Theoretical aspects of quarkonia production in pA collisions

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Apology for not being able to cover the tremendous amount of theoretical work done on this topic, …

The 2nd International Conference on the Initial Stages in High-Energy Nuclear Collisions (IS2014)

Embassy Suites Napa Valley, Napa, CA, December 3rd - 7th, 2014

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), …
  Kang, Ma, Qiu, Sterman (2014)

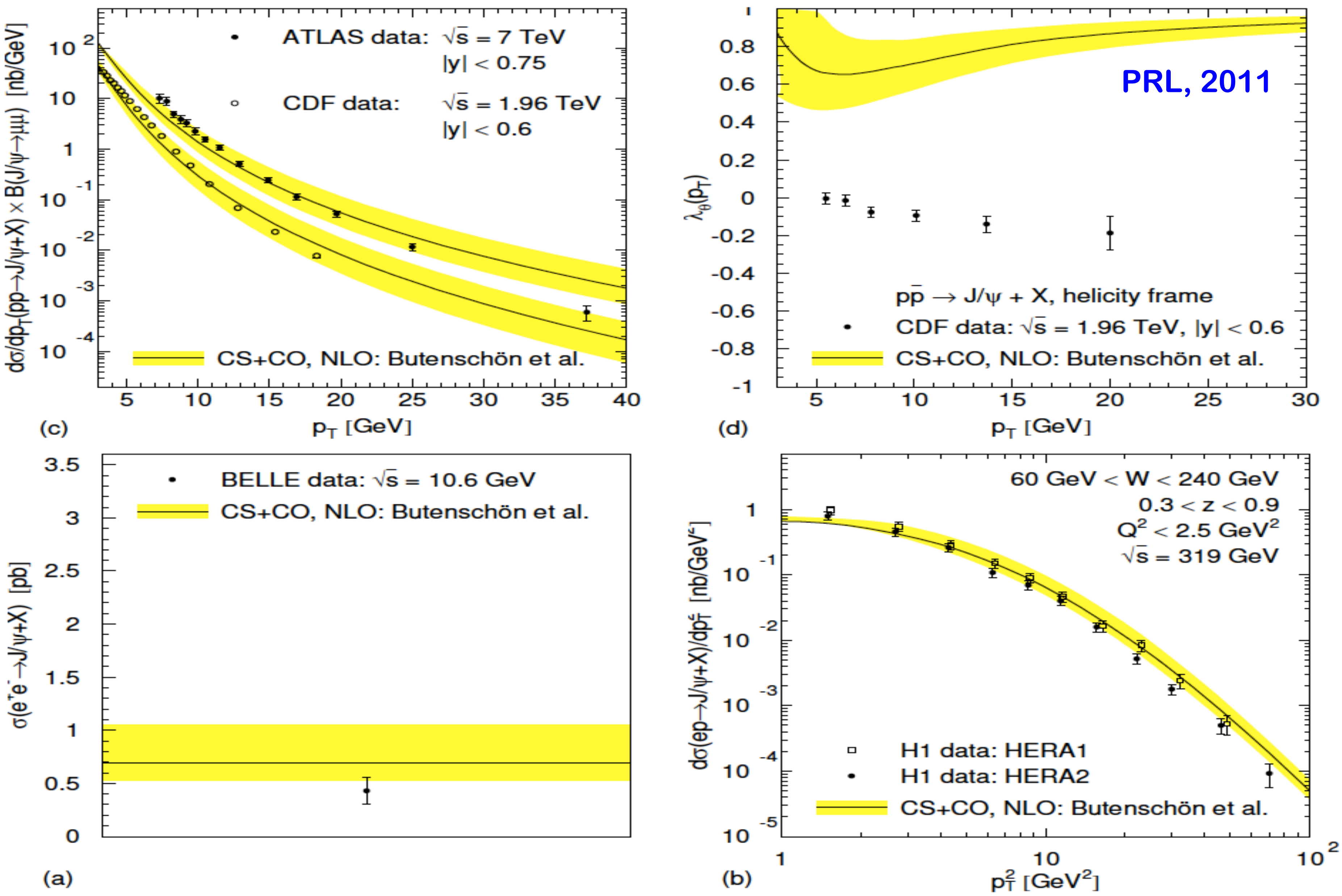
  $P_T >> M_H$: M_H/P_T power expansion + α_s – expansion

  Unknown, but universal, fragmentation functions – evolution

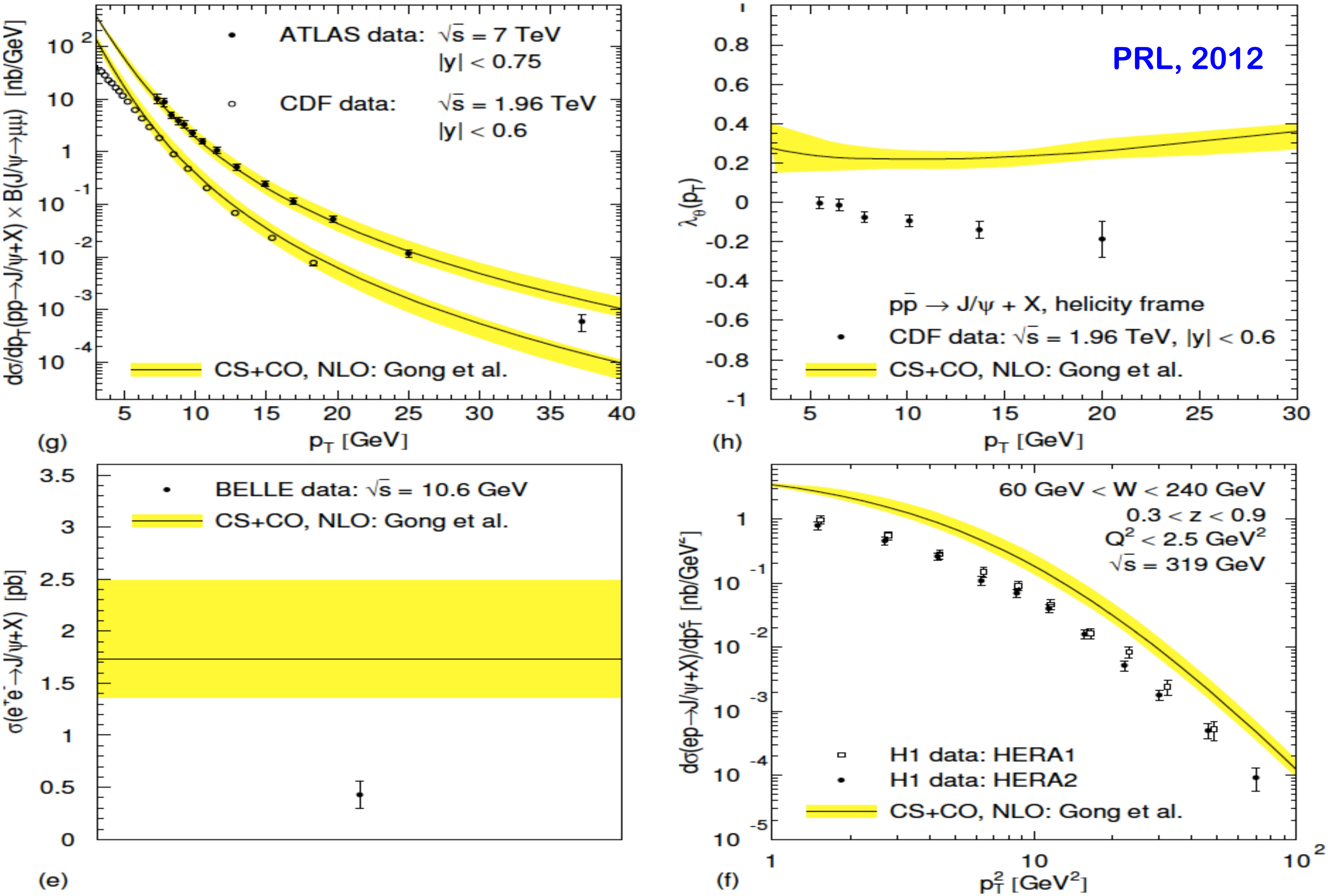
- Soft-Collinear Effective Theory + NRQCD: 2012 –

  Fleming, Leibovich, Mehen, …

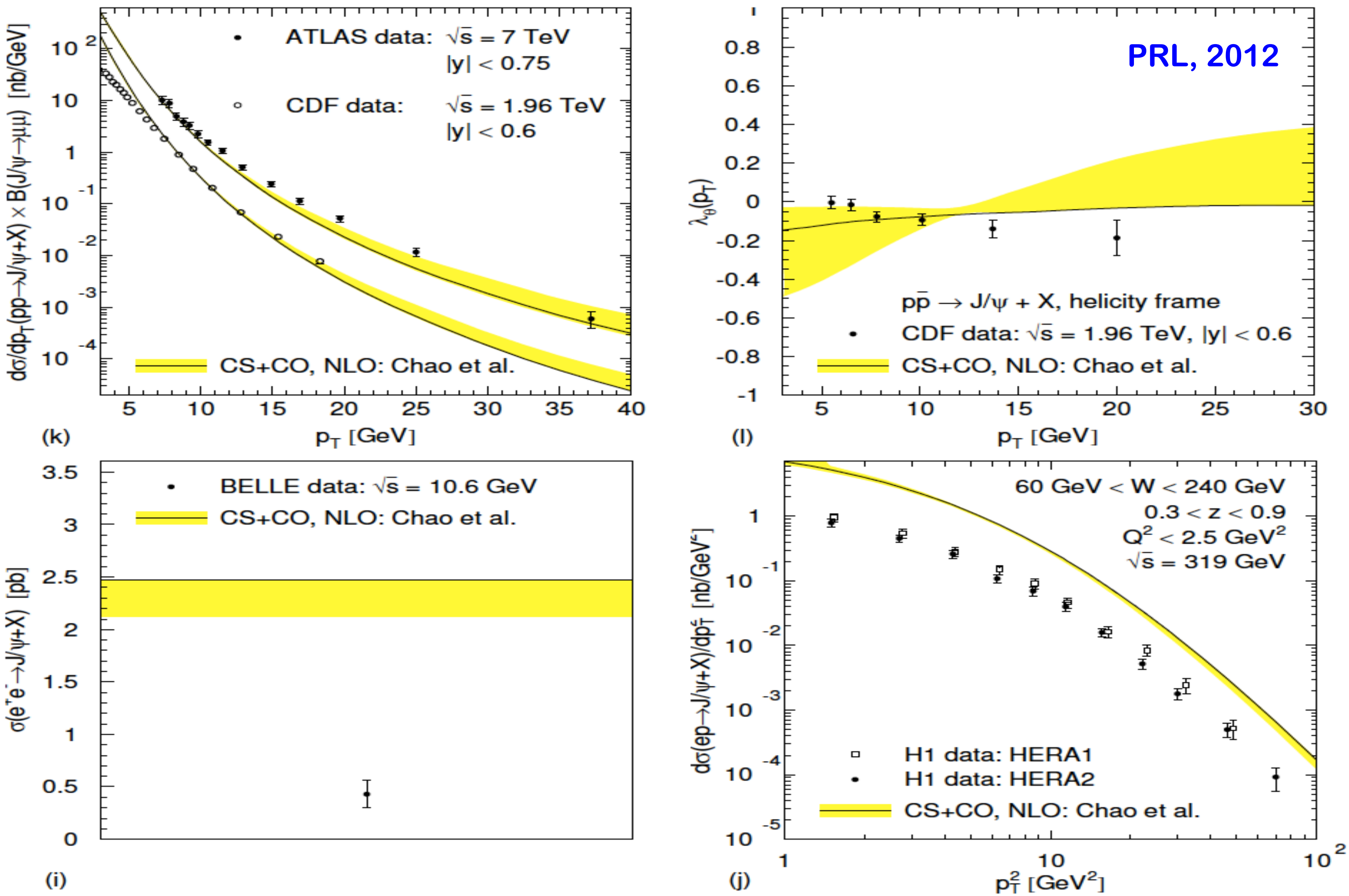
NLO NRQCD vs data – Butenschoen et al.



