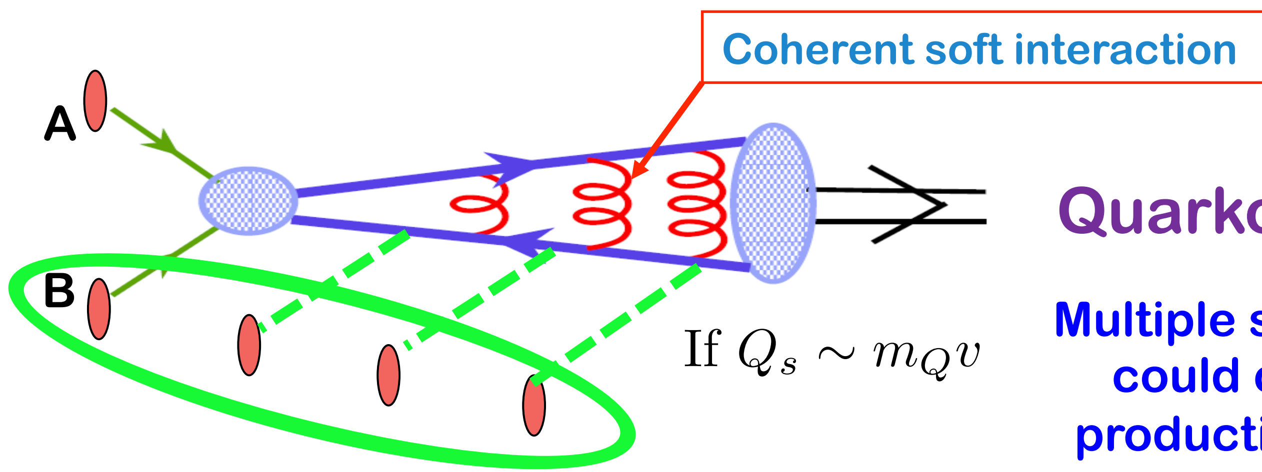


✧ Leads to a shift in y and p_T

- Suppression in forward y
- Broadening in p_T

Without including shadowing, this leads to the same production rate if integrating over y and p_T

- Multiple scattering resolves the quark and antiquark:

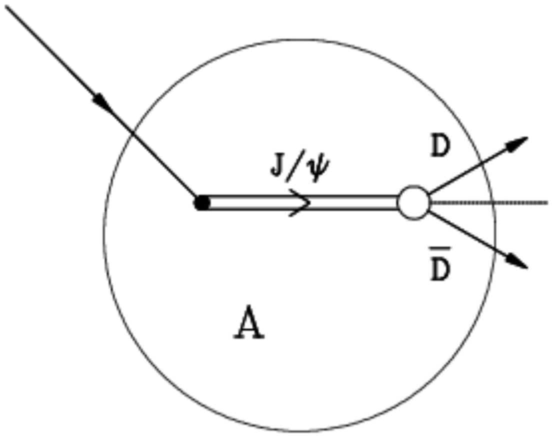


Quarkonium

Multiple scattering could change production rate!!

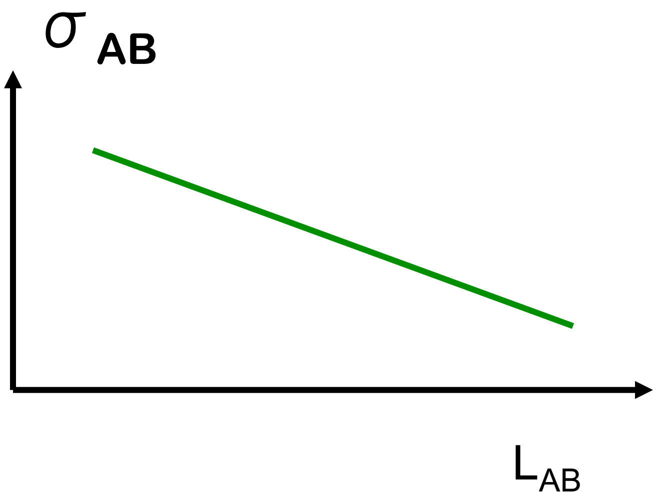
Production in pA collisions

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



- Glauber model:

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



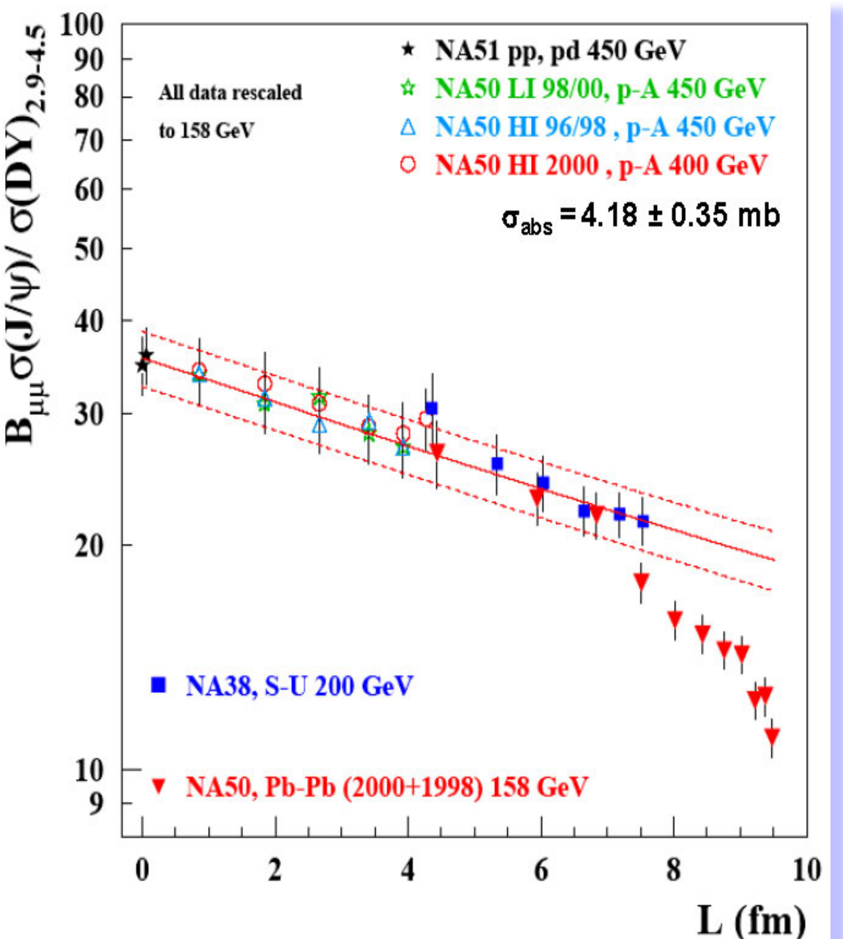
- Expect a straight line on a semi-log plot

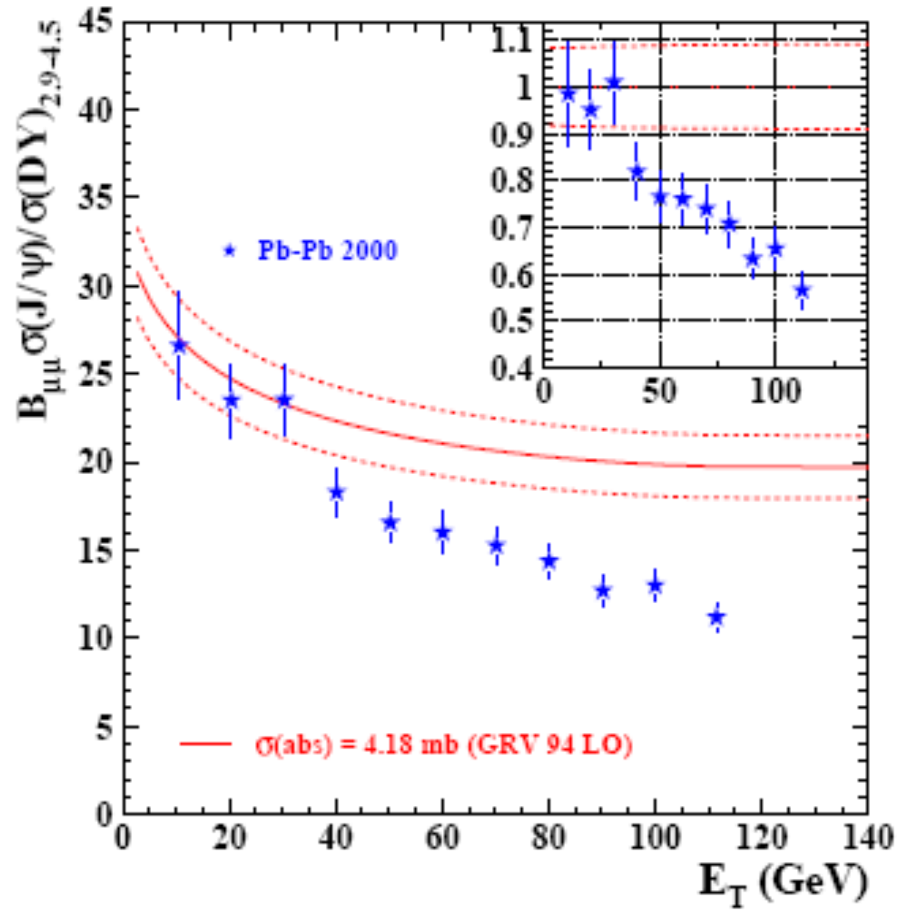
- Need a much too larger σ_{abs}

Suppression in total production rate

- **Anomalous suppression:**

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





Suppression in total production rate

- Multiple scattering in A:
- Final-state:

  Increases the relative momentum of the pair

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

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

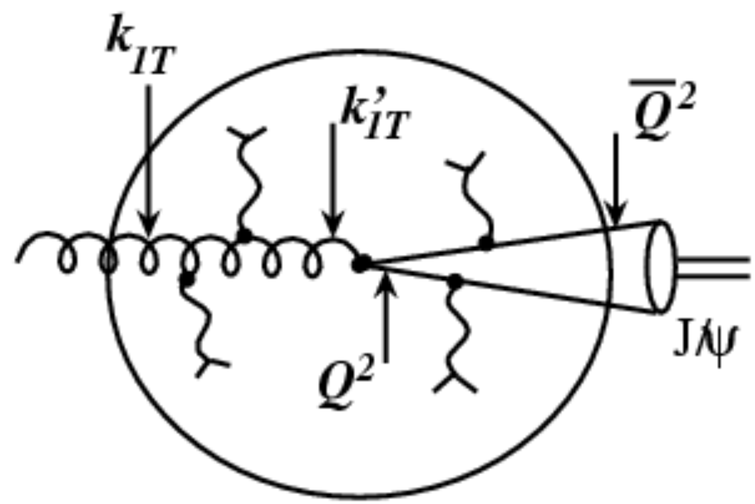
  Suppression of J/ψ

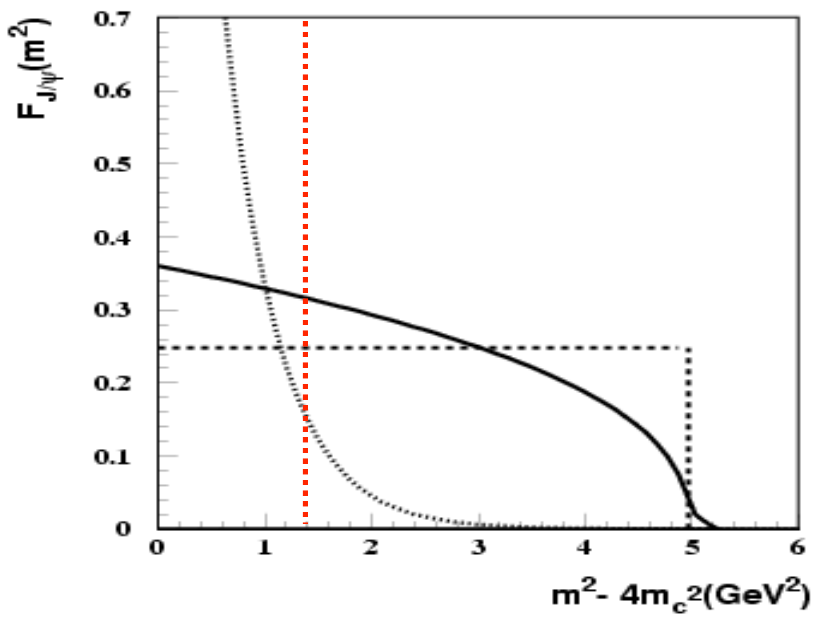
  $$\varepsilon \sim \hat{q} \sim \langle \Delta q_T^2 \rangle$$

