QCD Master Class 2017

18-24 June 2017
Saint-Jacut-de-la-Mer
Europe/Paris timezone

Theory of Quarkonium Production

Jianwei Qiu
Theory Center, Jefferson Lab

June 19-24, 2017

Lecture seven/eight

Theory Center

Jefferson Lab
EXPLORING THE NATURE OF MATTER

The plan for my eight lectures

- **The Goal:**

  To understand the theory of heavy quarkonium production, and strong interaction dynamics in terms of QCD

- **The Plan (approximately):**

  Inclusive production of a single heavy quarkonium

  The November Revolution

  Theoretical models and approximations

  Surprises and anomalies

  QCD factorization at the leading and next-to-leading power

  Five lectures

  Heavy quarkonium associate and in medium production

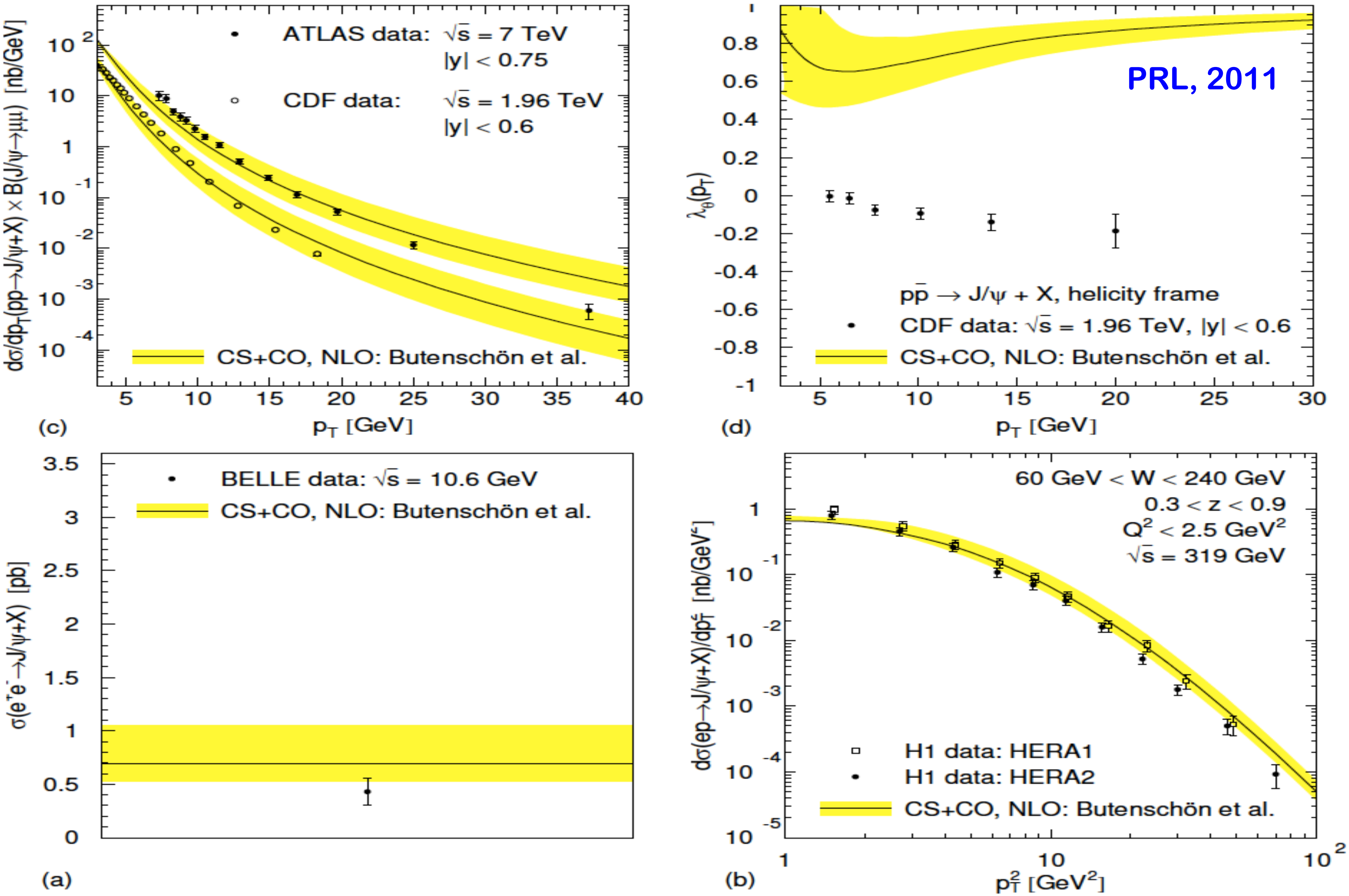
  Quarkonium associate production

  Quarkonium production in a jet

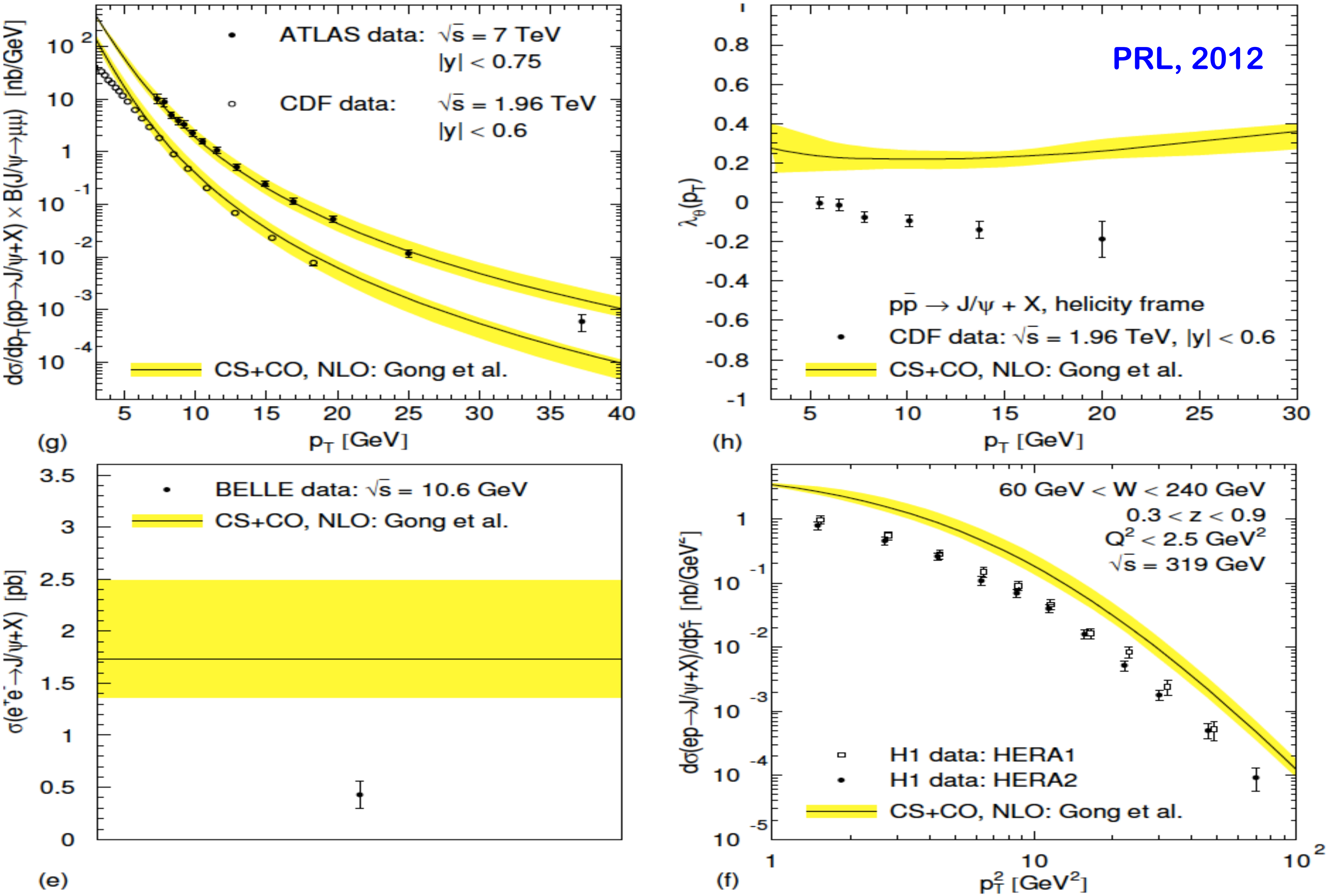
  Quarkonium production in cold/hot medium