NLO NRQCD vs data – Gong et al.



NLO NRQCD vs data – Chao et al.



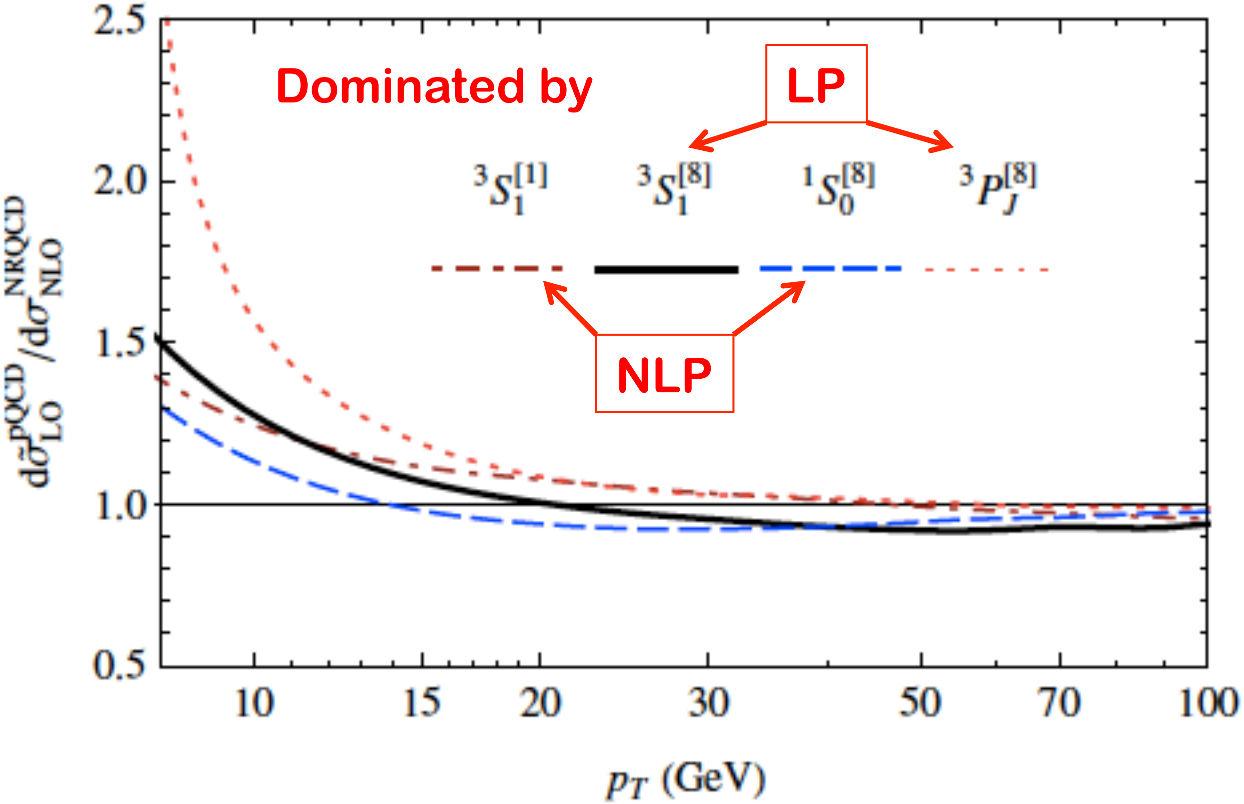
QCD factorization – Kang et al.

Kang, Ma, Qiu and Sterman, 2014

$$d\sigma_{A+B\to H+X}(p_T) = \sum_f d\hat{\sigma}_{A+B\to f+X}(p_f = p/z) \otimes D_{H/f}(z, m_Q)$$

$$+ \sum_{[Q\bar{Q}(\kappa)]} d\hat{\sigma}_{A+B\to[Q\bar{Q}(\kappa)]+X}(p(1\pm\zeta)/2z, p(1\pm\zeta')/2z) \otimes \mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta',m_Q)$$

- Channel-by-channel comparison with NLO NRQCD:



independent of NRQCD matrix elements

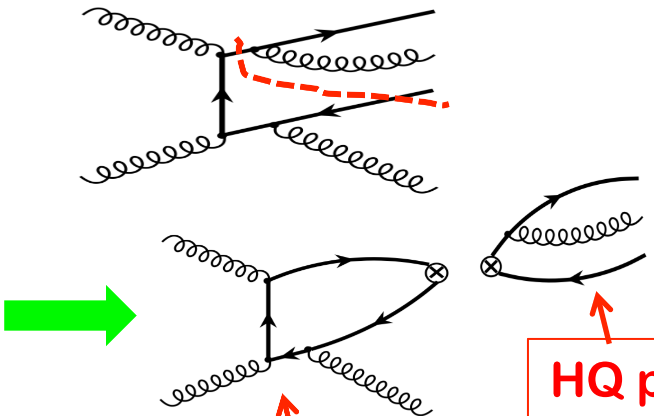
LO QCD analytical results reproduce NLO NRQCD calculations (numerical)

PRL, 2014

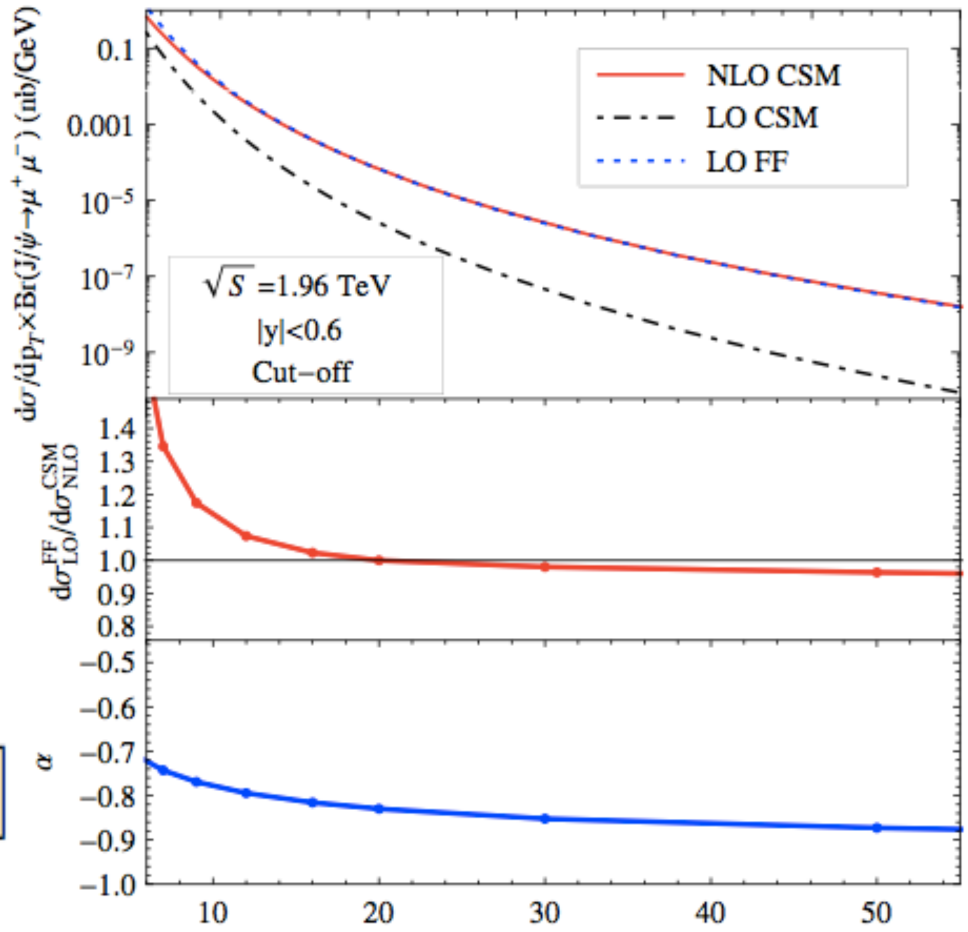
LO QCD + LO NRQCD factorization

Kang, Ma, Qiu and Sterman, 2014

- Color singlet as an example:



$$\sigma^{(\mathrm{NLO})}_{\mathrm{NRQCD}} \propto \left[d\hat{\sigma}^{A(\mathrm{LO})}_{ab\to[Q\bar{Q}(v8)]} \otimes \mathcal{D}^{(\mathrm{LO})}_{[Q\bar{Q}(v8)]\to J/\psi} + d\hat{\sigma}^{S(\mathrm{LO})}_{ab\to[Q\bar{Q}(a8)]} \otimes \mathcal{D}^{(\mathrm{LO})}_{[Q\bar{Q}(a8)]\to J/\psi} \right]$$



Reproduce NLO CSM for p_T > 10 GeV!

Cross section + polarization

QCD Factorization = better controlled HO corrections!