- Threshold effect leads to different effective σ_{abs}

  Curved line for R_{pA}

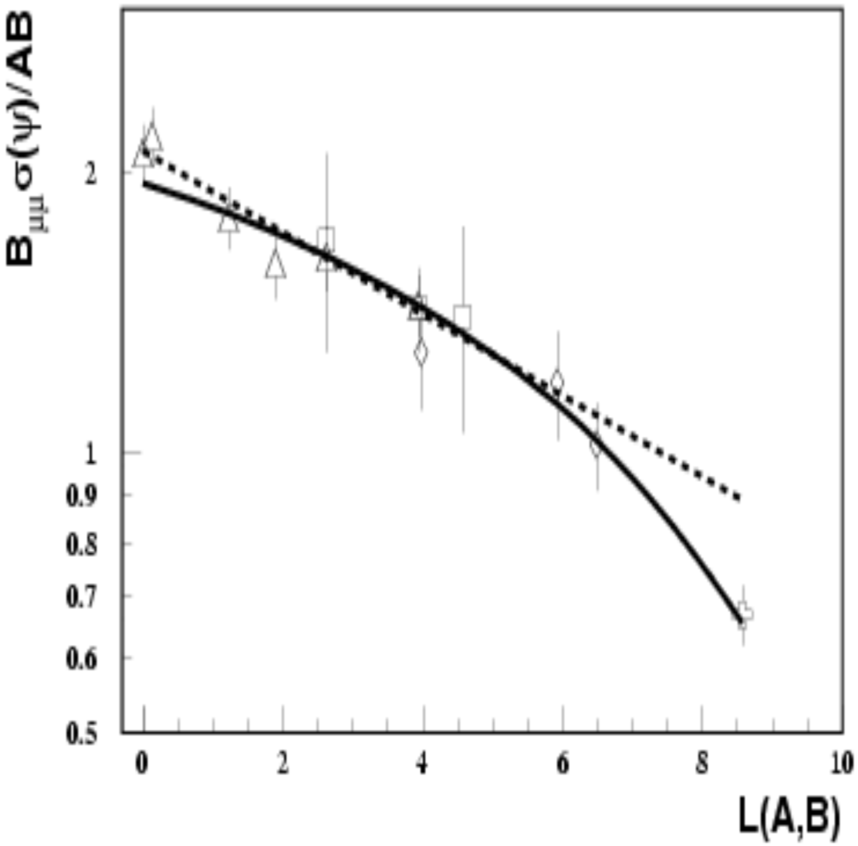
- Different suppression for ψ'

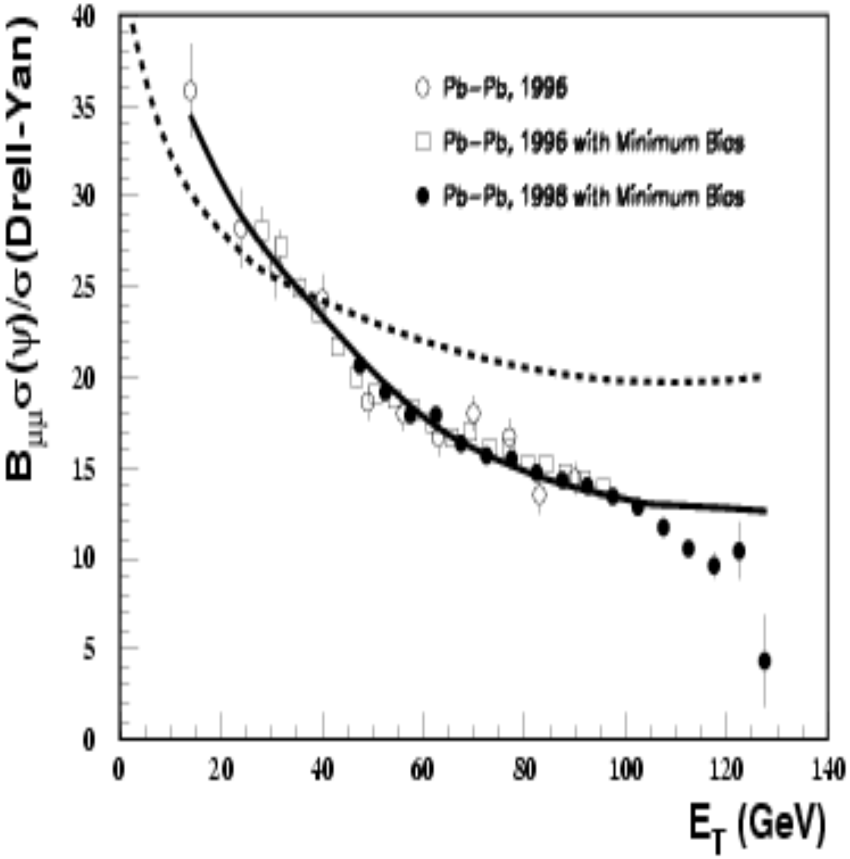




Suppression in total production rate

Qiu, Vary, Zhang, PRL 2002





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

✧ Exact shape of transition distribtions?

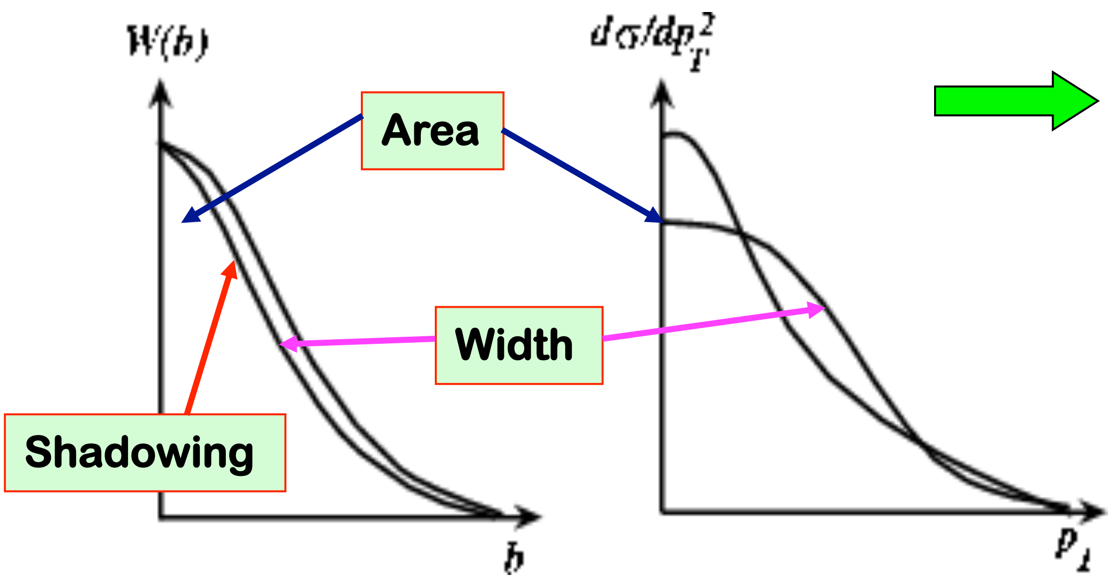
✧ Transverse momentum broadening

Quarkonium pT distribution

- Quarkonium production is dominated in low p_T region
- Both quarkonium and Drell-Yan low p_T distributions at collider energies are determined by the gluon shower of incoming partons (initial-state effect)

Qiu, Zhang, PRL, 2001

- Because of heavy quark mass, final-state interactions suppress the formation of J/ψ, but should not be an important factor for low p_T spectrum

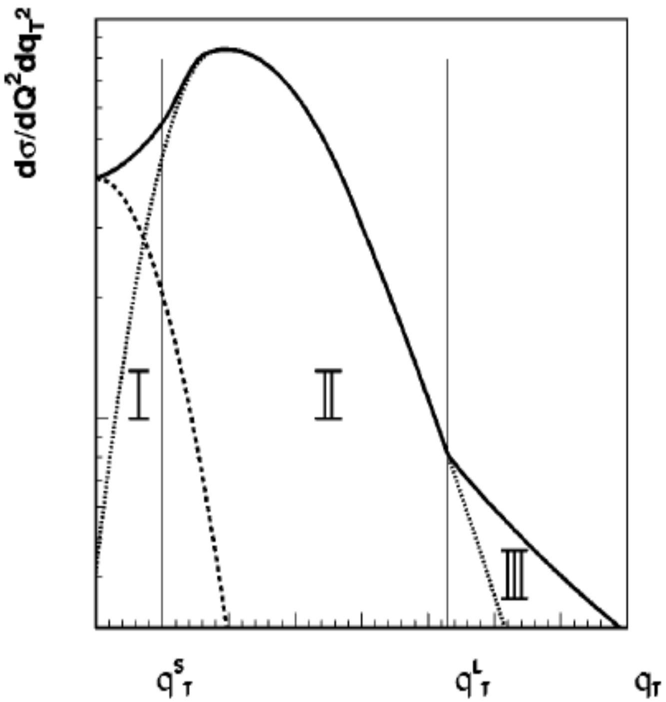


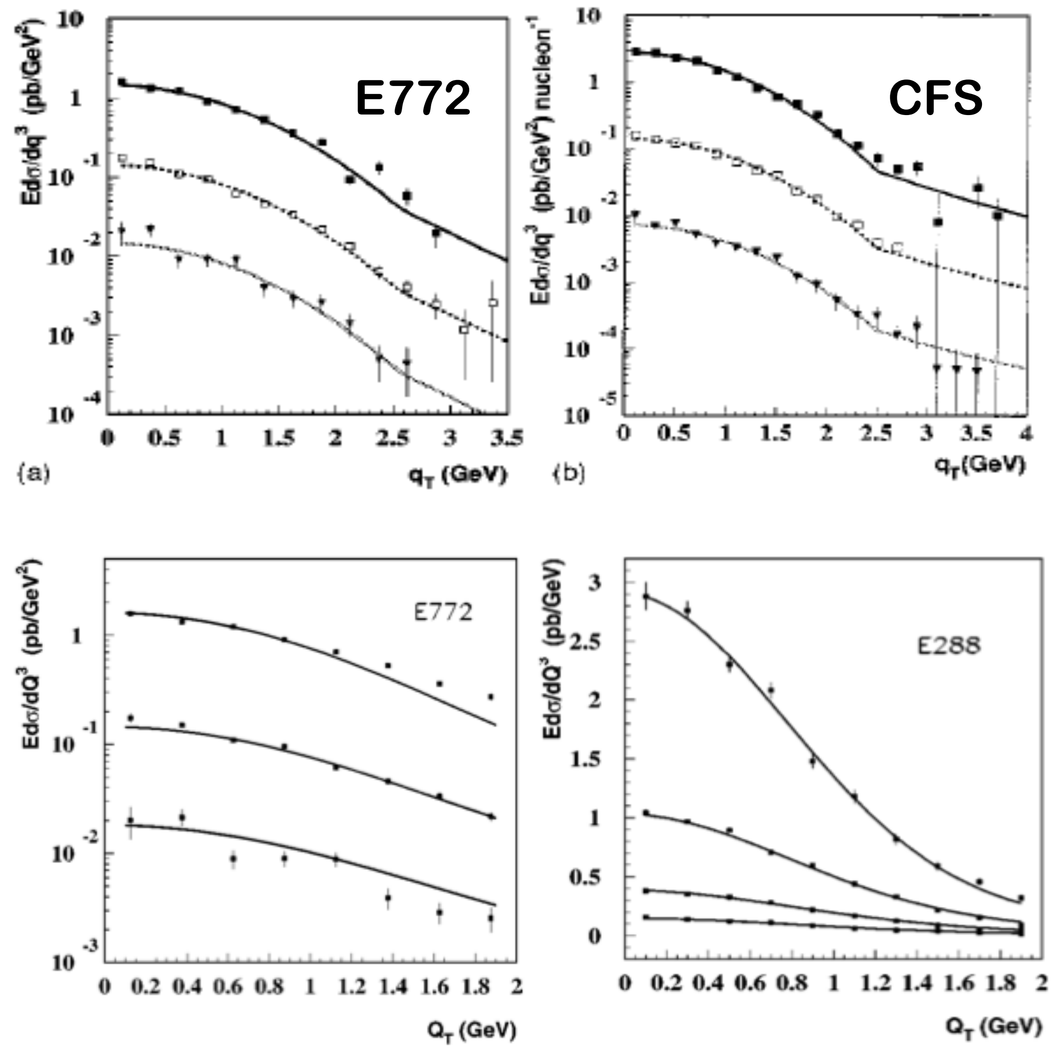
- ✧ Similar p_T broadening, but, different magnitude
- ✧ Extra overall suppression for J/ψ