  Three lectures

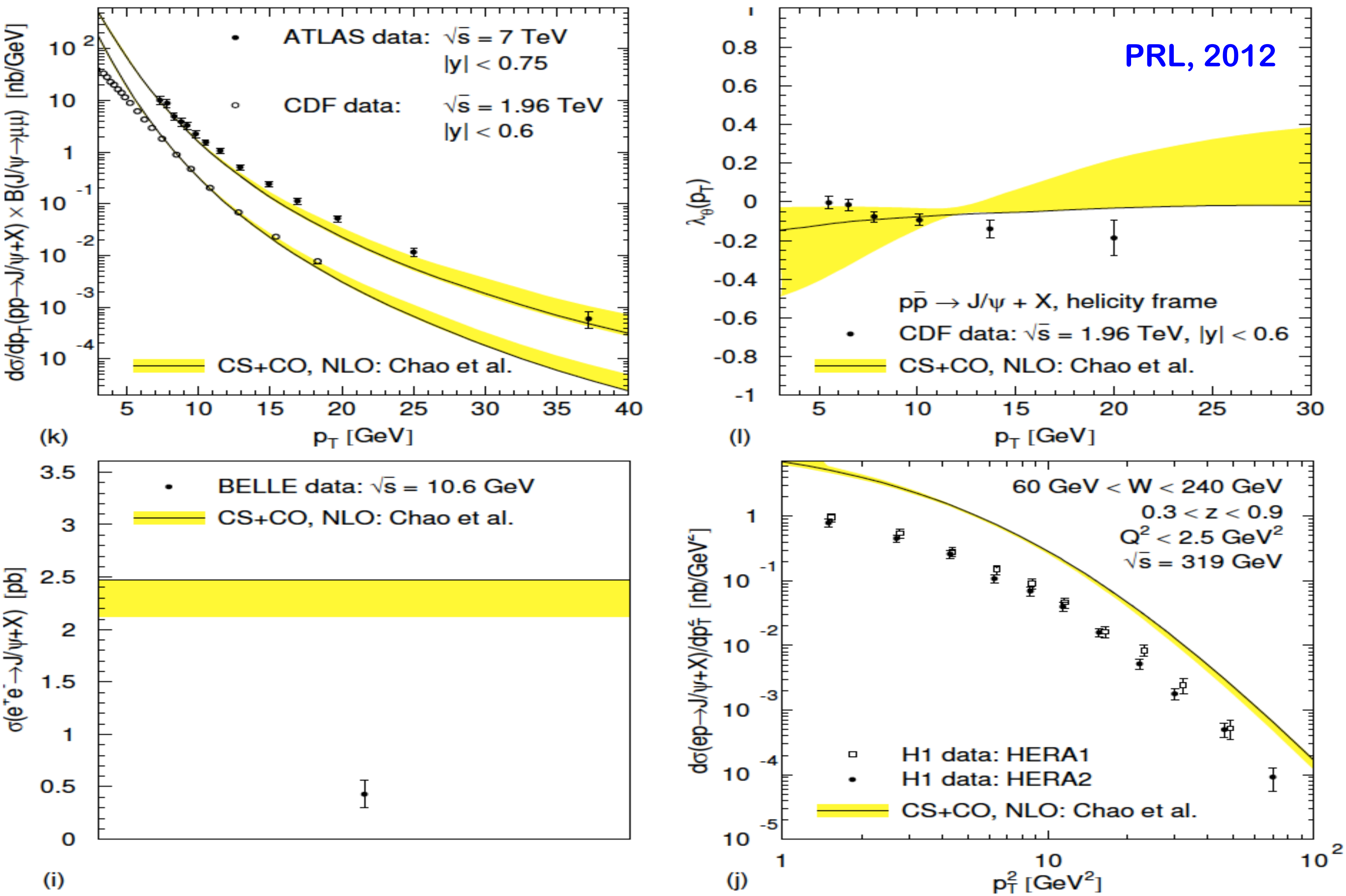
NLO theory fits – Butenschoen et al.



NLO theory fits – Gong et al.



NLO theory fits – Chao et al.



J/Ψ-production and polarization within a jet

Kang et al. 1702.03287

❑ Jet fragmentation function:

$$F^{J/\psi}(z_h, p_T) = \frac{d\sigma^{J/\psi}}{dp_T d\eta dz_h} \Bigg/ \frac{d\sigma}{dp_T d\eta}$$

Jet cross section with a fully reconstructed J/Ψ within it

Inclusive jet cross section

$$z_h \equiv p^+_{J/\psi}/p^+_{\rm jet}$$

❑ Production and factorization:

$$\frac{d\sigma^{J/\psi}}{dp_T d\eta dz_h} = \sum_{a,b,c} f_a \otimes f_b \otimes H^c_{ab} \otimes \mathcal{G}^{J/\psi}_c$$

✧ Semi-inclusive fragmenting jet function:

$$\mathcal{G}^{J/\psi}_i(z, z_h, p^+_{\rm jet}R, \mu) = \sum_j \int_{z_h}^1 \frac{dz'_h}{z'_h} \mathcal{J}_{ij}(z, z_h/z'_h, p^+_{\rm jet}R, \mu) \times D^{J/\psi}_j(z'_h, \mu) + \mathcal{O}(m^2_{J/\psi}/(p^+_{\rm jet}R)^2)$$

✧ Fragmentation function:

$$D_{i\to J/\psi}(z'_h, \mu_0) = \sum_n \hat{d}_{i\to[Q\bar{Q}(n)]}(z'_h, \mu_0)\langle \mathcal{O}^{J/\psi}_{[Q\bar{Q}(n)]}\rangle$$

J/Ψ -production and polarization within a jet

Kang et al. 1702.03287

❑ Jet fragmentation function:

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Jet cross section with a fully reconstructed J/Ψ within it

Inclusive jet cross section

$$z_h \equiv p^+_{J/\psi}/p^+_{\text{jet}}$$

❑ Polarization:

$$\frac{d\sigma^{J/\psi(\to \ell^+\ell^-)}}{d\cos\theta} \propto 1 + \lambda_F \cos^2\theta.$$

$$\lambda_F(z_h, p_T) = \frac{F_T^{J/\psi} - F_L^{J/\psi}}{F_T^{J/\psi} + F_L^{J/\psi}}$$

✧ Physical constraint:

$$|\lambda_F(z_h, p_T)| \le 1$$

Since $F_{T,L}^{J/\psi}$ are positive

✧ Expansion in terms of NRQCD LDMEs:

$$F_{T,L}^{J/\psi}(z_h, p_T) \sum_{[Q\bar{Q}(n)]} \hat{F}_{T,L}^{[Q\bar{Q}(n)]}(z_h, p_T, \Lambda)\langle 0|\mathcal{O}^{J/\psi}_{[Q\bar{Q}(n)]}(\Lambda)|0\rangle$$