QCD factorization vs NRQCD factorization

- **QCD factorization – valid to the 1st two powers in $1/P_T$:**
  - Expand physical cross section in powers of $1/P_T$ (LP + NLP + …)
  - Factorization at each power in $1/p_T$: perturbative coef. $\otimes$ fragmentation
  - Factorization of LP and NLP is "proved" to be valid for all powers of α_s

- **NRQCD factorization – conjectured:**
  - Expand physical cross section in powers of relative velocity of HQ
  - Expand the coefficient of each term in powers of α_s
  - Verified to NNLO in α_s for the leading power term in the *v*-expansion

- **Connection or matching:**

  If NRQCD factorization for fragmentation functions is valid,

$$E_P \frac{d\sigma_{A+B\to H+X}}{d^3P}(P, m_Q) \equiv E_P \frac{d\sigma^{\rm QCD}_{A+B\to H+X}}{d^3P}(P, m_Q = 0)$$

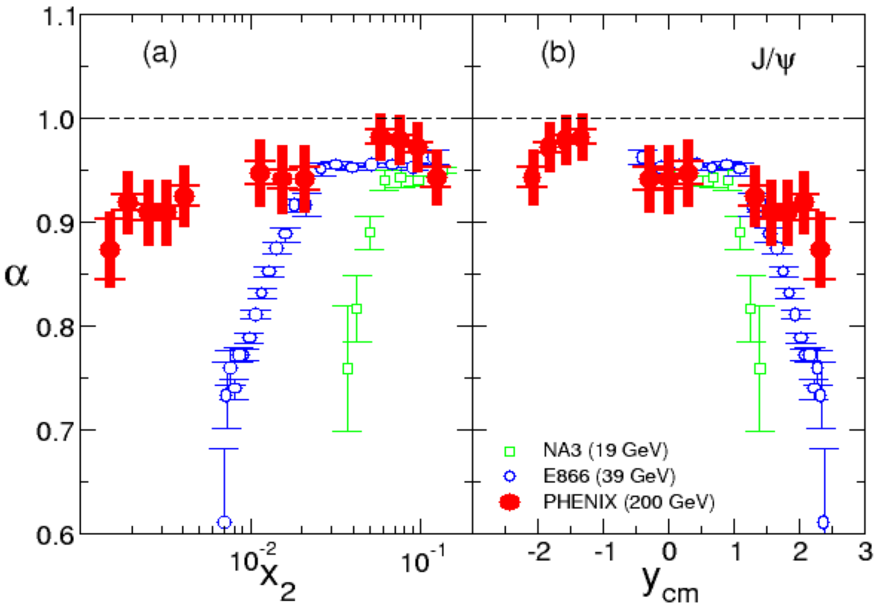
$$+E_P \frac{d\sigma^{\rm NRQCD}_{A+B\to H+X}}{d^3P}(P, m_Q \neq 0) - E_P \frac{d\sigma^{\rm QCD-Asym}_{A+B\to H+X}}{d^3P}(P, m_Q = 0)$$

Mass effect + P_T region ($P_T \gtrsim m_Q$)

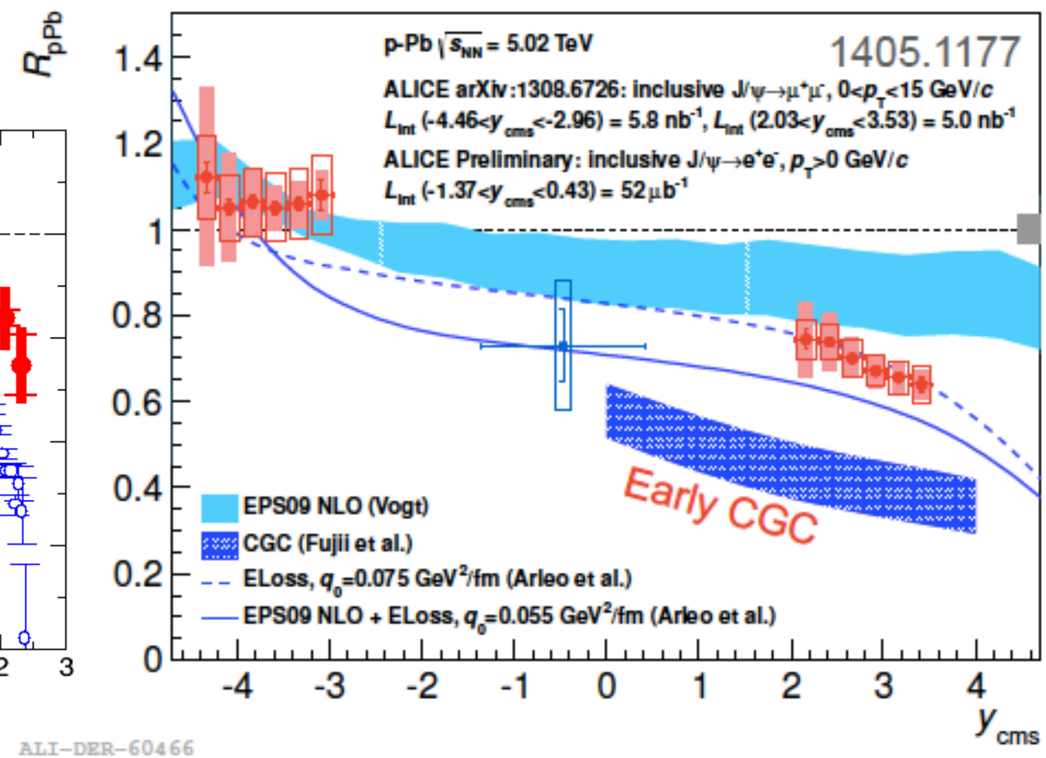
See Raju's talk for lower P_T

Production in p(d)+A collisions

❑ Puzzling rapidity dependence:



Fixed target + RHIC exp'ts



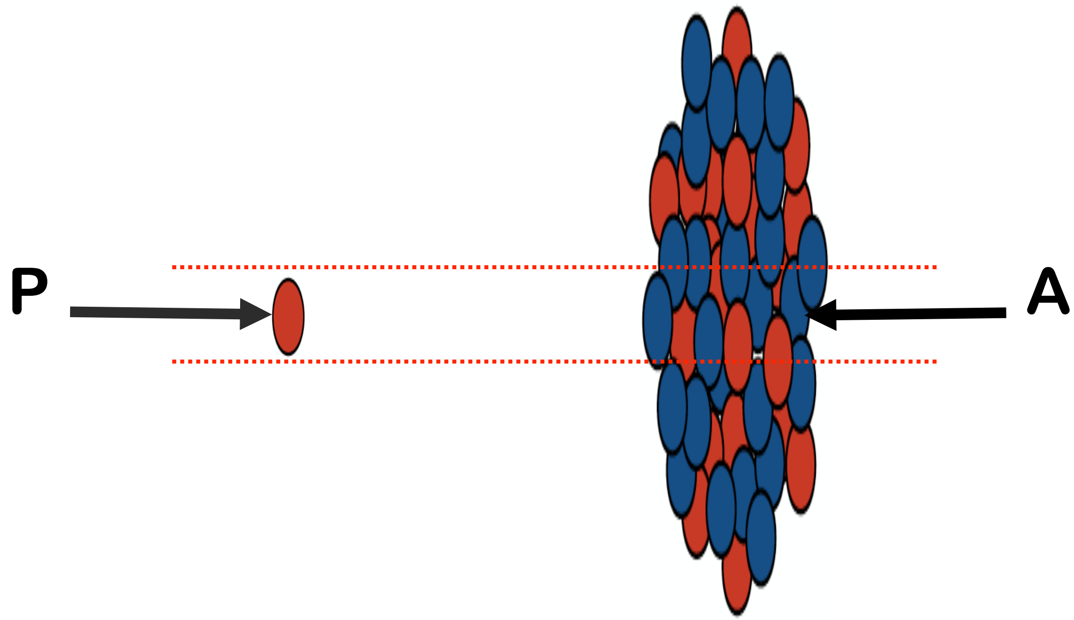
LHCb has similar forward rapidity result

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

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

Production in p(d)+A collisions

❑ Proton (deuteron) – Nucleus Collisions:



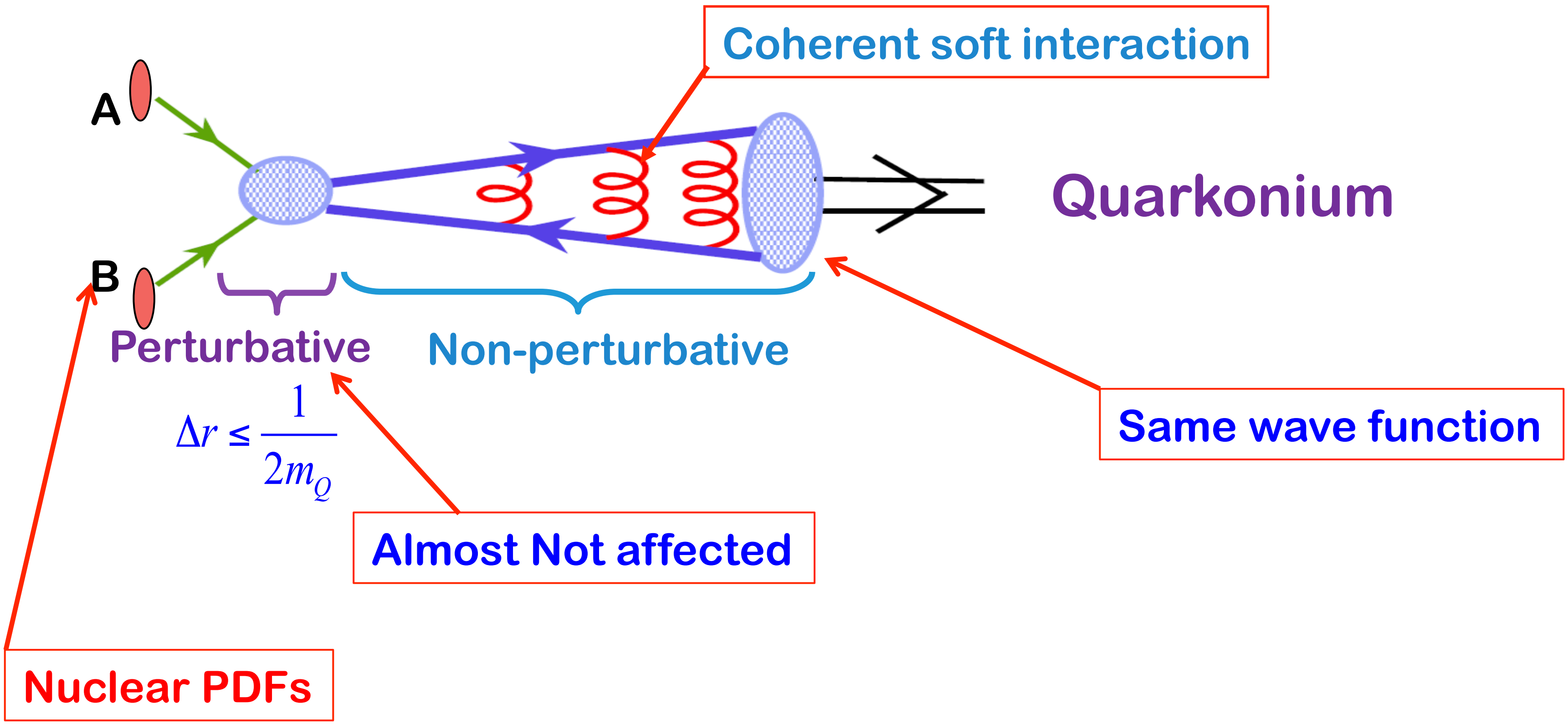
✧ NO QGP (m_Q >> T)! ➡ Cold nuclear effect for the “production”