Guo, Qiu, Zhang, PRL, PRD, 2000

Quarkonium pT distribution

❑ **PT spectrum is not completely perturbative:** Guo, Qiu, Zhang, PRD 2002





I) **Intrinsic**

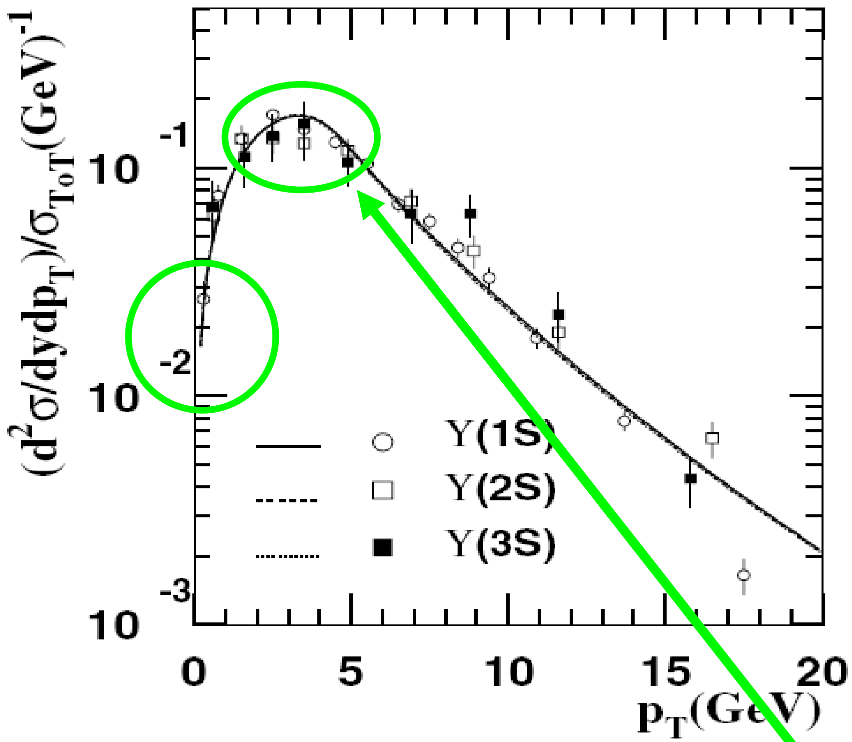
II) **Shower – Sudakov**

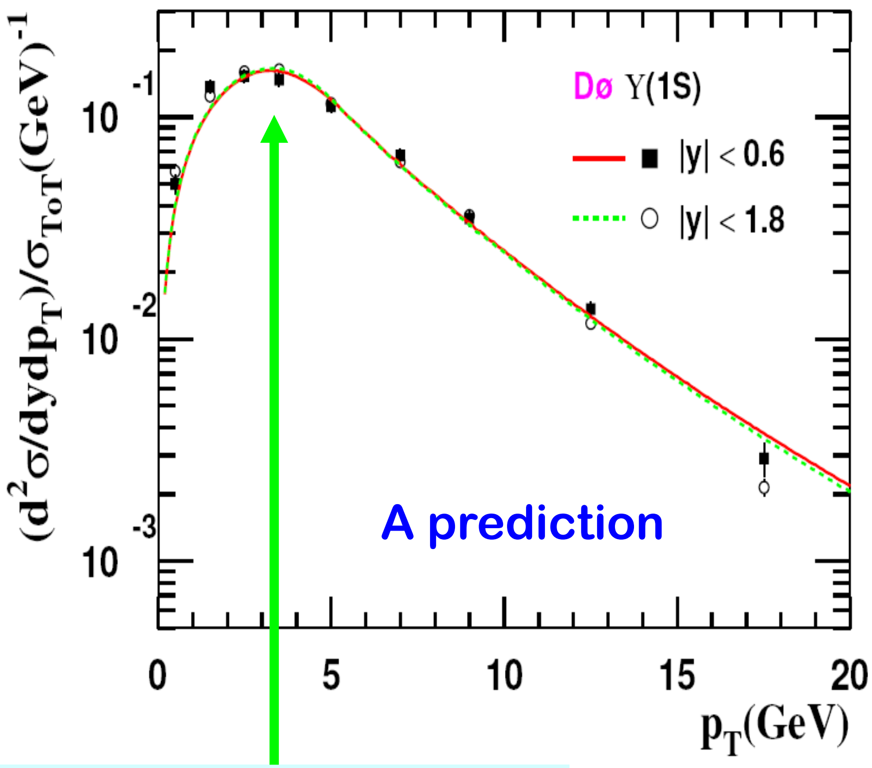
III) **Perturbative tail**

Quarkonium pT distribution

- Υ-spectrum is almost perturbative:

Berger, Qiu, Wang, PRD 2005





I) Intrinsic

II) Shower – Sudakov

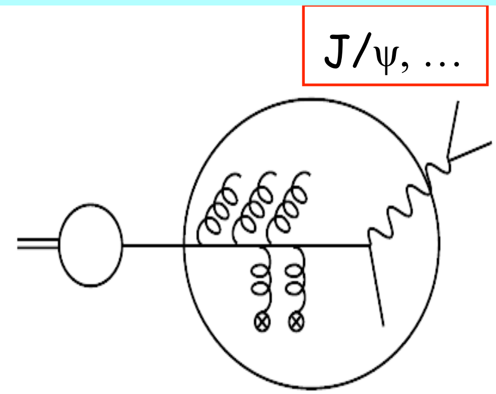
III) Perturbative tail

Dominated by perturbative small-b contribution in its Fourier conjugate space

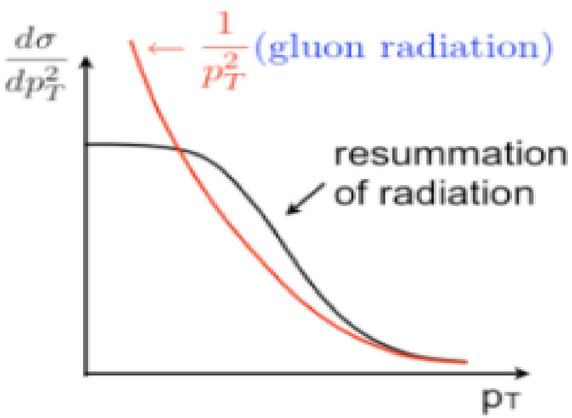
all order resummation of soft gluon shower

A-dependence of the pT distribution

- **Multiple scattering in medium:**
  - Each scattering is too soft to calculate perturbatively
  - Resummation + multiple scattering (small-x limit)



- **Moment of P_T-distribution:**
  - more inclusive – calculable
  - based on observed particles only
  - less sensitive to hadronization



- **Broadening:**
  - Sensitive to the medium properties
  - Perturbatively calculable

$$\langle (q_T^2)^n \rangle = \frac{\int dq_T^2 (q_T^2)^n \, d\sigma/dq_T^2}{\int dq_T^2 \, d\sigma/dq_T^2}$$

$$\Delta \langle q_T^2 \rangle = \langle q_T^2 \rangle_{AB} - \langle q_T^2 \rangle_{NN}$$

A-dependence of the P_T distribution

- Ratio of x-sections:

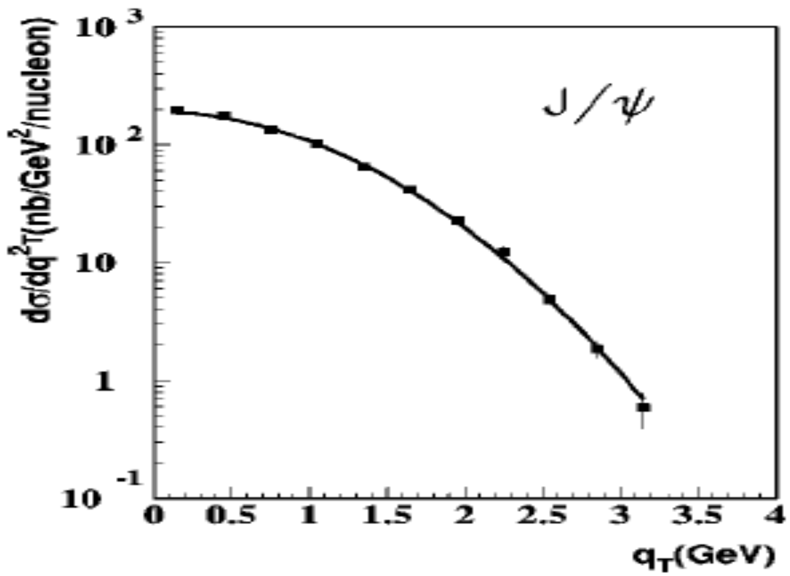
Guo, Qiu, Zhang, PRL, PRD 2002

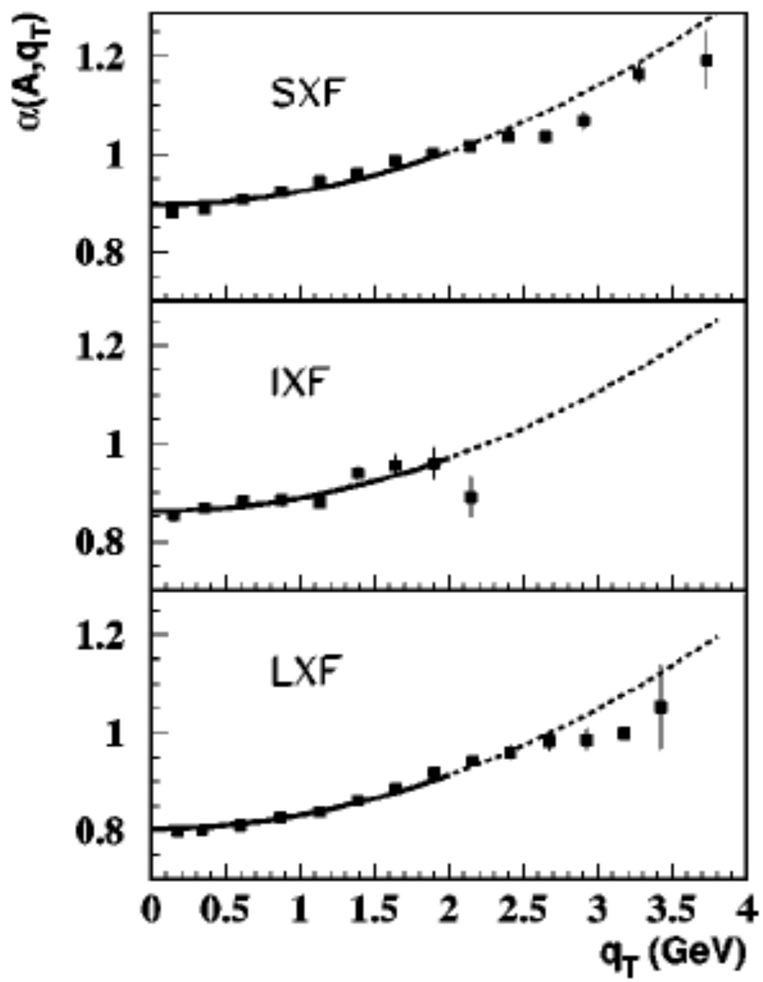
$$R(A,q_T) \equiv \frac{1}{A}\frac{d\sigma^{hA}}{dQ^2\,dq_T^2} \Big/ \frac{d\sigma^{hN}}{dQ^2\,dq_T^2} \equiv A^{\alpha(A,q_T)-1}$$

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

Similar formula for J/ψ

- Spectrum and ratio:

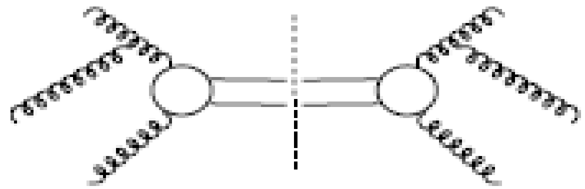




Broadening of heavy quarkonia

Kang, Qiu, PRD77(2008)

- **Initial-state only:**



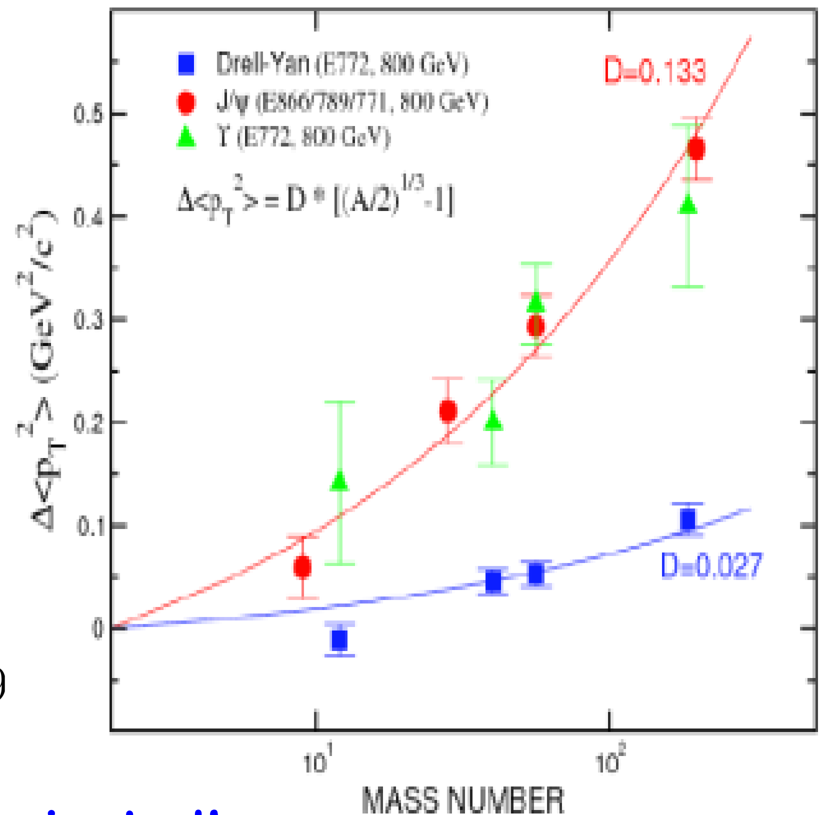
$$\Delta\langle q_T^2\rangle^{(I)}_{J/\psi} = C_A\left(\frac{8\pi^2\alpha_s}{N_c^2-1}\,\lambda^2\,A^{1/3}\right)$$

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

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

Clear $A^{1/3}$ dependence

But, wrong normalization!