➡ Linear combination of LDMEs, like p_T spectrum in NRQCD

J/Ψ-production and polarization within a jet

Kang et al. 1702.03287

❑ Fitting values of LDMEs:

	$\langle\mathcal{O}(^3S_1^{[1]})\rangle$ GeV^3	$\langle\mathcal{O}(^1S_0^{[8]})\rangle$ 10^{-2} GeV^3	$\langle\mathcal{O}(^3S_1^{[8]})\rangle$ 10^{-2} GeV^3	$\langle\mathcal{O}(^3P_0^{[8]})\rangle$ 10^{-2} GeV^5
Bodwin	0 [a]	9.9	1.1	1.1
Butenschoen	1.32	3.04	0.16	−0.91
Chao	1.16	8.9	0.30	1.26
Gong	1.16	9.7	−0.46	−2.14

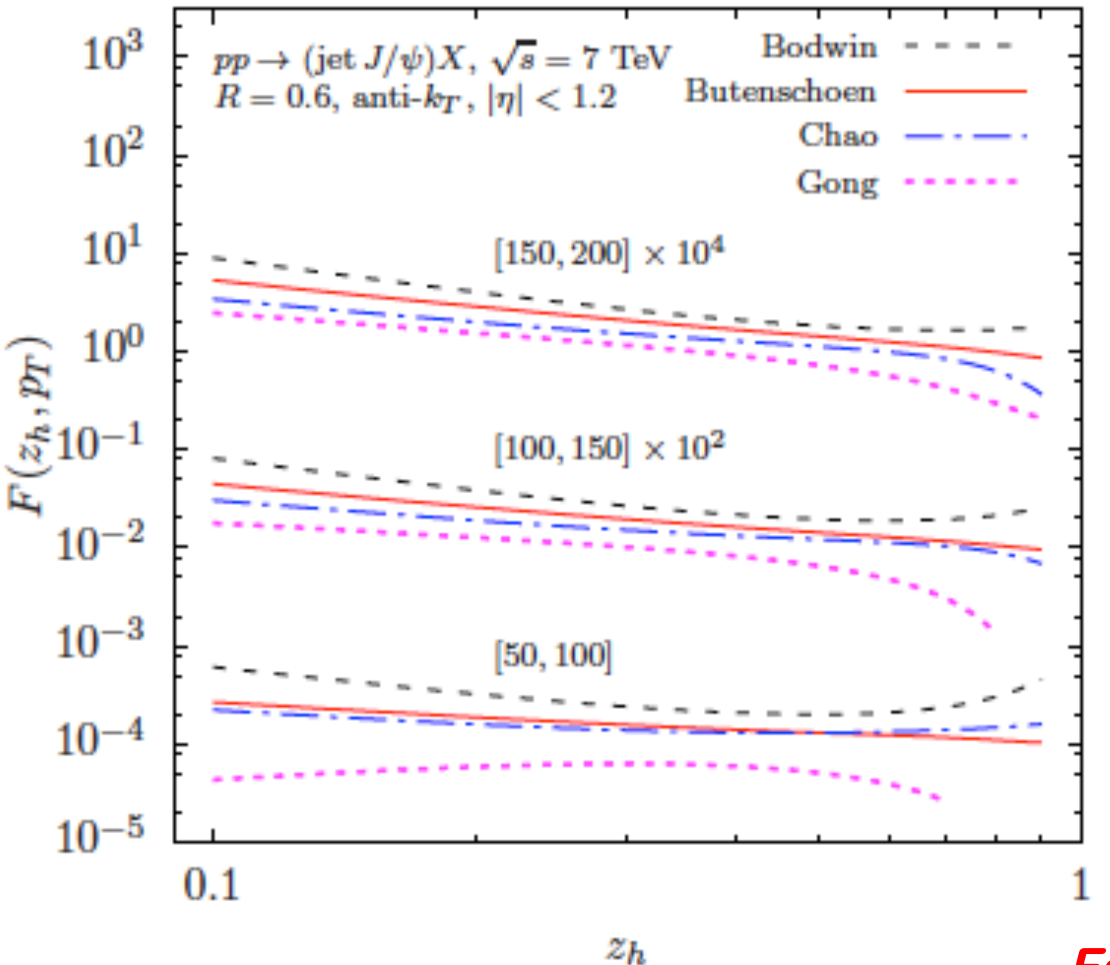
TABLE I. J/ψ NRQCD LDMEs from four different groups.