✧ Necessary calibration for AA collisions

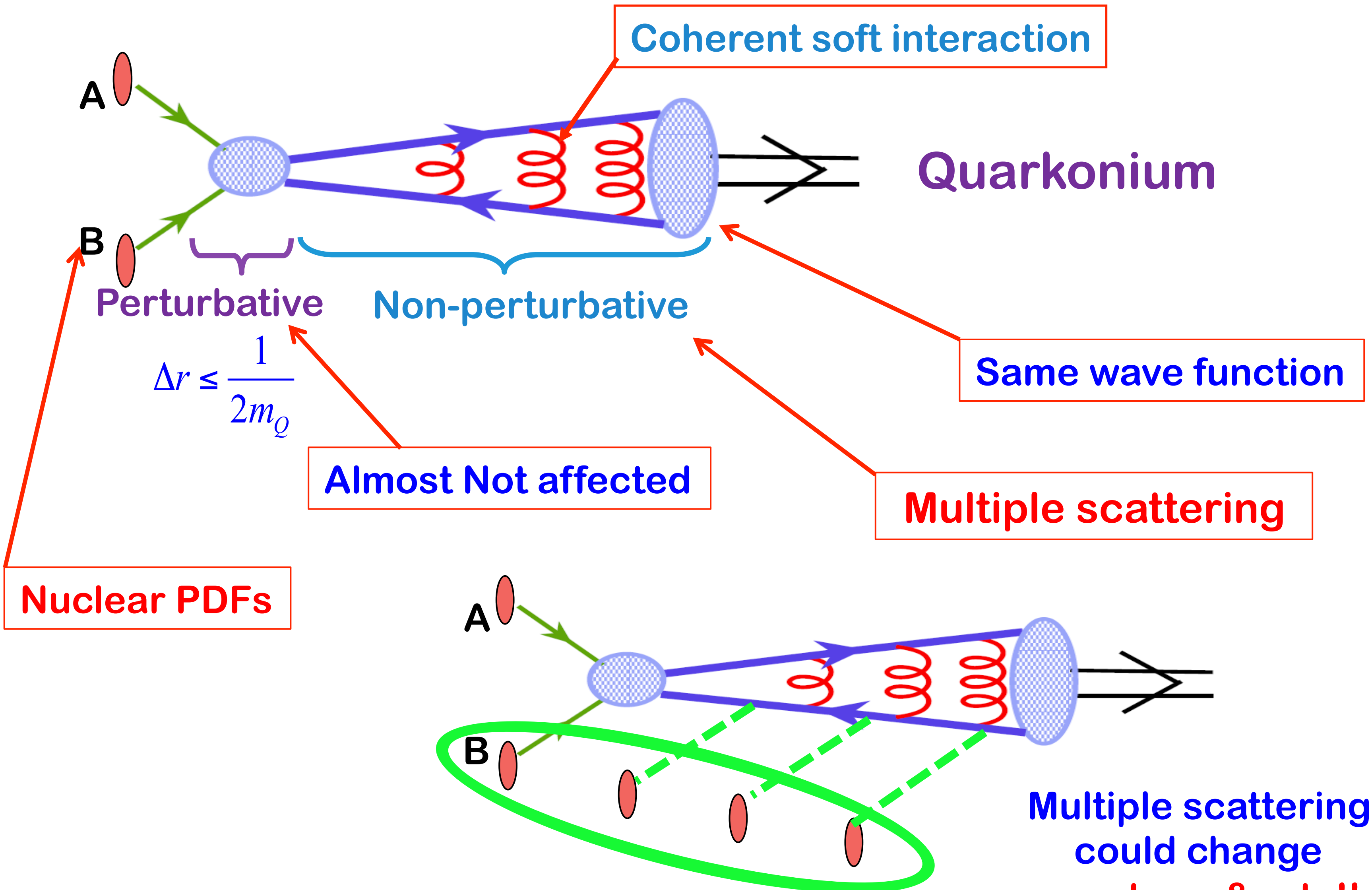
✧ Hard probe (m_Q >> 1/fm) ➡ quark-gluon structure of nucleus!

Nucleus is not a simple superposition of nucleons!

Production in p(d)+A collisions

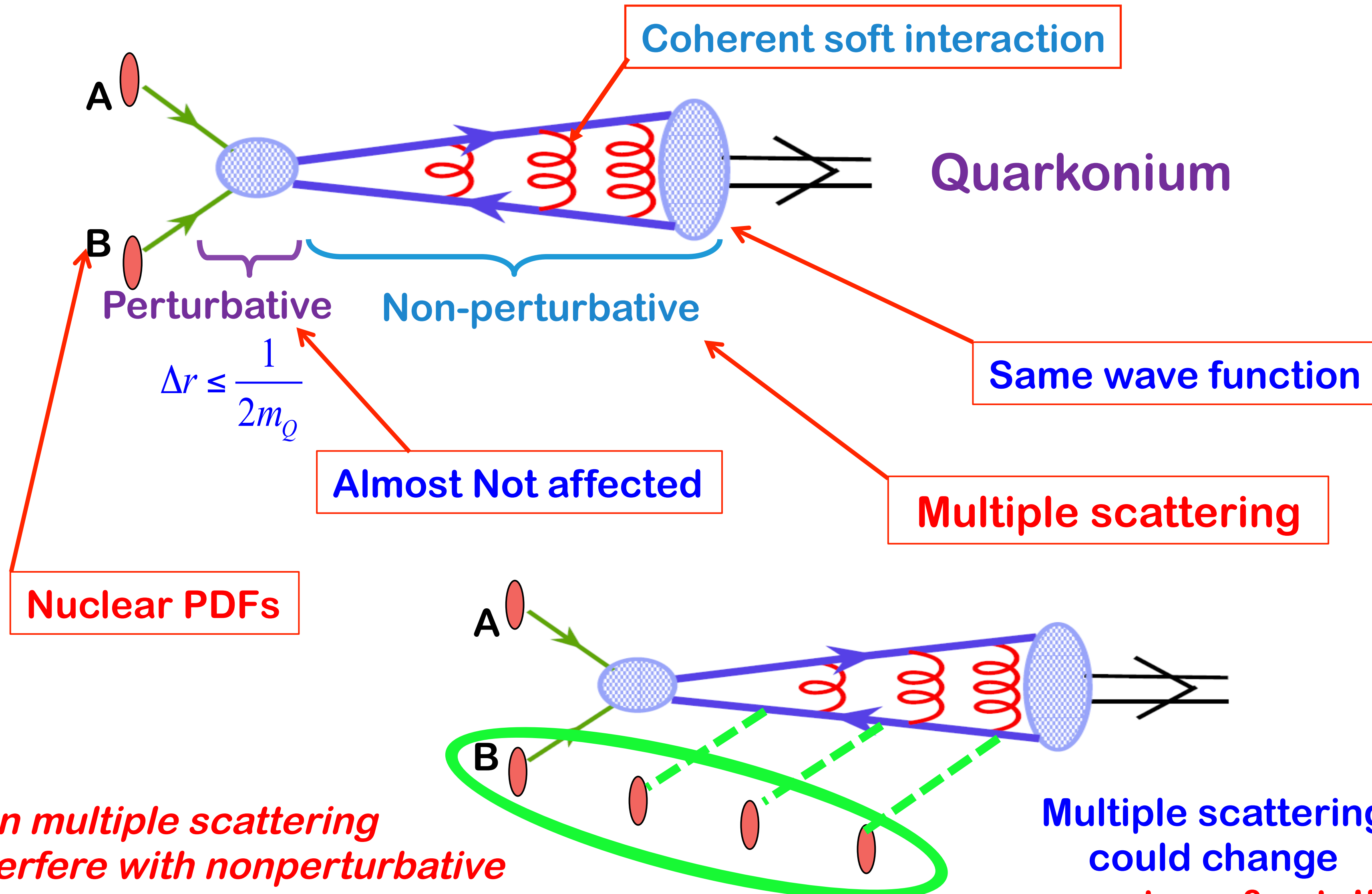


Production in p(d)+A collisions



Multiple scattering could change spectrum & rate!!

Production in p(d)+A collisions



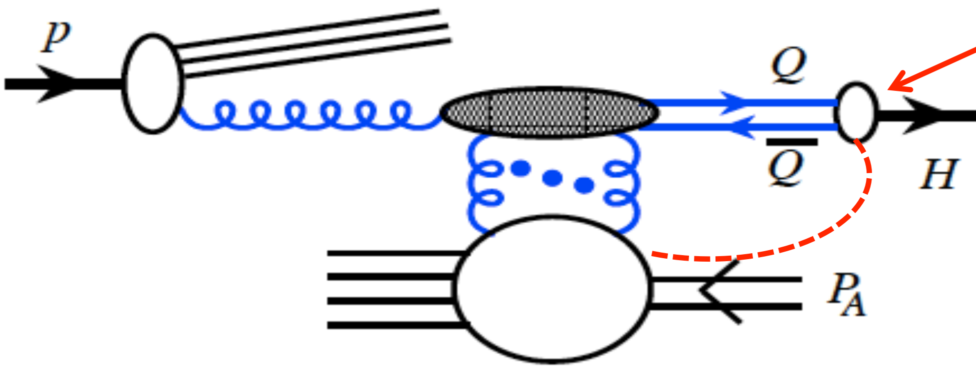
Can multiple scattering interfere with nonperturbative formation of quarkonia?

Multiple scattering could change spectrum & rate!!