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

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

Final-state effect – octet channel dominated!

Only depend on observed quarkonia

J.C.Peng, hep-ph/9912371

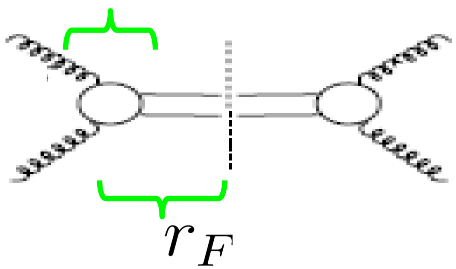
Johnson,et al, 2007

Final-state multiple scattering

Kang, Qiu, PRD77(2008)

- **Heavy quarkonium is unlikely to be formed when the heavy quark pair was produced**

$$r_H \leq \frac{1}{2m_c} \sim \frac{1}{15}\,\mathrm{fm}$$



- ✧ **If the formation length:** $r_F \leq R_N \sim 1\mathrm{fm}$

  no A-enhancement from final-state interaction

- ✧ **If the formation length:** $r_F \geq R_A$

  additional $A^{1/3}$-type enhancement from the final-state interaction

- **Final-state effect depends on how quarkonium is formed**

  NRQCD model, color evaporation model, …

Color evaporation model

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

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

- **Multiparton correlation:**

$$\begin{aligned} T^{(F)}_{g/A}(x) = T^{(I)}_{g/A}(x) &= \int \frac{dy^-}{2\pi} e^{ixp^+y^-} \int \frac{dy_1^- dy_2^-}{2\pi} \theta(y^- - y_1^-)\theta(-y_2^-) \\ &\quad \times \frac{1}{xp^+} \langle p_A | F_\alpha{}^+(y_2^-) F^{\sigma +}(0) F^+{}_\sigma(y^-) F^{+\alpha}(y_1^-) | p_A \rangle \\ &= \lambda^2 A^{4/3} \phi_{g/A}(x) \end{aligned}$$

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

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

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

NRQCD model

- Cross section:

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

- Broadening:

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

Hard parts:

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

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

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

Only color octet channel contributes

- Leading features:

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

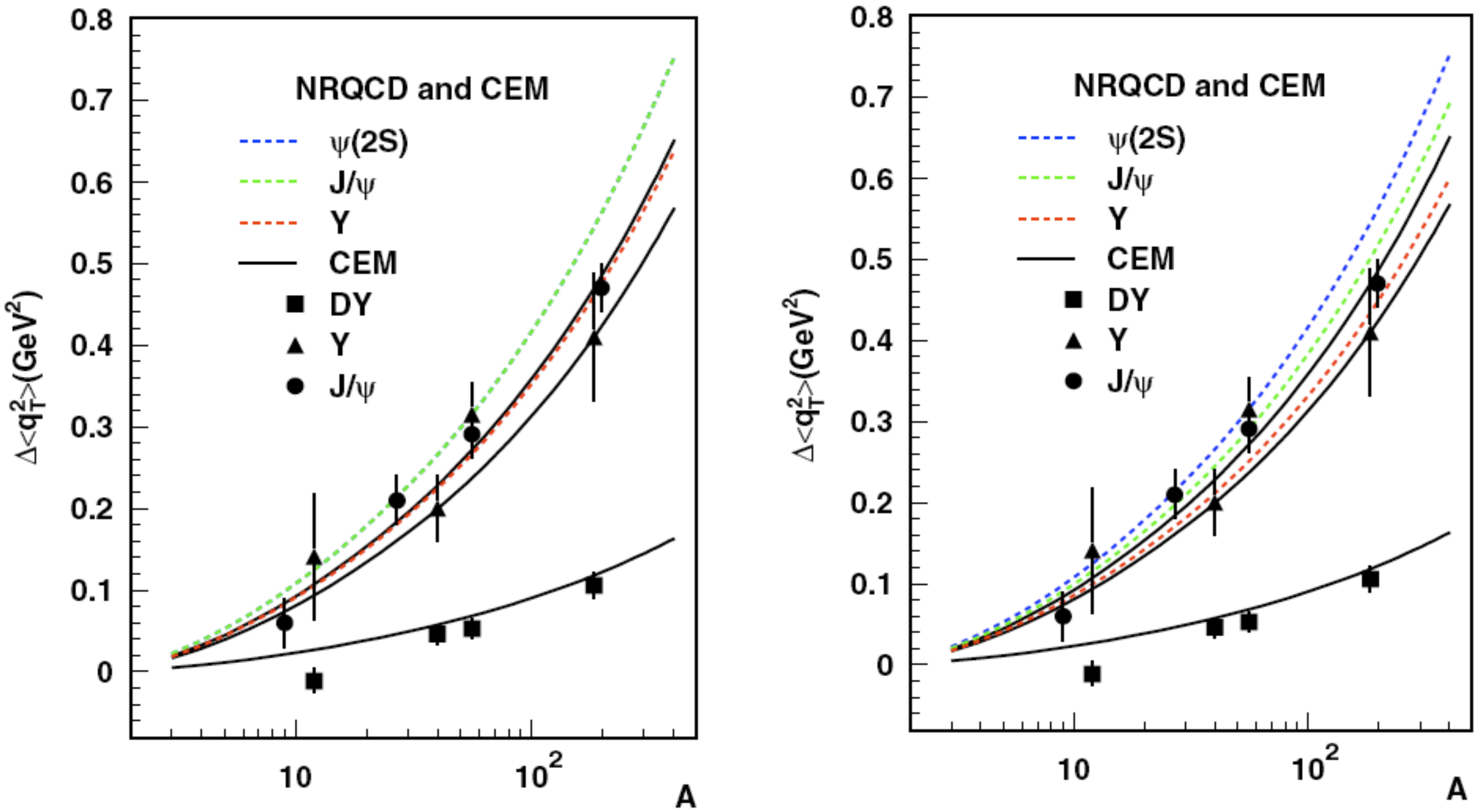
Broadening of heavy quarkonia in p(d)+A

- Final-state effect is important:

Kang, Qiu, PRD77(2008)

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

in both CEM and NRQCD



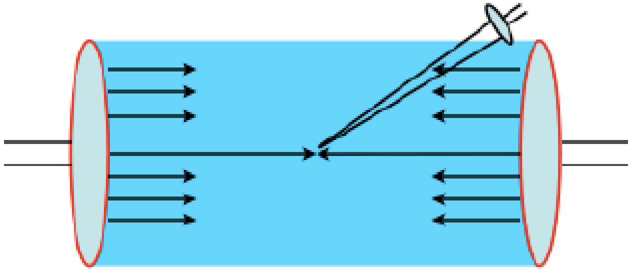
- Mass – independence, not very sensitive to the feeddown

Broadening of heavy quarkonia in A+A

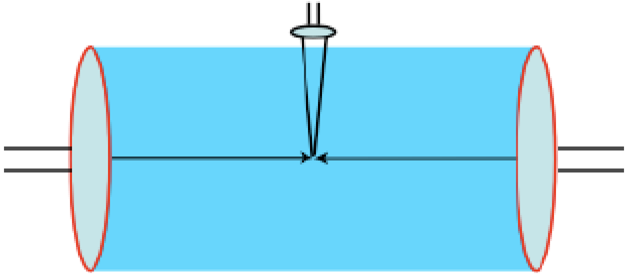
- If no hot medium was formed:

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

Superposition of pA

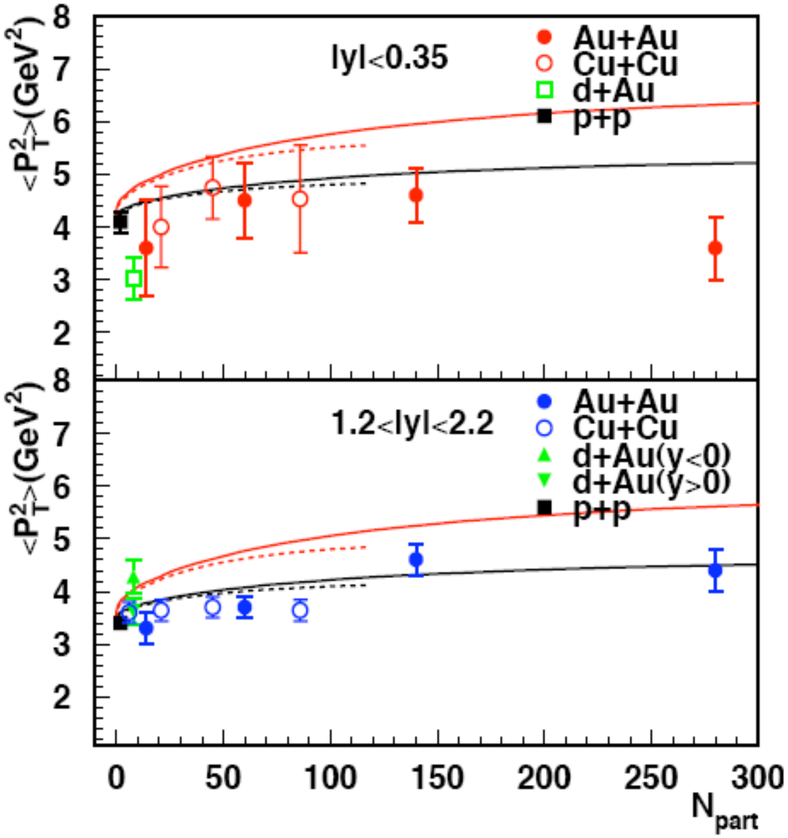


- If hot medium is formed:



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

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

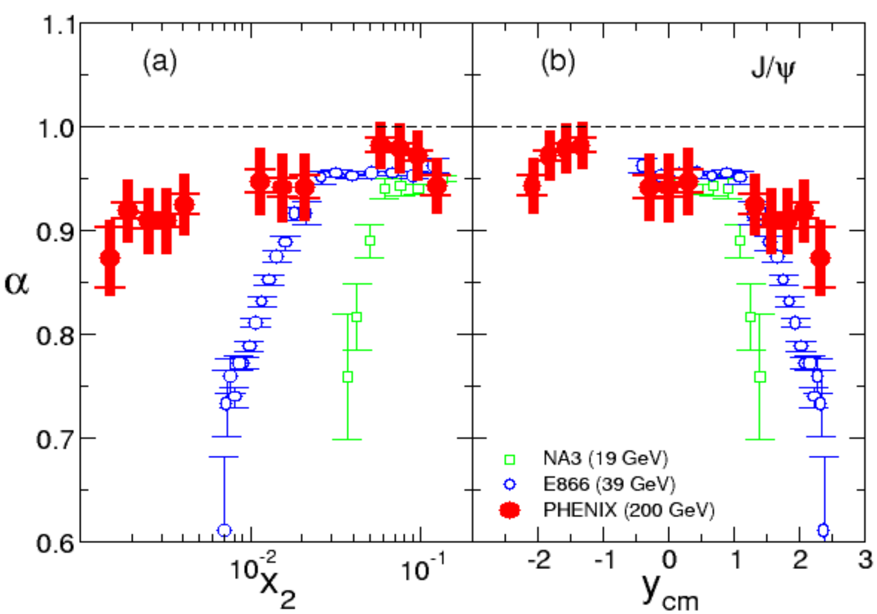


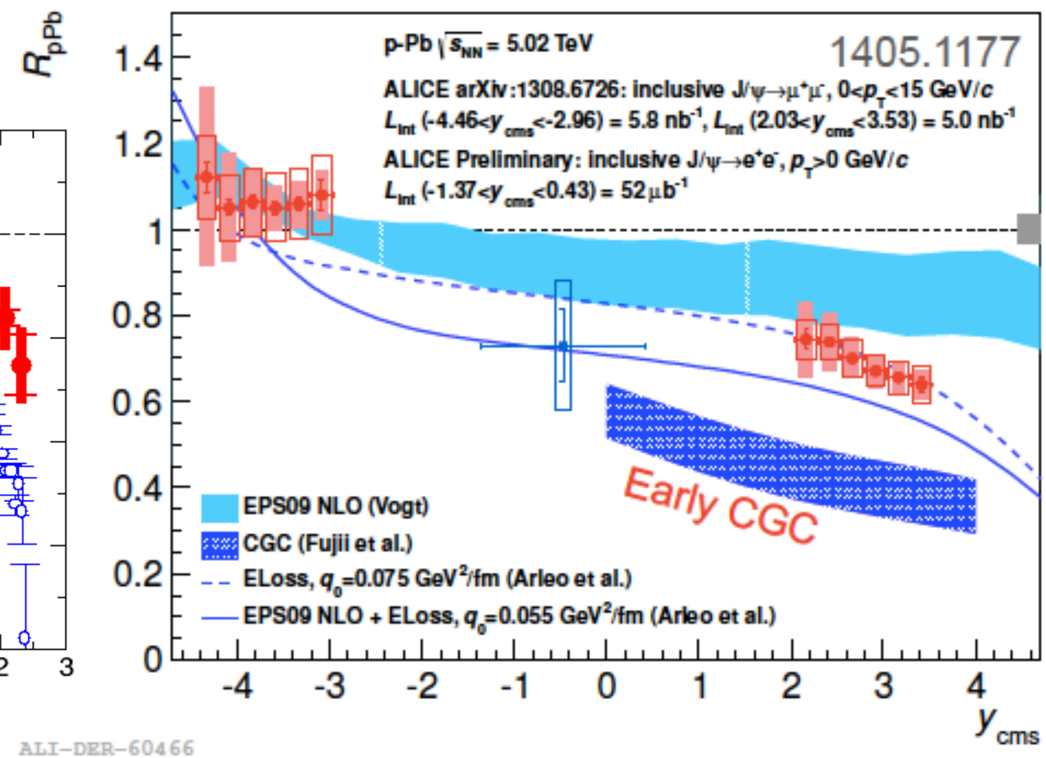
$\Delta\langle q_T^2\rangle_{AA}$ **could be less than 0!**

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)**

Multiple scattering in DIS

- **Consequence of OPE for inclusive DIS:**

$$\sigma^h_{phys} = \hat{\sigma}^i_2 \otimes [1 + C^{(1,2)}\alpha_s + C^{(2,2)}\alpha_s^2 + \ldots] \otimes T_2^{i/h}(x)$$
$$+ \frac{\hat{\sigma}^i_4}{Q^2} \otimes [1 + C^{(1,4)}\alpha_s + C^{(2,4)}\alpha_s^2 + \ldots] \otimes T_4^{i/h}(x)$$
$$+ \frac{\hat{\sigma}^i_6}{Q^4} \otimes [1 + C^{(1,6)}\alpha_s + C^{(2,6)}\alpha_s^2 + \ldots] \otimes T_6^{i/h}(x)$$
$$+ \ldots$$

Leading twist

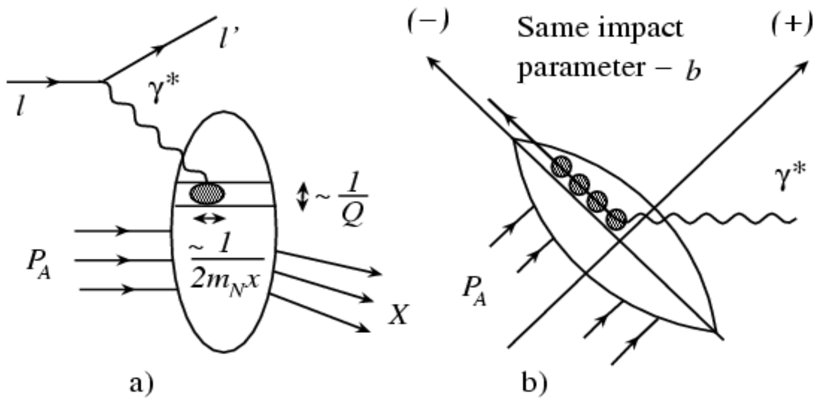
Power corrections

- **Predictive power:**
  - Coefficient functions are IR safe
  - Distributions/correlations/matrix elements are universal

- **Distributions are defined to remove all collinear divergences of the partonic scattering**

Size of power corrections

❑ **Coherent multiple scattering**



2D lightcone dynamics

$$d\sigma \approx d\sigma^{(S)} + d\sigma^{(D)} + \ldots$$

Naïve power counting:

$$\frac{d\sigma^{(D)}}{d\sigma^{(S)}} : \quad \alpha_s \frac{1/Q^2}{R^2} \left\langle F^{+\alpha} F_\alpha^+ \right\rangle A^{1/3}$$

❑ **Medium parton density:** $\left\langle F^{+\alpha} F_\alpha^+ \right\rangle$

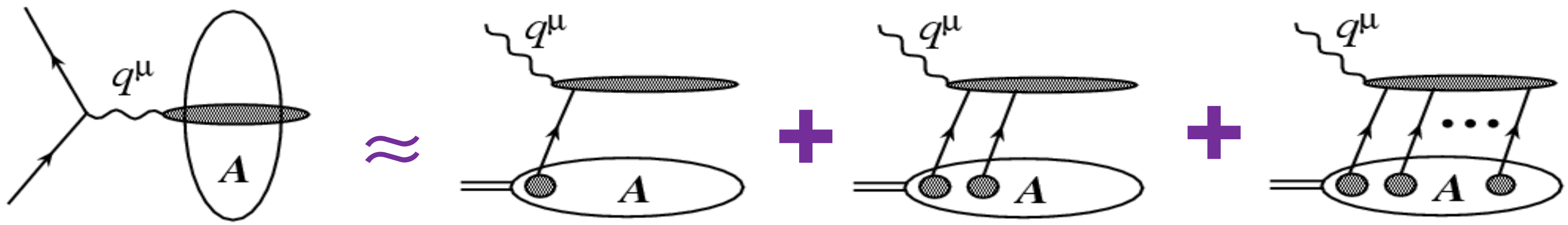
❑ **For a hard probe:** $\dfrac{\alpha_s}{Q^2 R^2} = 1$

❑ **Nuclear size enhancement:** $A^{1/3} \le 6$

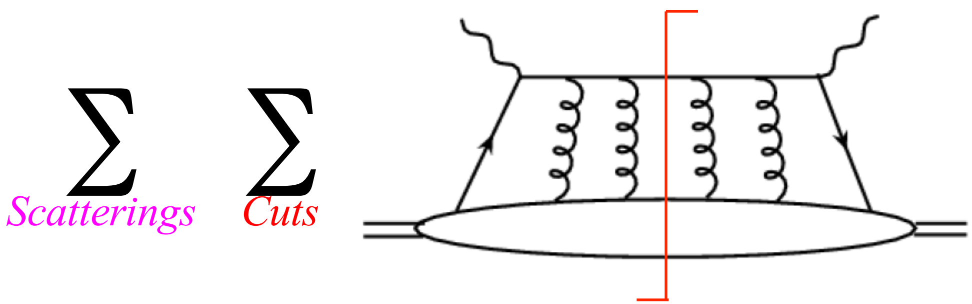
❑ **Small x enhancement:** $-\dfrac{\partial}{\partial x}\varphi(x)$

Tree-level power corrections to DIS

- At small x, the hard probe covers several nucleons, coherent multiple scattering could be equally important at low Q



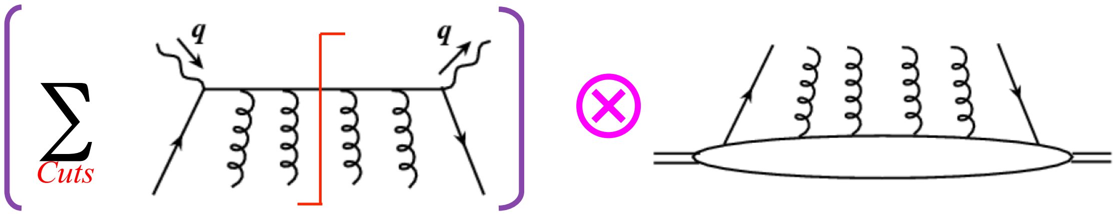
- To take care of the coherence, we need to sum over all cuts for a given forward scattering amplitude



Summing over all cuts is also necessary for IR cancellation

Multi-parton correlation functions

❑ Parton momentum convolution:



$$\propto \int \prod_i dy_i^- \; e^{i x_i p^+ y_i^-} \langle P_A | \prod_i F^{+\perp}(y_i^-) | P_A \rangle$$

All coordinate space integrals are **localized** if **x** is large

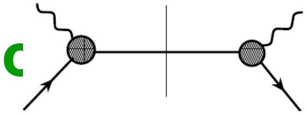
❑ Leading-pole approximation for dx_i integrals :

- ✧ dx_i integrals are fixed by the poles (no pinched poles)
- ✧ $x_i=0$ removes the exponentials
- ✧ dy integrals can be extended to the size of nuclear matter

Leading-pole leads to highest powers in medium length, a much smaller number of diagrams to worry about

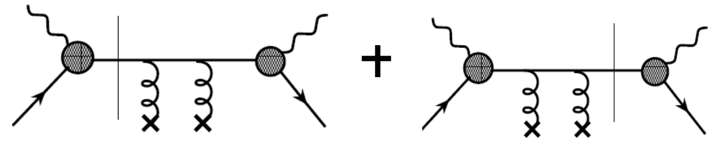
Multiple coherent scattering to DIS

❑ **LO contribution to DIS cross sectic**



$\Rightarrow \delta(x - x_B)$

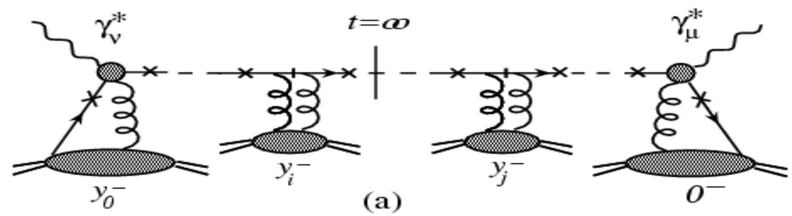
❑ **NLO contribution:**



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

$$\int \frac{dy_2^- dy_1^-}{(2\pi)^2}\left[F^{+\alpha}(y_2^-) F_\alpha^{\ +}(y_1^-)\right]\theta(y_2^-) \qquad x_B\left[-\frac{d}{dx}\delta(x - x_B)\right]$$

❑ **Nth order contribution:**



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

Infrared safe!

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

Resummed contribution to structure functions

- **Transverse structure function:**

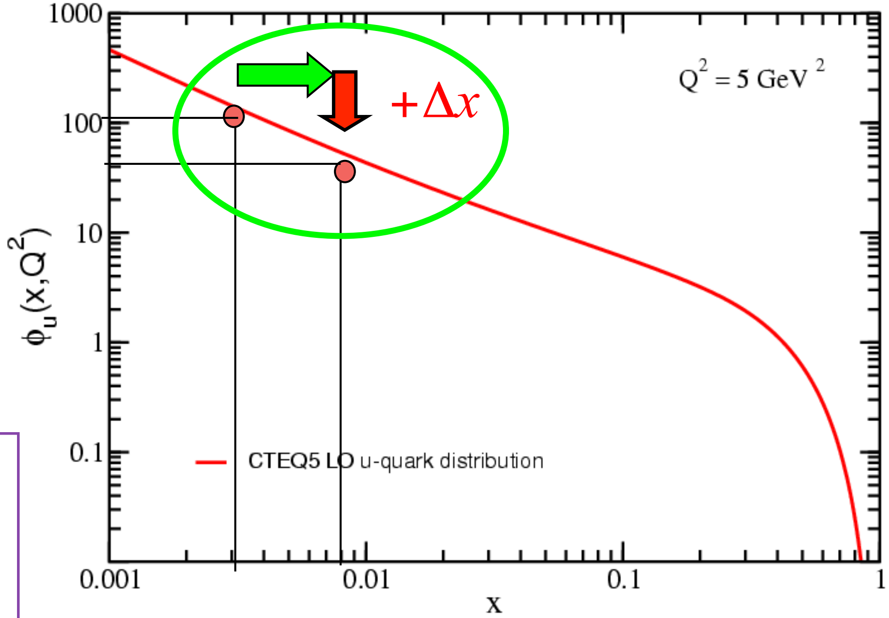
Qiu and Vitev, PRL (2004)