All fit the J/Ψ's p_T distribution

J/Ψ-production and polarization within a jet

Kang et al. 1702.03287

- Predictions:

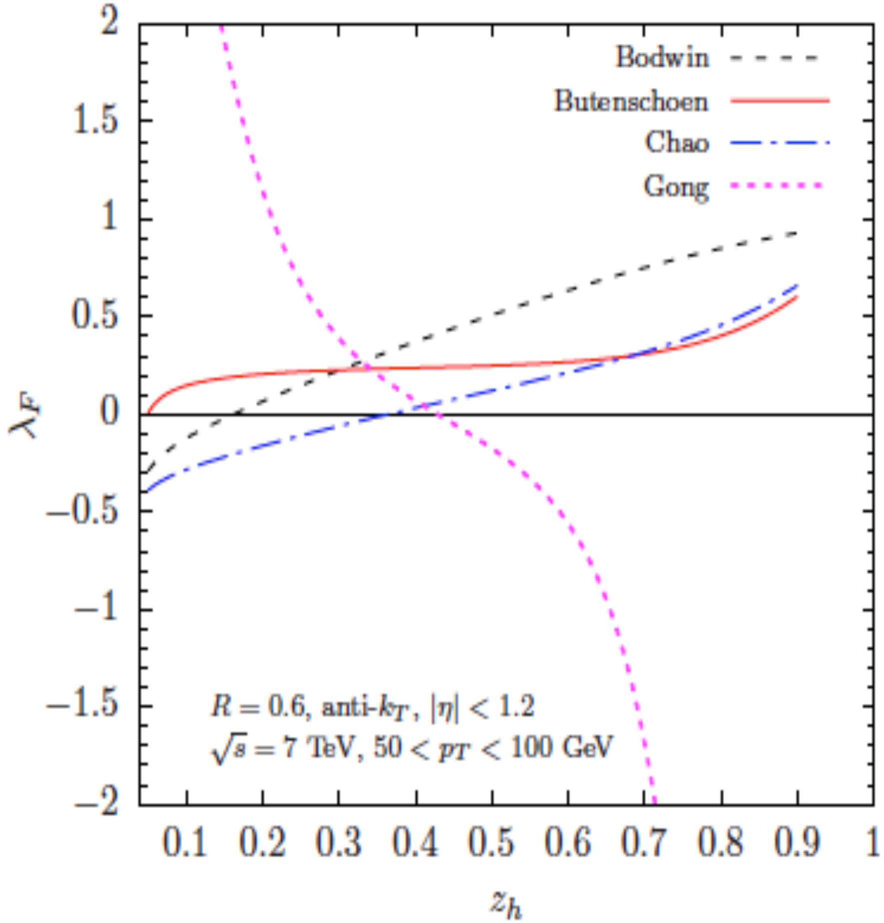


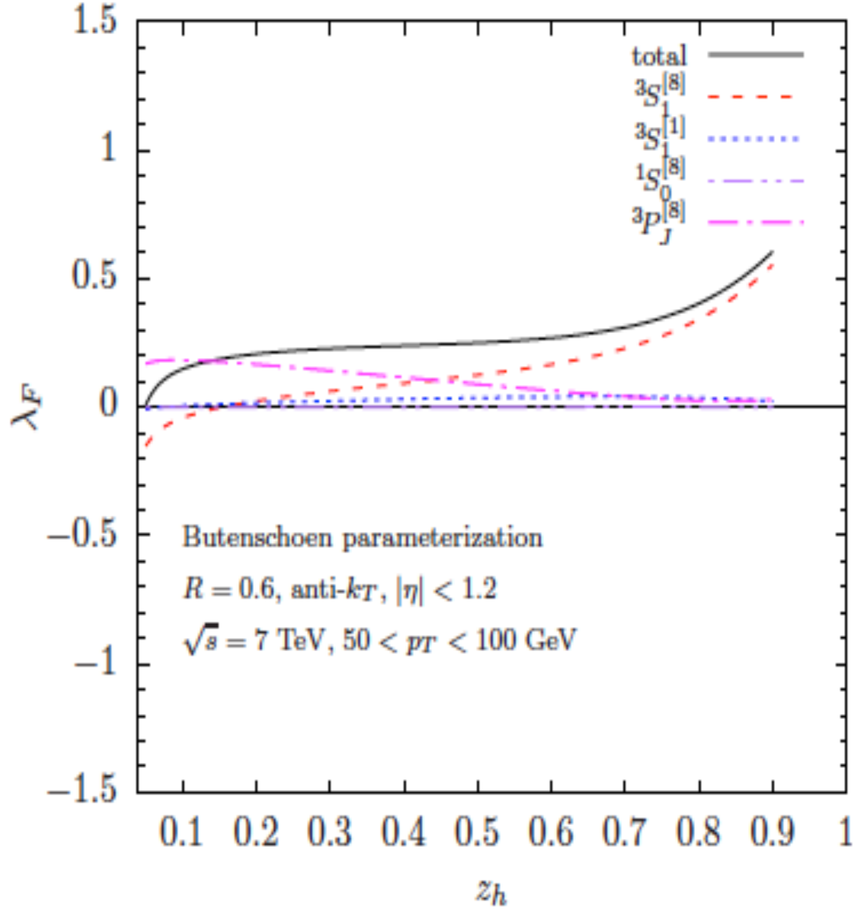
Factor of 10 difference in the predicted rate?!

J/Ψ-production and polarization within a jet

Kang et al. 1702.03287

❑ Predictions:





Bad LDMEs values: Negative "cross section"?!