Production with multiple scattering

Brodsky and Mueller, PLB 1988

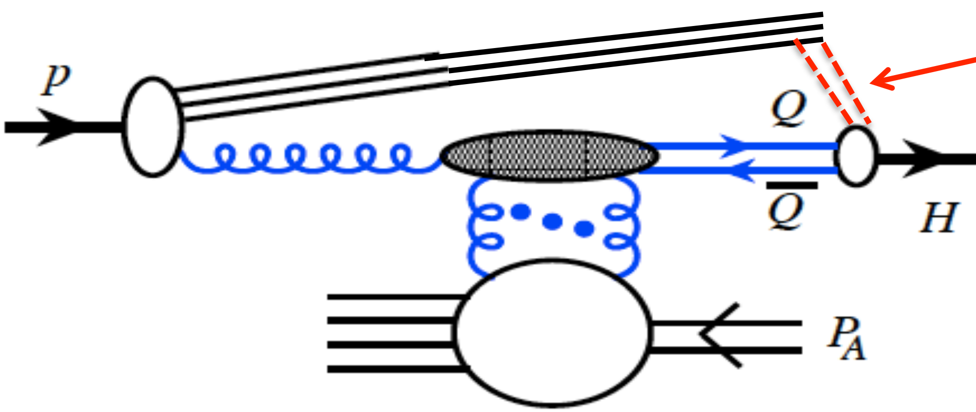
- ❑ *Backward* production in p(d)+A collisions:



J/Ψ could be formed Inside nucleus

Multiple scattering interfere with the non-perturbative hadronization – no factorization!!

- ❑ Production at low P_T (➔0) in p(d)+A collisions:



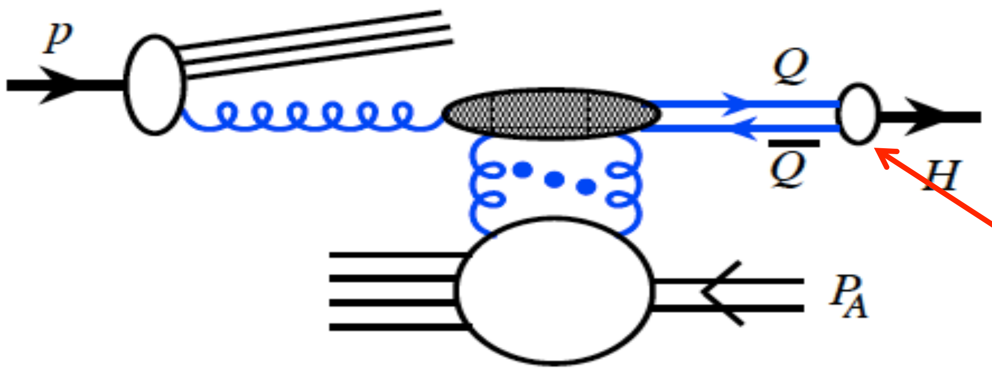
Co-mover interaction

to interfere with quarkonium formation - Break of factorization!!

Production with multiple scattering

Brodsky and Mueller, PLB 1988

- ❑ *Forward* production in p(d)+A collisions:



✧ Time dilation

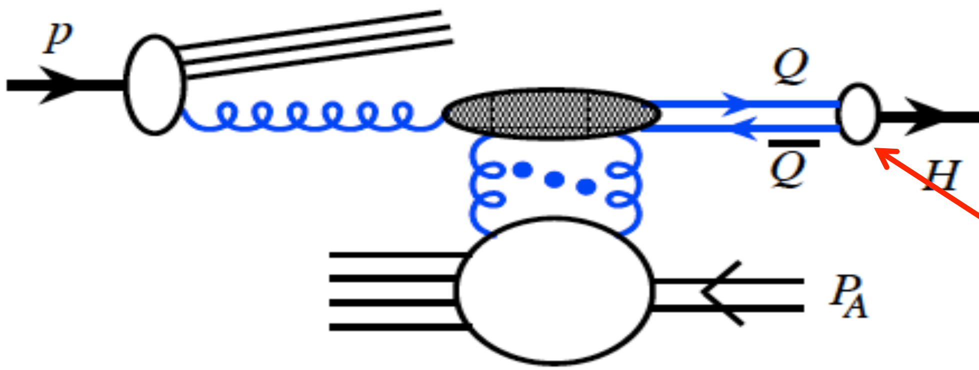
Non-perturbative formation of J/Ψ is far outside of nucleus

✧ Multiple scattering with incoming parton & heavy quarks, not J/Ψ

Production with multiple scattering

Brodsky and Mueller, PLB 1988

❑ *Forward* production in p(d)+A collisions:

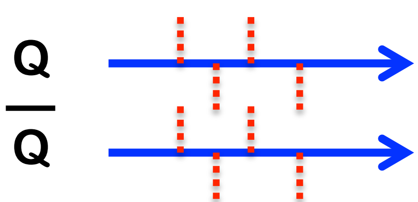


✧ Time dilation

Non-perturbative formation of J/Ψ is far outside of nucleus

✧ Multiple scattering with incoming parton & heavy quarks, not J/Ψ

- ◆ Induced gluon radiation – energy loss – suppression at large y
- ◆ Modified P_T spectrum – transverse momentum broadening
- ◆ De-coherence of the pair – different $Q\bar{Q}$ state to hadronize – lower rate



Soft multiple scattering – "random walk"

Momentum imbalance – larger invariant mass

Match to the tail of wave function - ``suppression"

Suppression in total production rate

Qiu, Vary, Zhang, PRL 2002

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

  Increases the invariant mass of the pair – hit open threshold

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

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

  Suppression of J/ψ

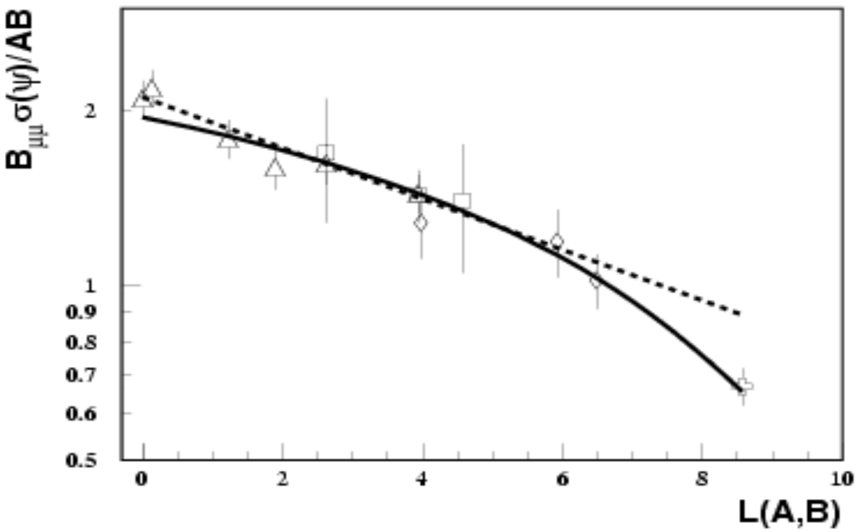
  $$\varepsilon \sim \hat{q} \sim \langle \Delta q_T^2 \rangle$$

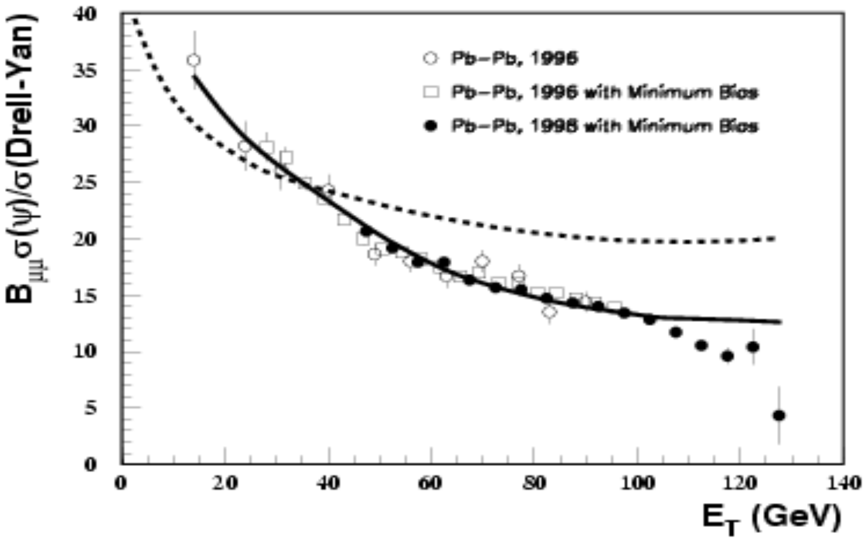
- ❑ **Threshold effect leads to different effective σ_{abs}**

  Curved line for R_{pA}

- ❑ **Different suppression for ψ'**

  Difference in threshold behavior

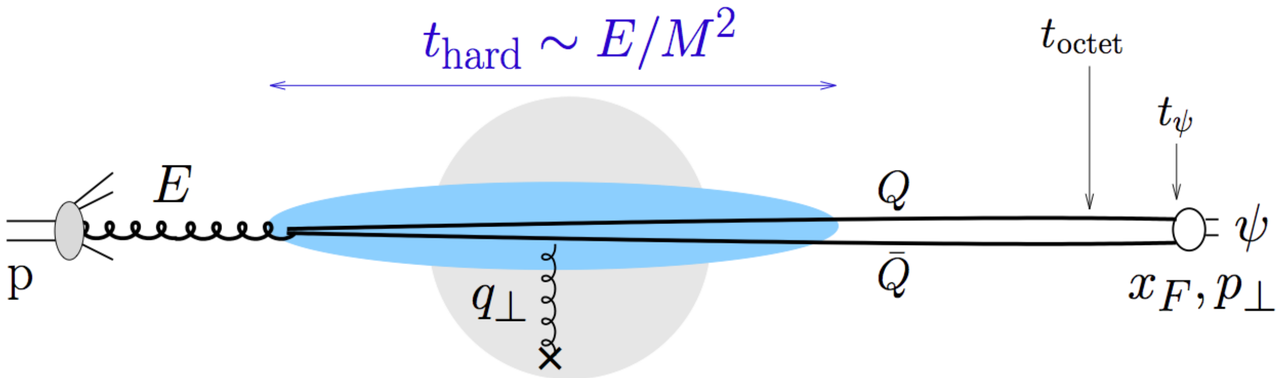




A-dependence in rapidity y (x_F) in p(d)+A

❑ Picture + assumptions:

Arleo, Peigne, 2012
Arleo, Kolevatov, Peigne, 2014



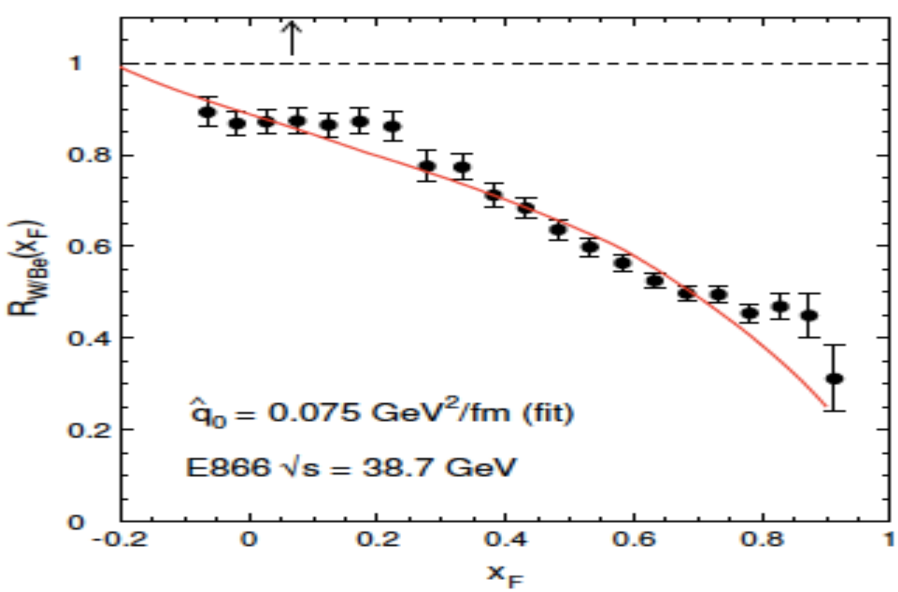
- Color neutralization happens on long time scales: $t_{\rm octet} \gg t_{\rm hard}$
- Medium rescatterings do not resolve the octet $c\bar{c}$ pair
- Hadronization happens outside of the nucleus: $t_\psi \gtrsim L$
- $c\bar{c}$ pair produced by gluon fusion

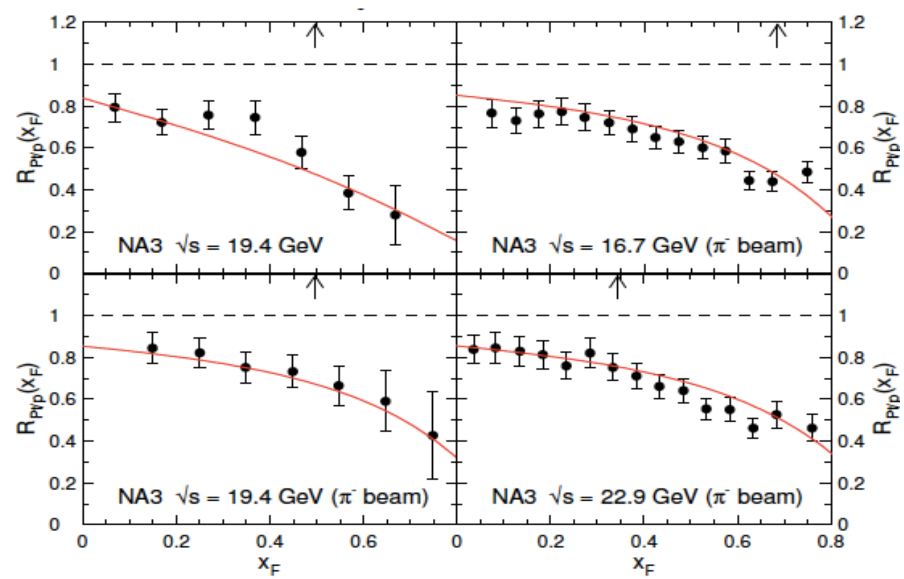
❑ Model energy loss:

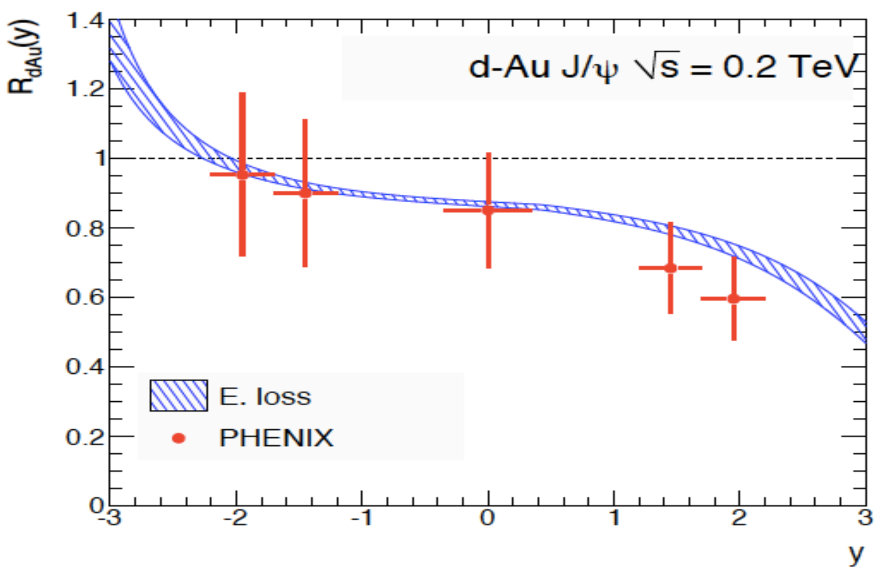
$$\frac{1}{A}\frac{d\sigma_{pA}}{dE}(E,\sqrt{s}) = \int_0^{\varepsilon_{\max}} d\varepsilon\, \mathcal{P}(\varepsilon, E)\, \frac{d\sigma_{pp}}{dE}(E+\varepsilon,\sqrt{s}) \qquad \hat{q}(x) \sim \hat{q}_0 \left(\frac{10^{-2}}{x}\right)^{0.3}$$

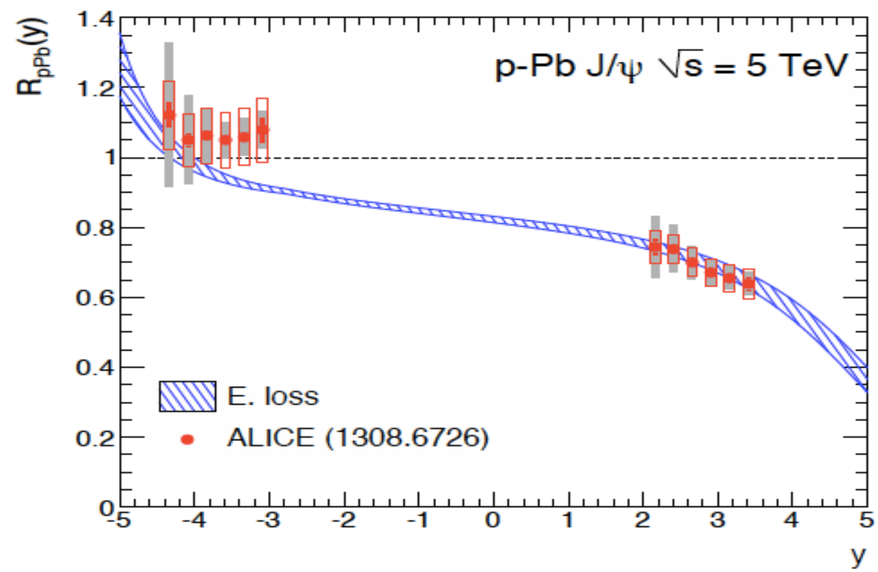
$\mathcal{P}(\varepsilon, E)$: **Quenching weight ~ scaling function of** $\sqrt{\hat{q}L}/M_\perp \times E$

A-dependence in rapidity y (x_F) in p(d)+A









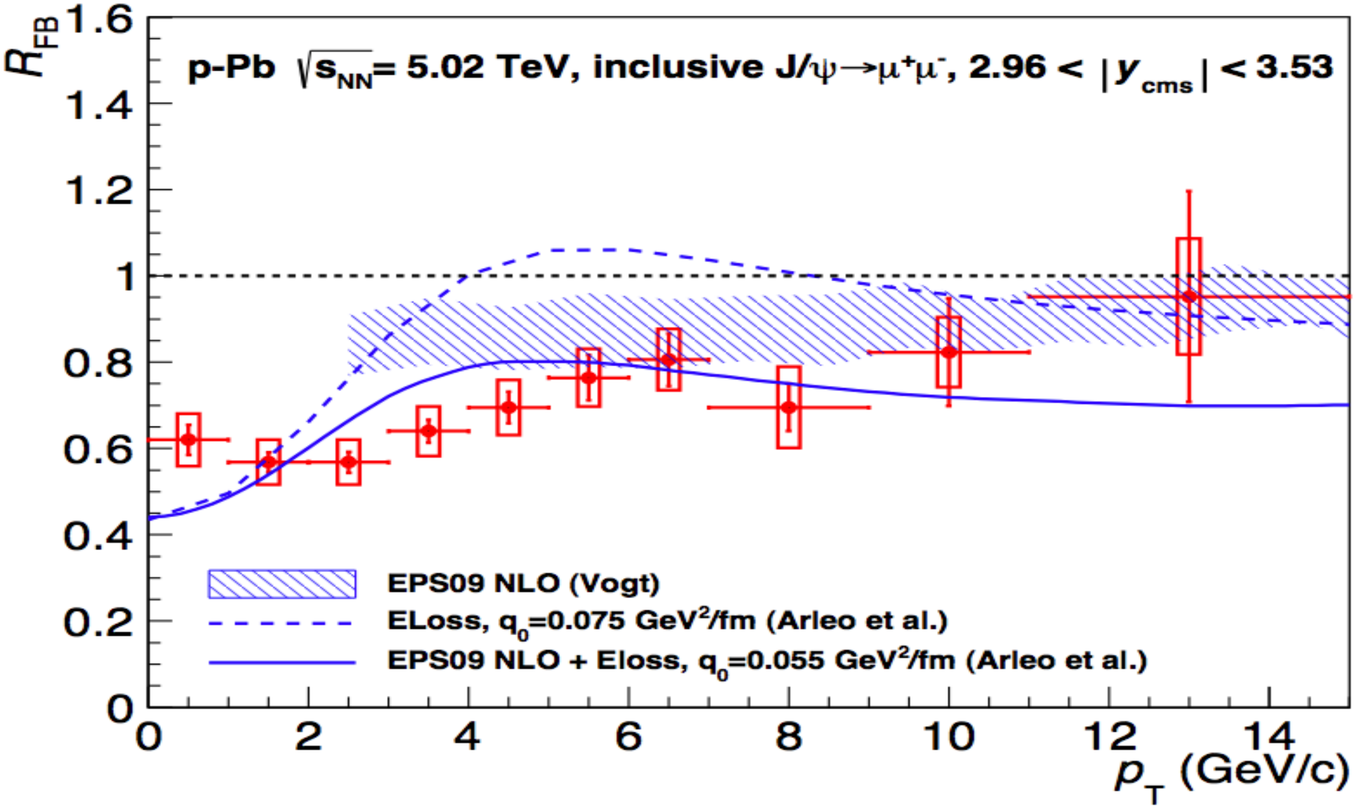
A-dependence in P_T in p(d)+A

- **Model:**

Arleo, Peigne, 2012
Arleo, Kolevatov, Peigne, 2014

$$\frac{1}{A}\frac{d\sigma_{\rm pA}^{\psi}}{dE\ d^2\vec{p}_\perp} = \int_\varepsilon\int_\varphi \mathcal{P}(\varepsilon, E)\,\frac{d\sigma_{\rm pp}^{\psi}}{dE\ d^2\vec{p}_\perp}\left(E+\varepsilon, \vec{p}_\perp - \Delta\vec{p}_\perp\right)$$