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

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

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

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

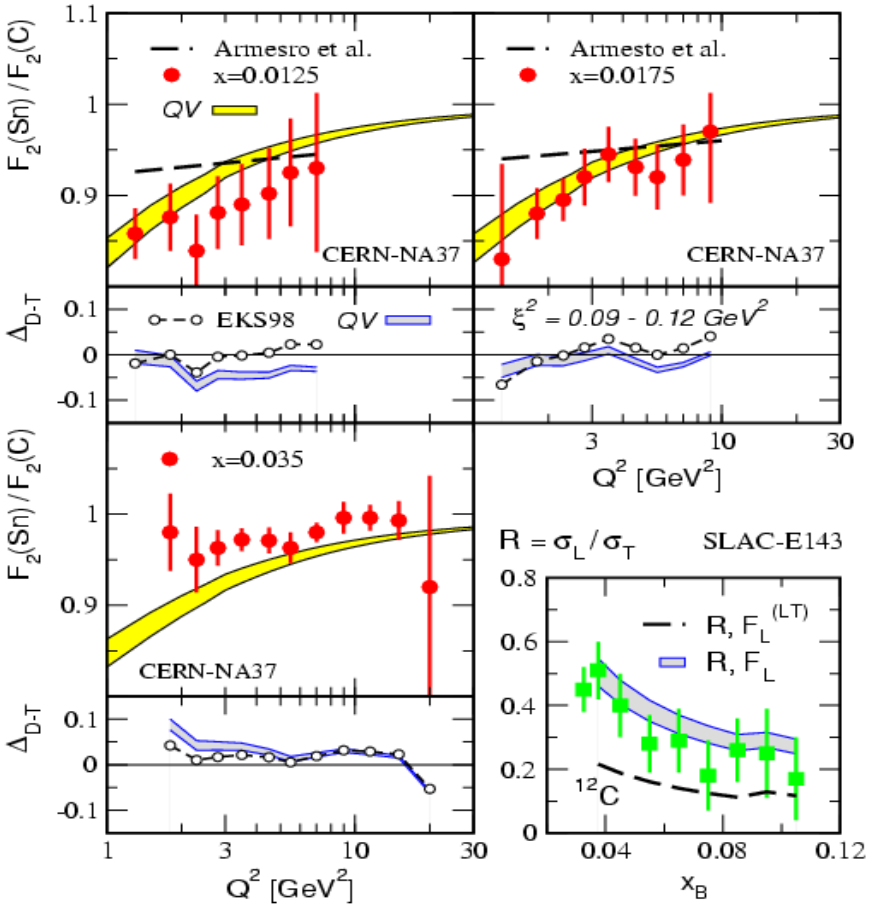


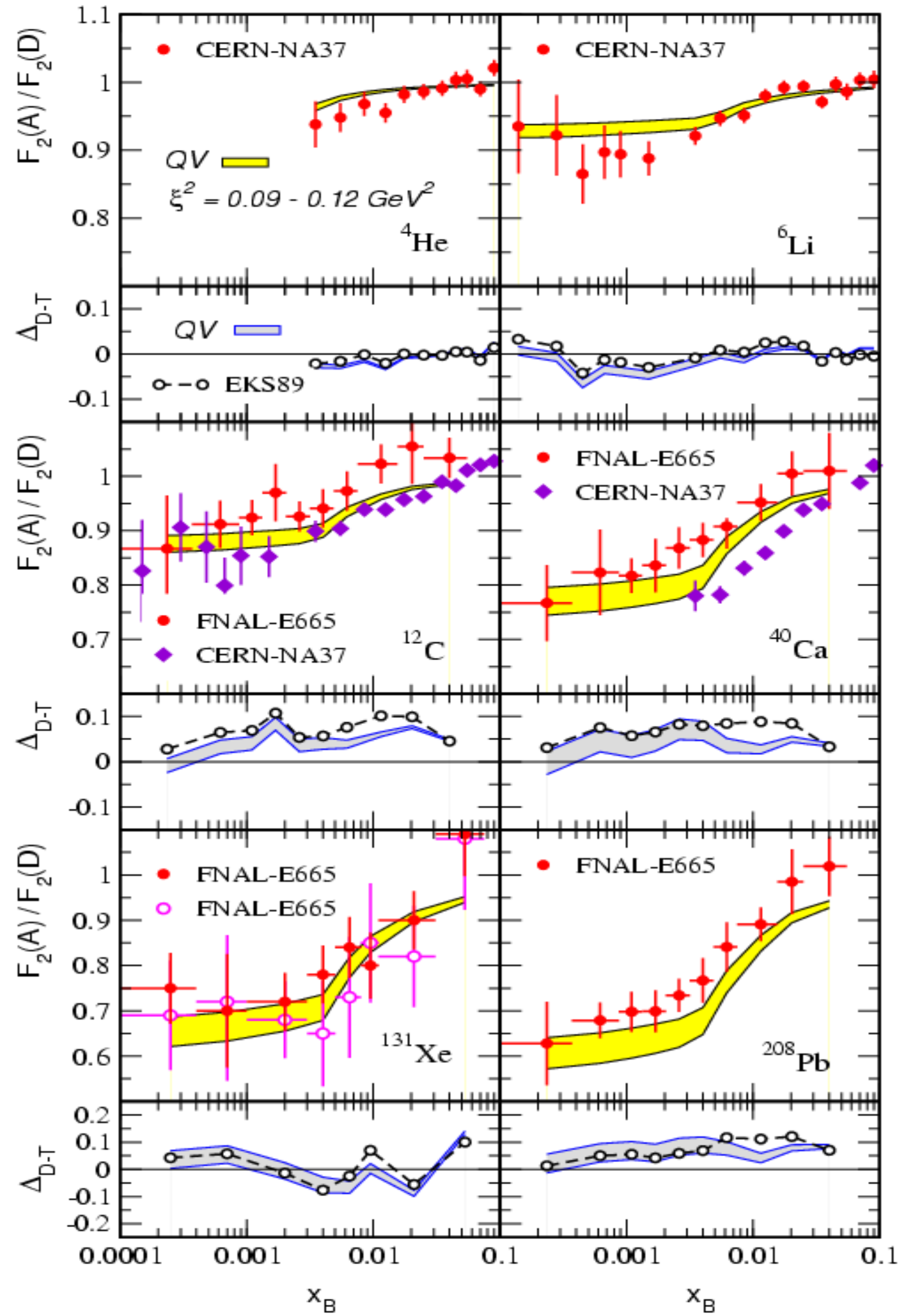
Single parameter for the power correction, and is proportional to the same characteristic scale

- **Similar result for longitudinal structure function**

Neglect LT shadowing upper limit of ξ^2

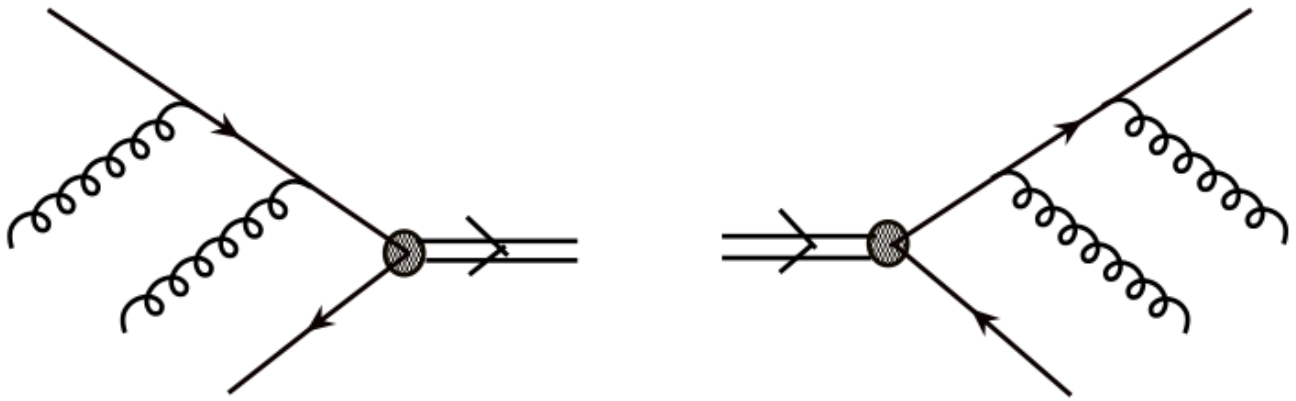
ξ^2 : 0.09 - 0.12 GeV^2





Rapidity dependence in p+A

❑ Resummed multiple scattering:



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

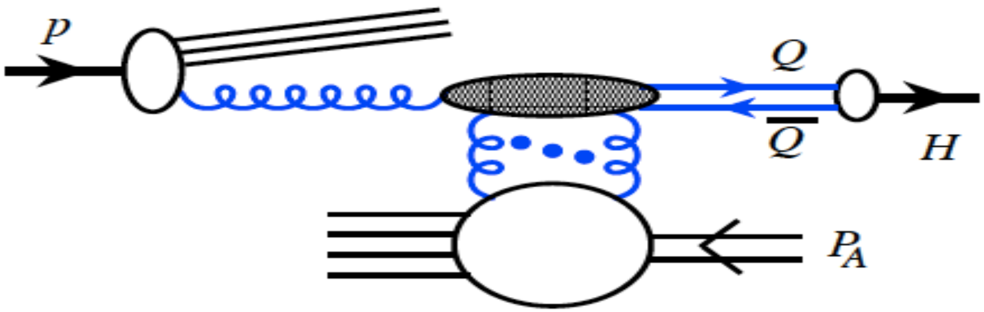
In the forward region,

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

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

Heavy quarkonium p_T distribution in pA

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



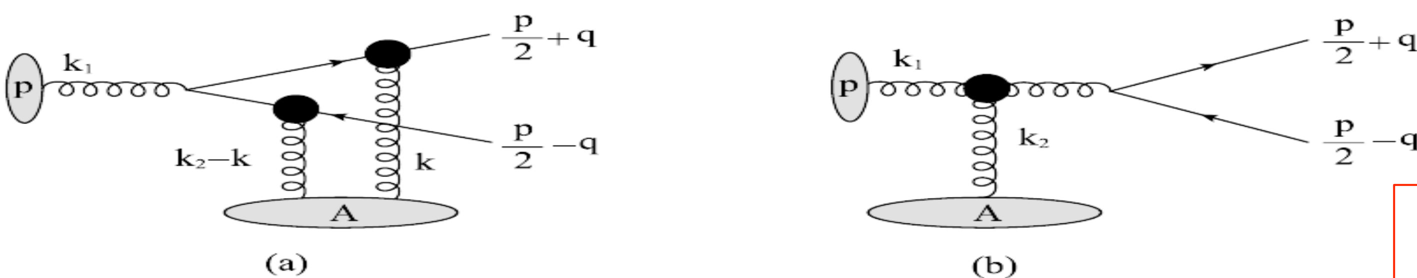
Time dilation factor:

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

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

Condition for multiple scattering not to interfere with hadronization

❑ Heavy quarkonium production in pA collisions:



No numerical prediction yet

✧ 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

Polarized p+A collisions

Excellent probe for distinguishing various contributions to SSA

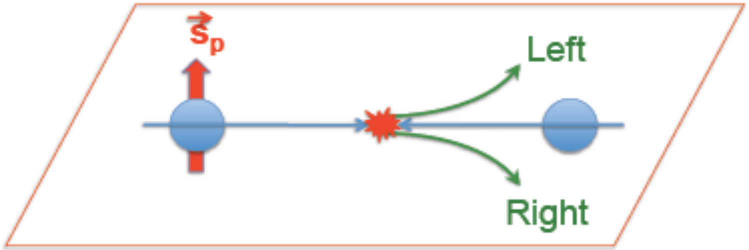
Excellent probe for studying small-x Physics

SSA increases as x_F (or y) increases

Polarized proton and A_N

❑ Definition:

Kang, Yuan, …



$$A_N \equiv \frac{\Delta\sigma(\ell,\vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell,\vec{s}) - \sigma(\ell,-\vec{s})}{\sigma(\ell,\vec{s}) + \sigma(\ell,-\vec{s})}$$

Difference of x-sections!