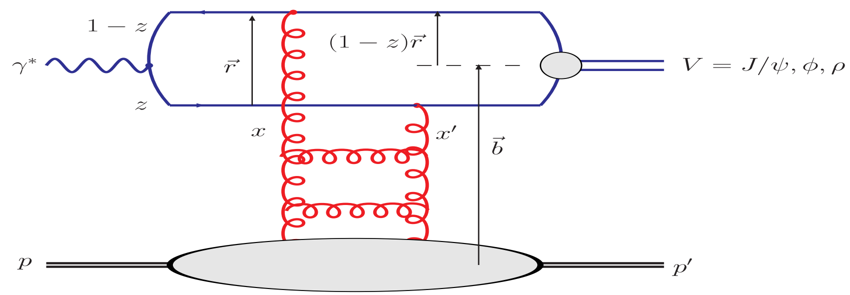
LHCb has been measuring the J/Ψ fragmenting function

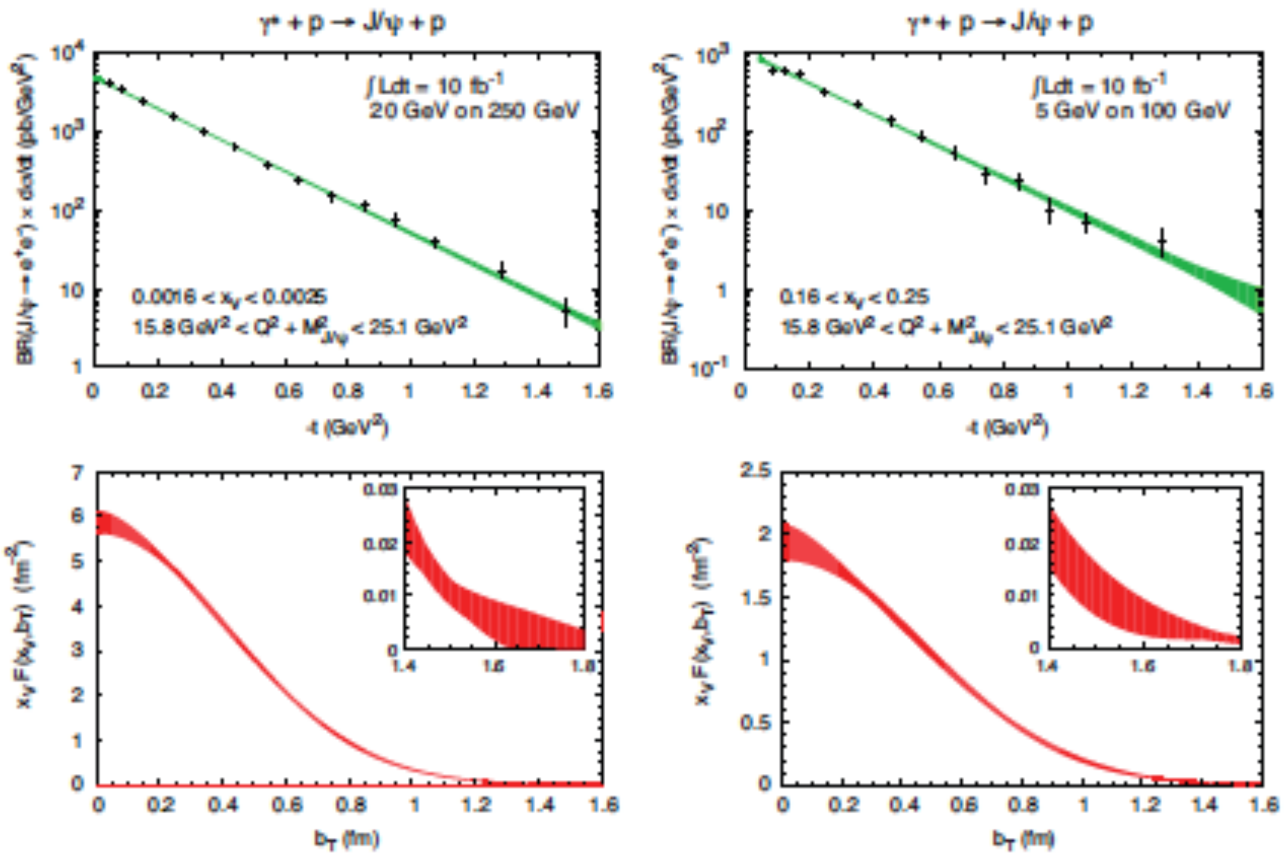
Exclusive production of heavy quarkonium

EIC WP, 1212.1701

- Exclusive DIS:

A folden process
for imagining gluon





Double $c\bar{c}$ production in e^+e^-

- **Inclusive production:**

$$\sigma(e^+e^- \to J/\psi c\bar{c})$$

Belle: $(0.87^{+0.21}_{-0.19} \pm 0.17)$ pb

NRQCD: ~ 0.07 pb

Kiselev, et al 1994,
Cho, Leibovich, 1996
Yuan, Qiao, Chao, 1997

- **Ratio to light flavors:**

$$\sigma(e^+e^- \to J/\psi c\bar{c})/\sigma(e^+e^- \to J/\psi X)$$

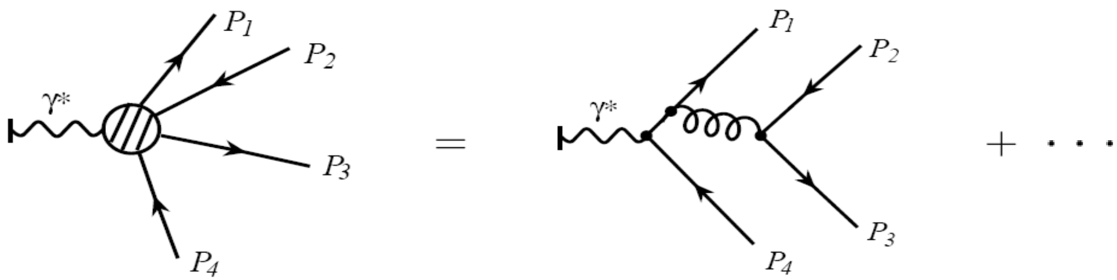
Belle: $0.59^{+0.15}_{-0.13} \pm 0.12$

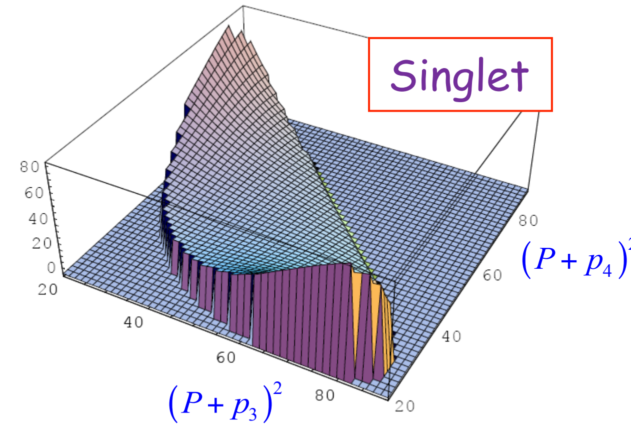
Message:

Production rate of $e^+e^- \to J/\psi c\bar{c}$ **is larger than all these channels:** $e^+e^- \to J/\psi gg, e^+e^- \to J/\psi q\bar{q}, \ldots$ **combined ?**

Associated production at B-factory

- **Kinematically preferred configuration:**

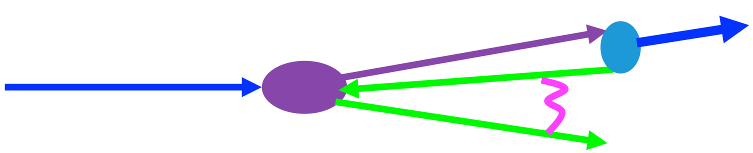




Production rate of a singlet charm quark pair is dominated by the phase space where $s_3=(P_1+P_2+P_3)^2$ or $s_4=(P_1+P_2+P_4)^2$ near its minimum

- **NRQCD formalism does not apply when there are more than one heavy quark velocity involved**

- **Color transfer enhances associated heavy quarkonium production**



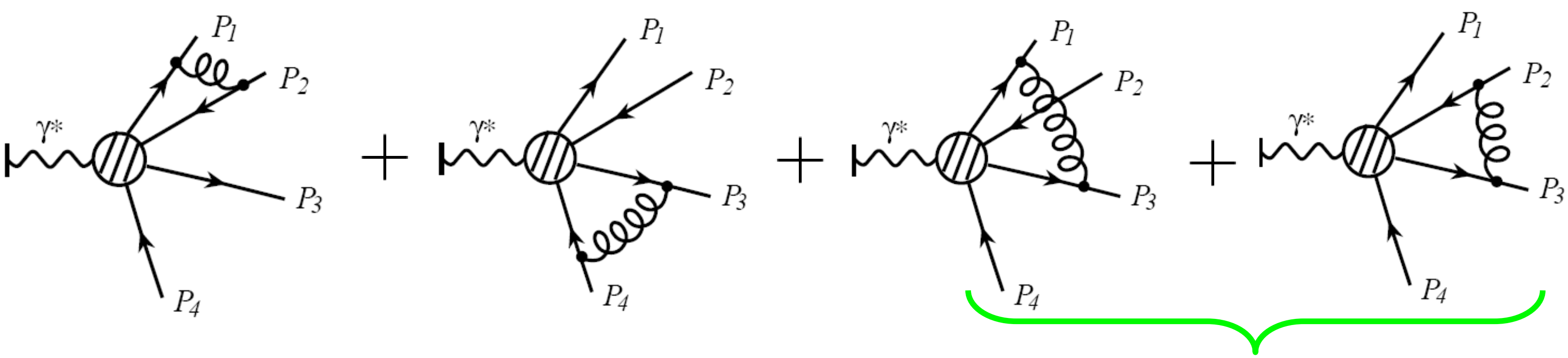
A heavy quark as a color source to enhance the transition rate for an octet pair to become a singlet pair