- **Nuclear A-dependence:** $R_{\rm pA}^{\psi}(y, p_\perp) \simeq R_{\rm pA}^{\rm loss}(y, p_\perp)\cdot R_{\rm pA}^{\rm broad}(p_\perp)$



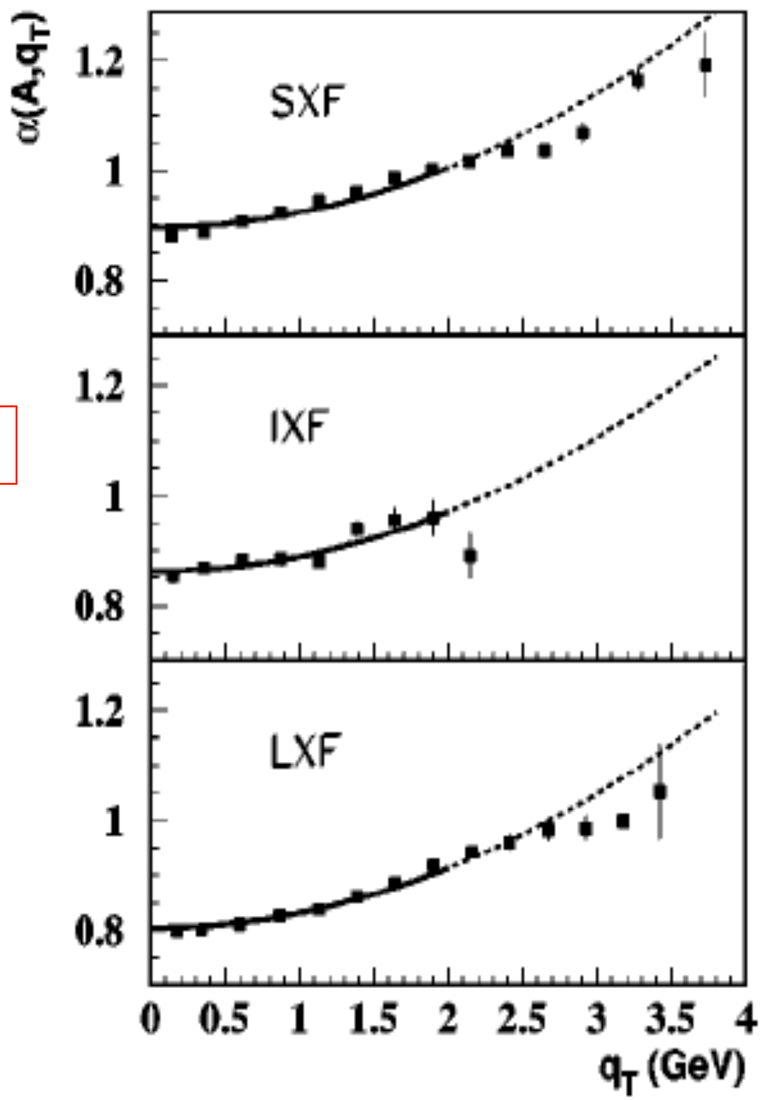
A-dependence in P_T in p(d)+A

Guo, Qiu, Zhang, PRL, PRD 2002

- Ratio of x-sections:

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

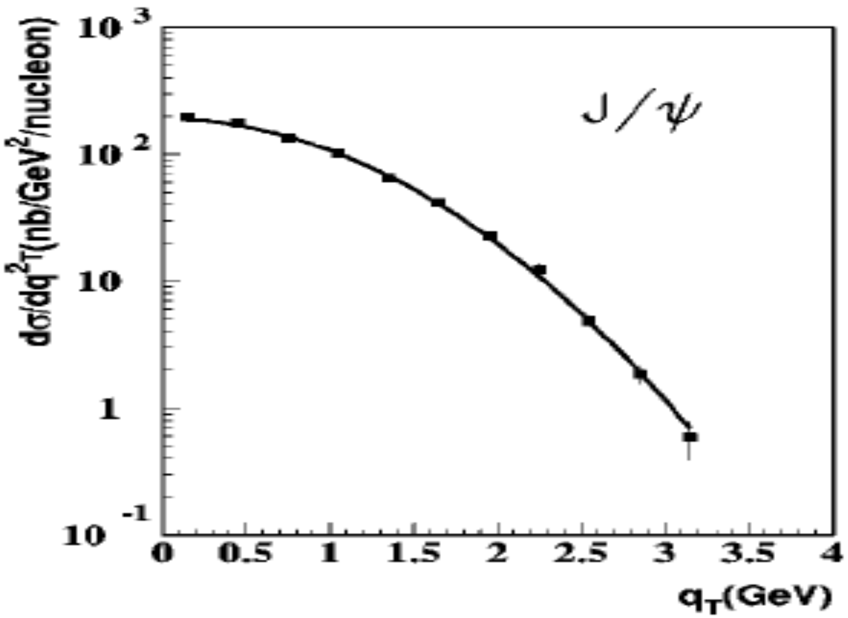
$$\approx 1 + \frac{\Delta\langle q_T^2\rangle}{A^{1/3}\langle q_T^2\rangle_{\rm DY}^{hN}}\left[-1 + \frac{q_T^2}{\langle q_T^2\rangle_{\rm DY}^{hN}}\right]$$



Similar formula for J/ψ

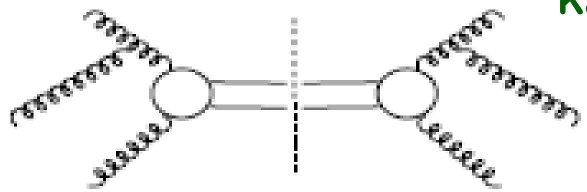
- Spectrum and ratio:

E772 data



Quarkonium P_T-broadening in p(d)+A

Kang, Qiu, PRD77(2008)



❑ Initial-state only:

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

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

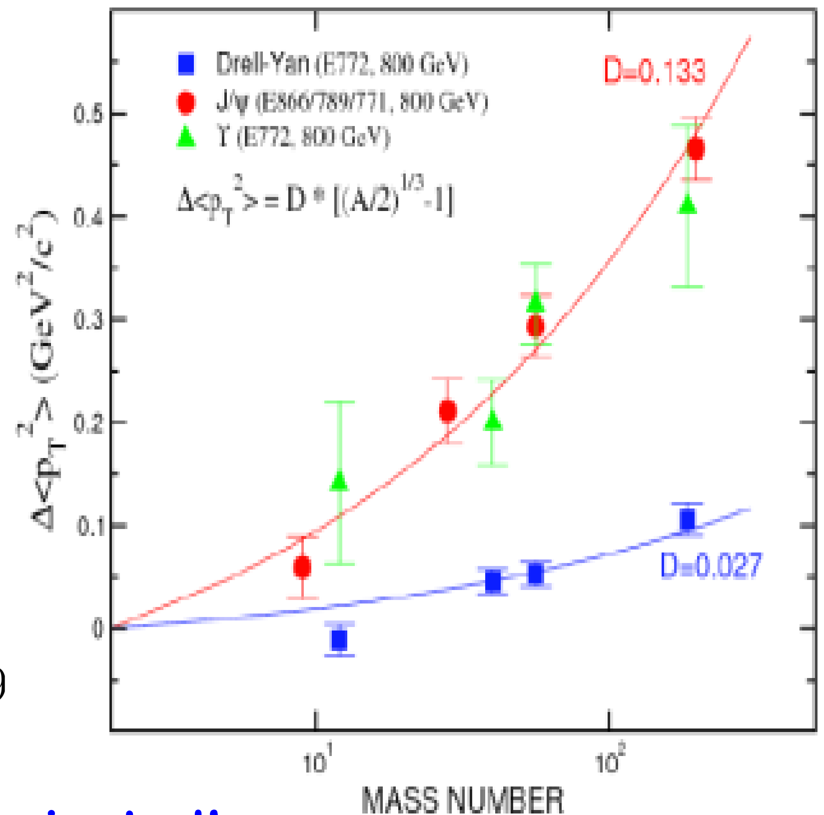
❑ Experimental data from d+A:

Clear $A^{1/3}$ dependence

But, wrong normalization!

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

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



Final-state effect – octet channel dominated!