❑ A_N proportional to the k_T slop of TMD:

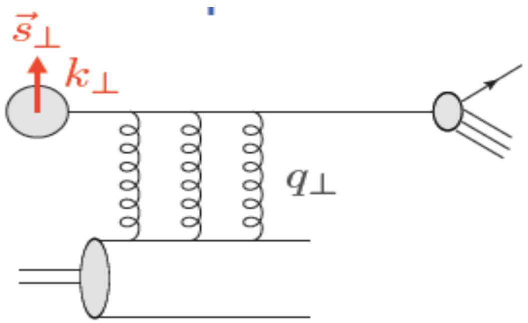
- Now spin-dependent cross section becomes

$$\frac{d\sigma}{dyd^2p_\perp} = \frac{K}{(2\pi)^2}\int d^2b \int_{x_F}^{1} \frac{dz}{z^2} \int d^2k_\perp x\epsilon^{\alpha\beta} s_\perp^\alpha k_\perp^\beta f_{1T}^{\perp,q}(x,k_\perp^2) F(x_A, q_\perp = p_\perp/z - k_\perp) D_{h/q}(z)$$

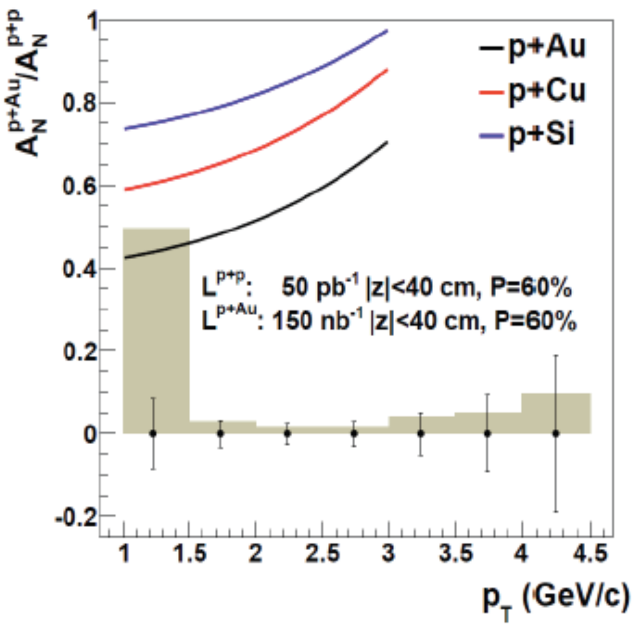
  - Linear kt associated with Sivers function, need another kt to have kt-integral non-vanishing, which can only come from the gluon distribution
  - Spin asymmetry is sensitive to the slope of the dipole gluon distribution in kt-space

A unique opportunity

❑ Polarized p+A:



Kang & Yuan, 1106.1375
Kovchegov & Sievert, 1201.5890
Kang & Xiao, 1212.4809



- ✓Take advantage of large single spin asymmetry A_N in forward region
- ✓A_N is an azimuthal effect, spin-dependent function is $k_\perp$-odd function

↓

- ✓Thus A_N will pick up the slope of the gluon distribution in momentum space, which is controlled by saturation scale

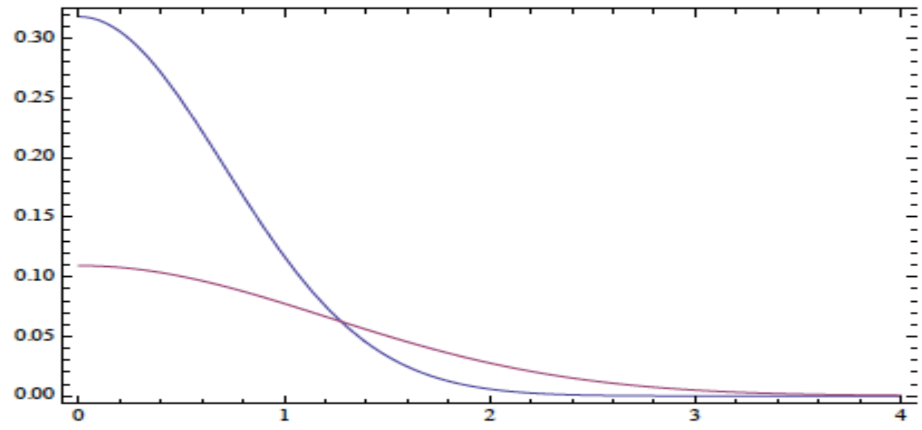
$$A_N \propto \frac{dF(x_g, q_\perp)}{dq_\perp} \sim Q_s$$

$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{p_T^2 \lesssim Q_s^2} \approx \frac{Q_{s,p}^2}{Q_{s,A}^2} \qquad \left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{p_T^2 \gg Q_s^2} = 1$$

Saturation scale depenence

- ❑ **Nuclear TMD is broadened:**

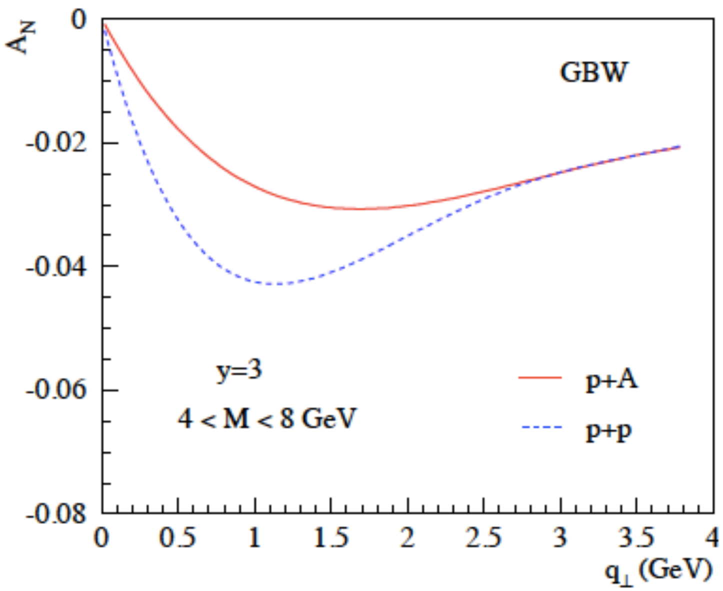
$$F(x,q_\perp) = \frac{1}{\pi Q_s^2(x)} e^{-q_\perp^2/Q_s^2(x)}$$

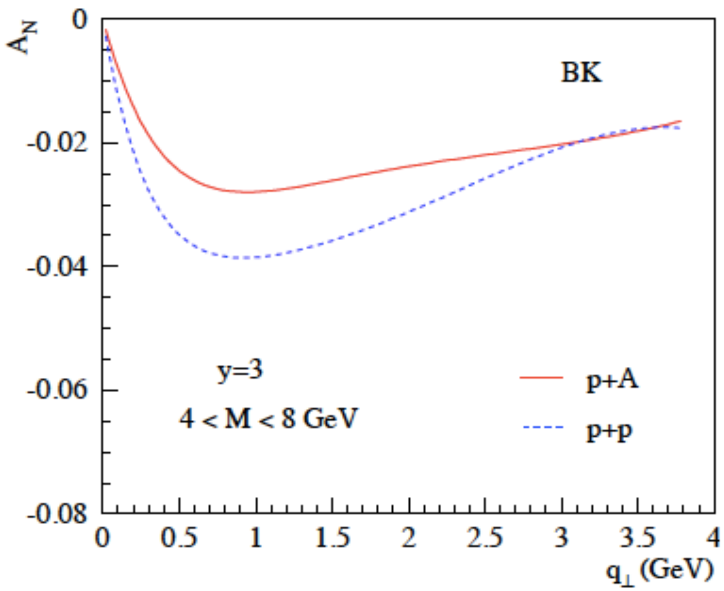


Smaller slop in kT

Smaller contribution to AN

- ❑ **Expectation:**





Sources of contribution to A_N

- The source of single spin correlation for $A^{\uparrow} + B \to h(p_\perp) + X$

$$\begin{aligned}\Delta\sigma &= T_{a,F}(x,x) \otimes \phi_{b/B}(x') \otimes H_{ab\to c}(p_\perp, \vec{s}_T) \otimes D_{c\to h}(z) && \text{(I)}\\ &+ \delta q_{a/A}(x) \otimes T^{(\sigma)}_{b,F}(x',x') \otimes H'_{ab\to c}(p_\perp, \vec{s}_T) \otimes D_{c\to h}(z) && \text{(II)}\\ &+ \delta q_{a/A}(x) \otimes \phi_{b/B}(x') \otimes H''_{ab\to c}(p_\perp, \vec{s}_T) \otimes D^{(3)}_{c\to h}(z,z) && \text{(III)}\\ &+ m_q \delta q_{a/A}(x) \otimes \phi_{b/B}(x') \otimes H'''_{ab\to c}(p_\perp, \vec{s}_T) \otimes D_{c\to h}(z) && \text{(IV)}\end{aligned}$$

Term	meaning	collinear	small-x	Remarks
(I)	Sivers $T_{q,F}(x,x)$	Qiu-Sterman 91, 98 hep-ph/9806356	Boer-Dumitru-Hayashigaki, 2006 Kang-Xiao, 1212.4809	process dependence of Sivers function
(II)	Boer-Mulders $T^{(\sigma)}_{q,F}(x',x')$	Kanazawa-Koike, 2000 hep-ph/000727		small in the collinear formalism
(III)	Collins $D^{(3)}_{c\to h}(z,z)$	Kang-Yuan-Zhou, 2010 1002.0399	Kang-Yuan, 2011 1106.1375	Collins function is universal
(IV)	Kane-Pumplin-Repko $m_q\delta q(x)$	Kane-Pumplin-Repko, 1978	(different from KPR) Kovchegov-Sievert 1201.5890	small?? (because of quark mass?)

Separation of various sources

- ❑ **polarized p+p:**

  Jet, photon, vs single hadron - Sivers vs Collins

- ❑ **polarized p+A:**

Kang et al.

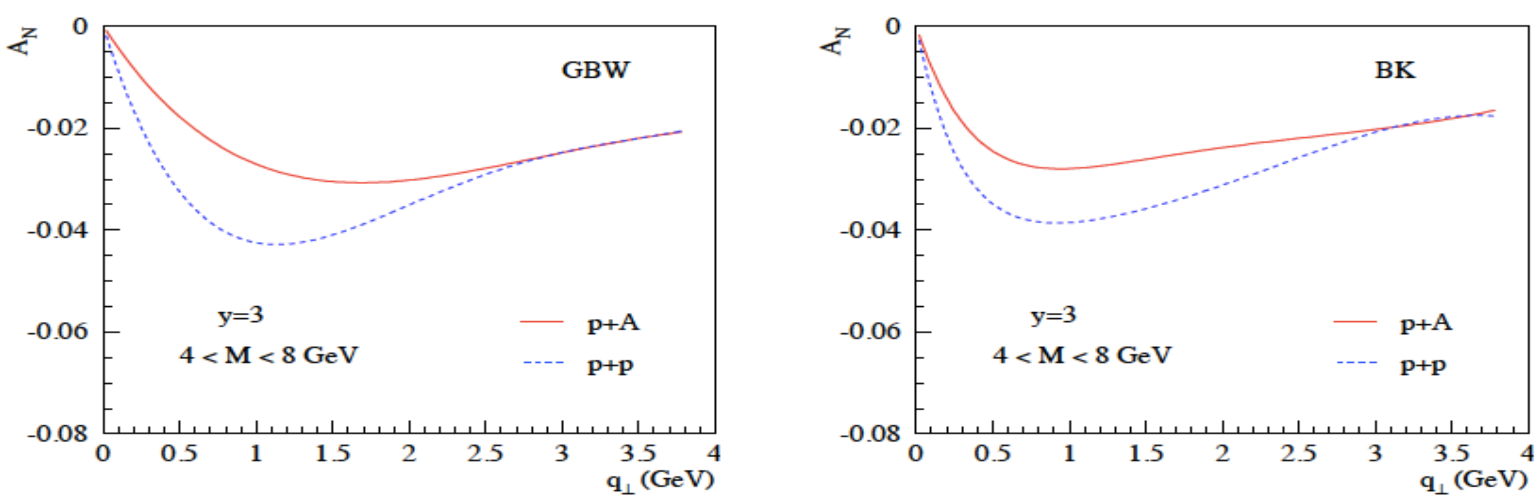
Magnitude + peak location

$$\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\Big|_{P_{h\perp}\ll Q_s^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2}\, e^{\frac{P_{h\perp}^2\,\delta^2}{Q_{sp}^4}} \qquad \frac{A_N^{pA\to h}}{A_N^{pp\to h}}\Big|_{P_{h\perp}\gg Q_s^2} \approx 1$$

Interesting test:

$$\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\Big|_{P_{h\perp}\gg Q_s^2} \to 0$$

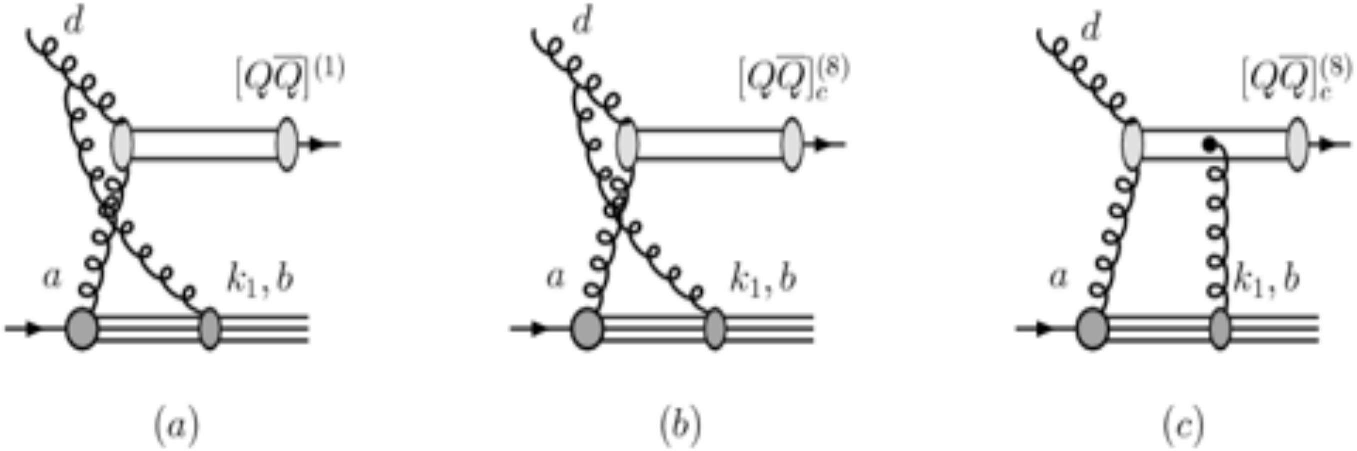
Kovchegov et al.