Only depend on observed quarkonia

J.C.Peng, hep-ph/9912371

Johnson,et al, 2007

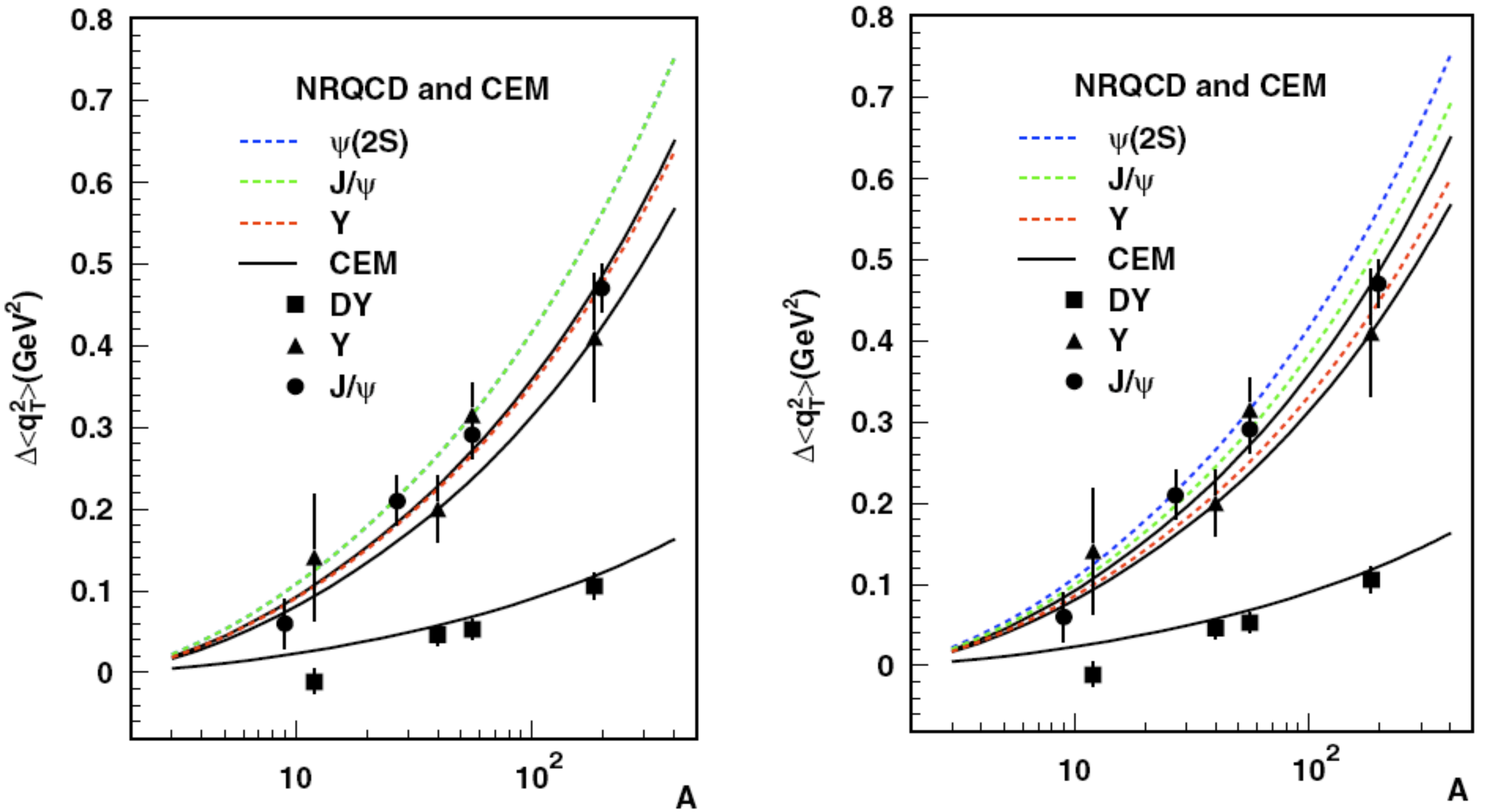
Broadening of heavy quarkonia in p(d)+A

Kang, Qiu, PRD77(2008)

- ❑ Final-state effect is important:

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

in both CEM and NRQCD

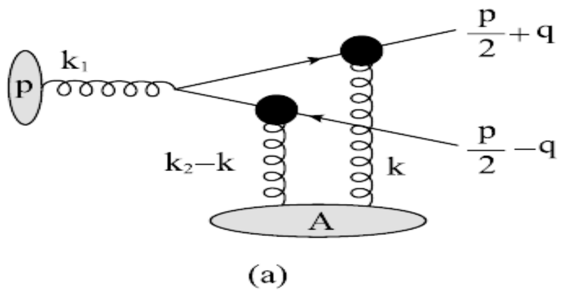


- ❑ Mass – independence, not very sensitive to the feeddown

Forward quarkonium production in p(d)+A

Kang, Ma, Venugopalan, JHEP (2014)
Qiu, Sun, Xiao, Yuan PRD89 (2014)

- Calculation of multiple scattering:



Coherent multiple scattering → suppression at large y

- Two existing calculations – slightly different emphases:

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

  See Raju's talk for preliminary numerical results

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

  No numerical results 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 both the p_T and y dependence

- Final-state multiple scattering could be an effective source of J/ψ suppression because of the sharp threshold behavior

- More discussion and work on QCD factorization are needed for p(d)+A collision. A weaker factorization might be true for A-dependence in p(d)+A, but, certainly not for A+A collisions

Thank you!

Backup slides

Final-state multiple scattering - CEM

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

Kang, Qiu, PRD77(2008)

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

- 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

❑ Cross section:

Kang, Qiu, PRD77(2008)

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

❑ Broadening:

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

Hard parts:

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

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

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

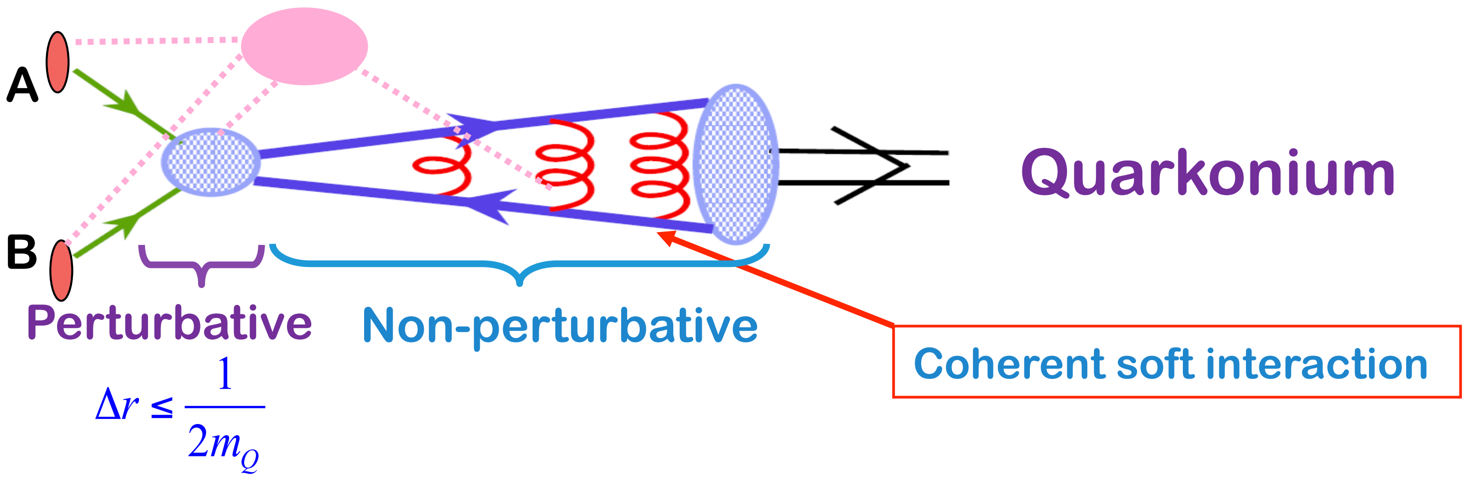
Only color octet channel contributes

❑ Leading features:

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

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

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

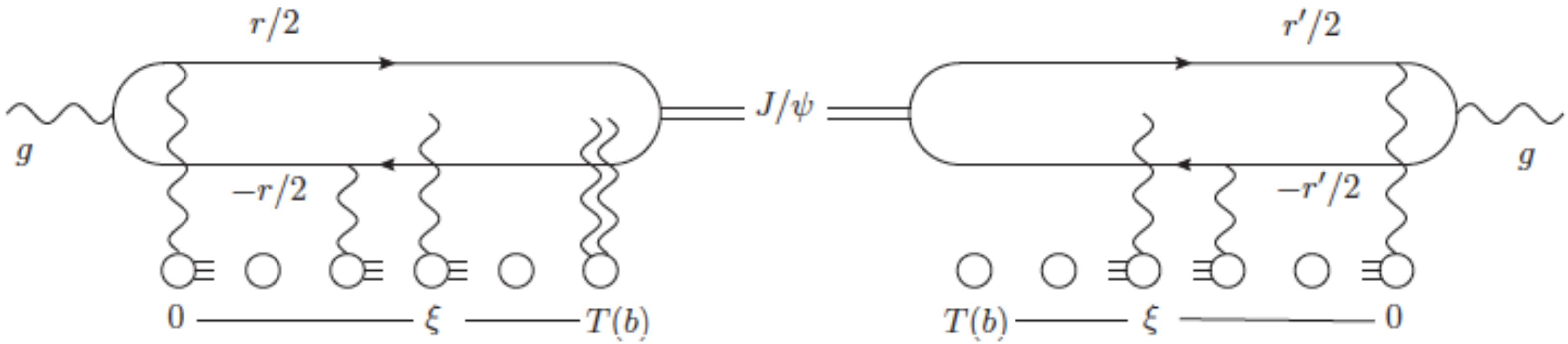
Models & Debates

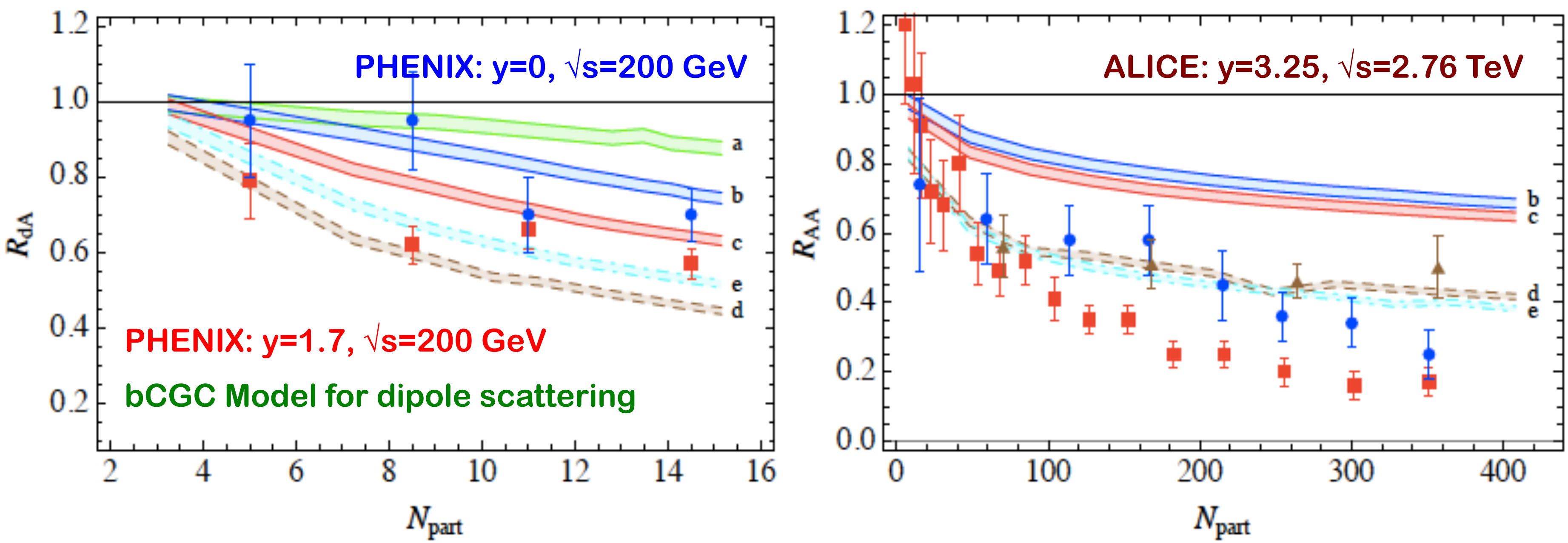
⇔ Different assumptions/treatments on $F_{[Q\bar{Q}(n)]\to J/\psi}(P_{J/\psi}, q^2)$
how the heavy quark pair becomes a quarkonium?

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)?