A_N of heavy quarkonium

F. Yuan

Naïve analysis from the leading order diagrams



- Color-singlet model: only initial state interaction, non-zero SSA
- Color-octet model: initial and final state interactions cancel out, no SSA

Low pT: $$A_N(P_{h\perp}) \propto \frac{P_{h\perp}\Delta}{Q_s^2} e^{-\frac{\delta^2 P_{h\perp}^2}{(Q_s^2)^2}}$$

High pT: $$A_N(P_{h\perp}) \approx \frac{2P_{h\perp}(\Delta^2+\delta^2)}{P_{h\perp}^2+6\Delta^2}$$

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 shape threshold behavior

- Polarized p+A at RHIC is a new and exciting opportunity

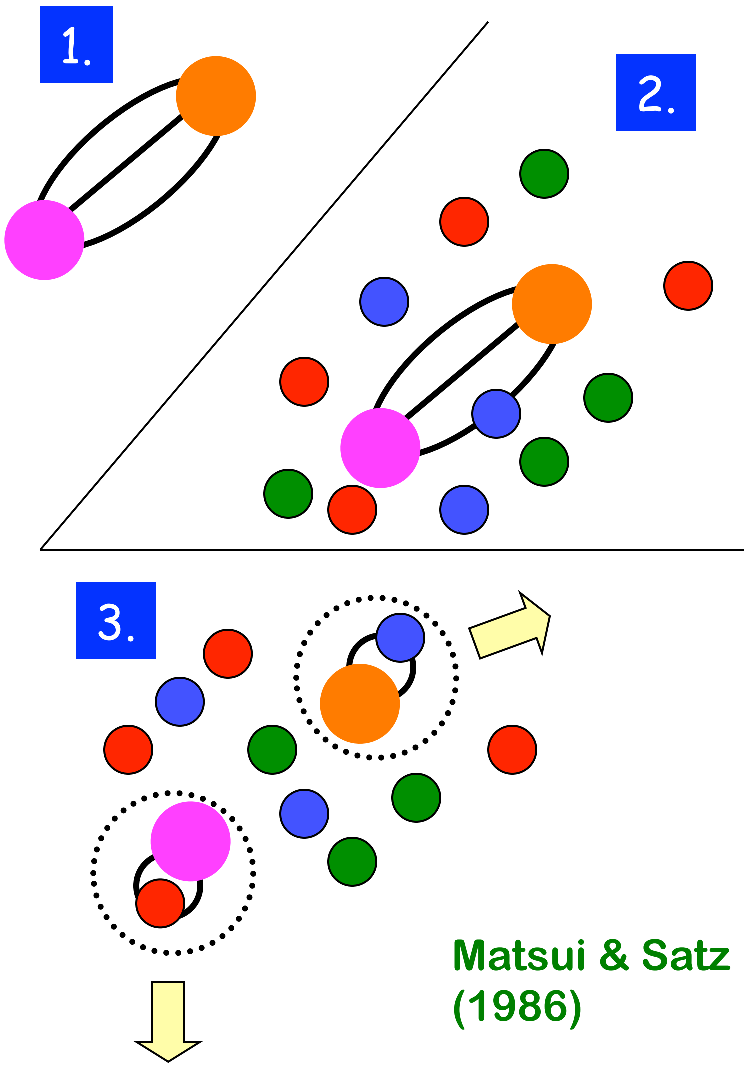
- More discussion and work on QCD factorization is needed for p+A collision. A weaker factorization is likely true to pA's A-dependence, but, not for AA collisions

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

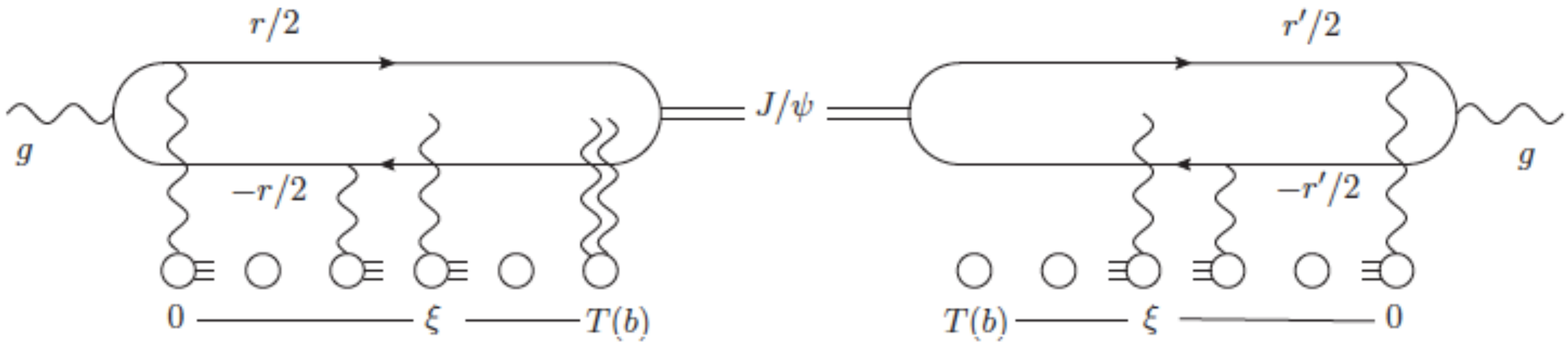


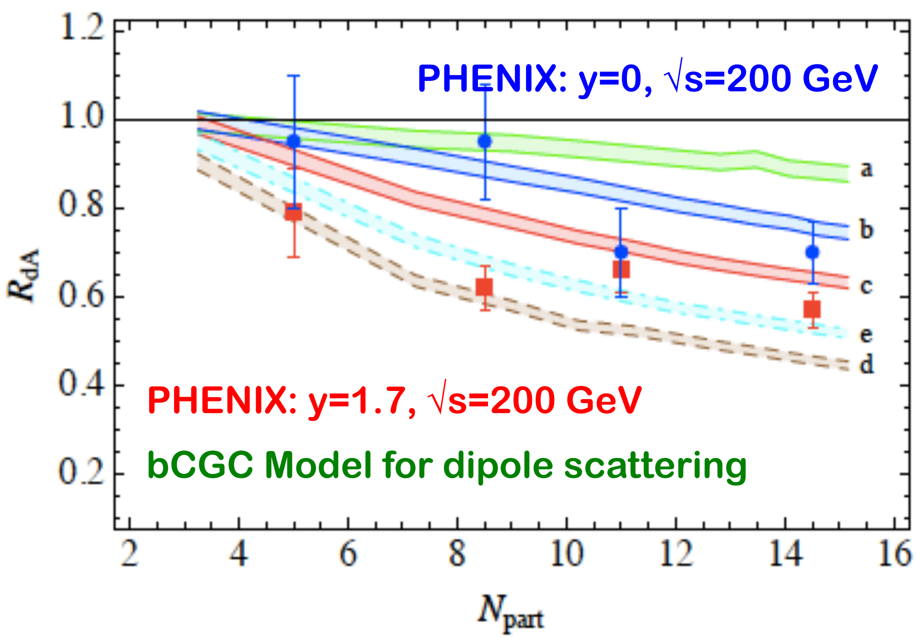
Matsui & Satz (1986)

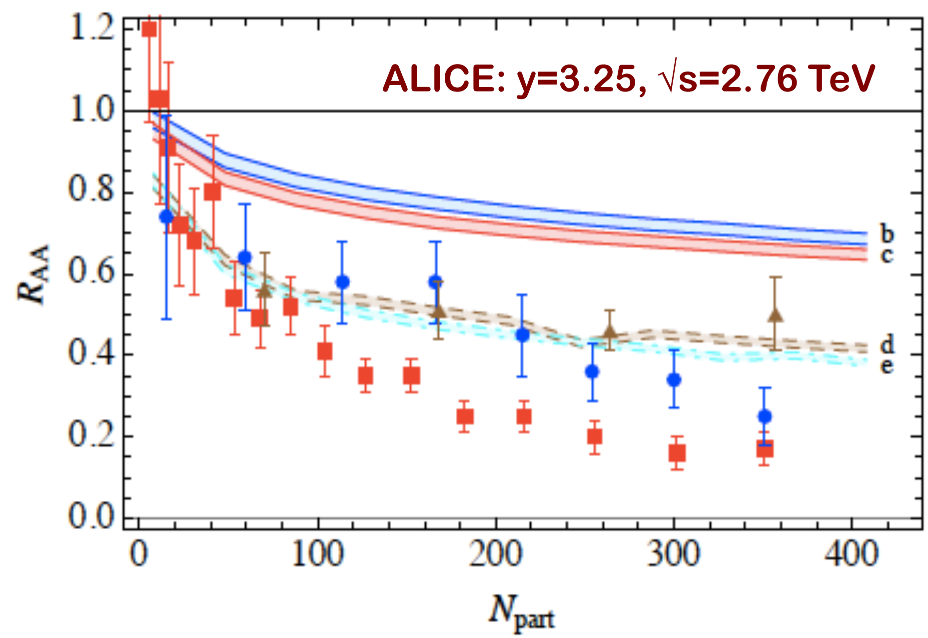
Multiple scattering in cold nuclear matter

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

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





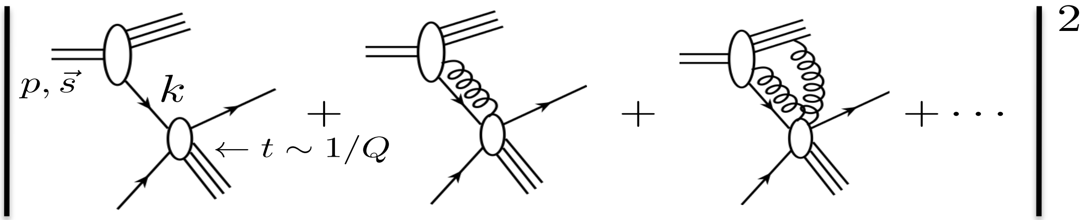


OK for pA, but, far off for AA – J/ψ melting in QGP (MS 1986)?

How collinear factorization generates SSA?

❑ Collinear factorization beyond leading power:

$\sigma(Q,\vec{s}) \propto$



$\left(\frac{\langle k_\perp \rangle}{Q}\right)^n$ – Expansion

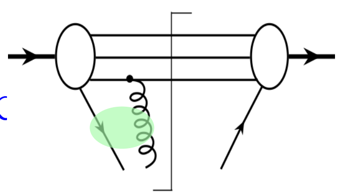
$$\sigma(Q, s_T) = H_0 \otimes f_2 \otimes f_2 + (1/Q)\, H_1 \otimes f_2 \otimes f_3 + \mathcal{O}(1/Q^2)$$

Too large to compete! (f_2) Three-parton correlation (f_3)

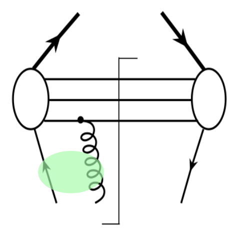
❑ Single transverse spin asymmetry:

Efremov, Teryaev, 82;
Qiu, Sterman, 91, etc.

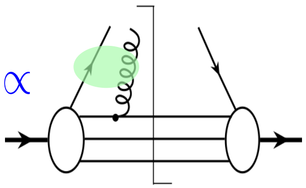
$$\Delta\sigma(s_T) \propto T^{(3)}(x,x) \otimes \hat{\sigma}_T \otimes D(z) + \delta q(x) \otimes \hat{\sigma}_D \otimes D^{(3)}(z,z) + \ldots$$

$T^{(3)}(x,x) \propto$ 

Qiu, Sterman, 1991, …

$D^{(3)}(z,z) \propto$ 

Kang, Yuan, Zhou, 2010

$T^{(3\sigma)}(x,x) \propto$ 

Kanazawa, Koike, 2000

Integrated information on parton's transverse motion!