Nayak, Qiu, Sterman, PRL 2007

Soft gluon enhancement – color transfer

- **Soft gluons between heavy quarks:**

Active pair: P_1, P_2; spectators: P_3, P_4



- **There are three heavy quark velocities:**

$$\beta_{ij} \equiv \sqrt{1 - 4m^2/(P_i + P_j)^2}$$

NRQCD approach is not well defined in this region

- **Soft gluon between a heavy quark pair:**

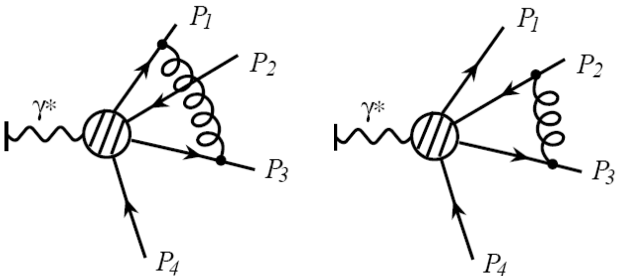
$$-i\, g^2 \int \frac{d^D k}{(2\pi)^D} \frac{4 P_i \cdot P_j}{[2P_i \cdot k + k^2 + i\epsilon][-2P_j \cdot k + k^2 + i\epsilon][k^2 + i\epsilon]}$$

$$= \frac{\alpha_s}{2\pi} \left[-\frac{1}{2\varepsilon} \left(\frac{1}{\beta_{ij}} + \beta_{ij} \right) (2\beta_{ij} - i\pi) \; + \ldots \right] \Longrightarrow i \frac{1}{\varepsilon} \frac{\alpha_s}{\beta_{ij}}$$

Associated production is enhanced

- **NLO correction to the amplitude:**

$$\mathrm{Im}\left[\mathcal{A}_{13}+\mathcal{A}_{23}\right] = \frac{\alpha_s}{4\varepsilon}\mathcal{A}^{(0)}(P_i)\left[\frac{1+\beta_{13}^2}{\beta_{13}} - \frac{1+\beta_{23}^2}{\beta_{23}}\right]$$



Does not contribute to NLO production rate in NRQCD

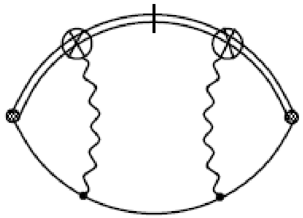
Zhang, Chao, PRL 2007

- **Estimate enhancement factor from NNLO in NRQCD approach:**

  - ✧ **Velocity expansion:**

$$\frac{1}{\beta_{13}} - \frac{1}{\beta_{23}} \sim -\frac{4}{\beta_S^3}\,\frac{q_S\cdot q}{m^2} \sim \frac{4}{\beta_S^2}\,v\,\cos\phi_S$$

$$\beta_S = \sqrt{\frac{-q_S^2}{m^2-q_S^2}}$$



$$P_3^\mu = \frac{P_0^\mu}{2}\sqrt{1-\frac{q_S^2}{m^2}} + q_S^\mu$$

$$P_0^\mu = (2m, 0) \text{ and } q_S\cdot P_0 = 0$$

  - ✧ **Velocity-ordered region:**

$$\beta_S < 1, \quad \frac{v}{\beta_S} < 1$$

  - ✧ **Enhancement factor:**

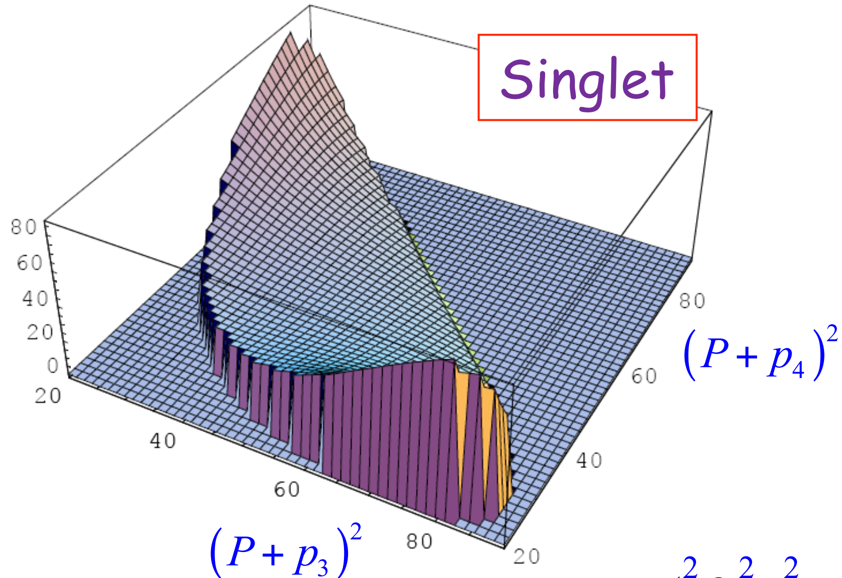
$$\left|A^{NNLO}_{Singlet}\right|^2 : \left(C_{8\to 1}\frac{\alpha_s^2 v^2}{\varepsilon^2}\right)\left(\frac{\pi^2}{\beta_s^4}\right)\left|A^{LO}_{Octet}\right|^2$$

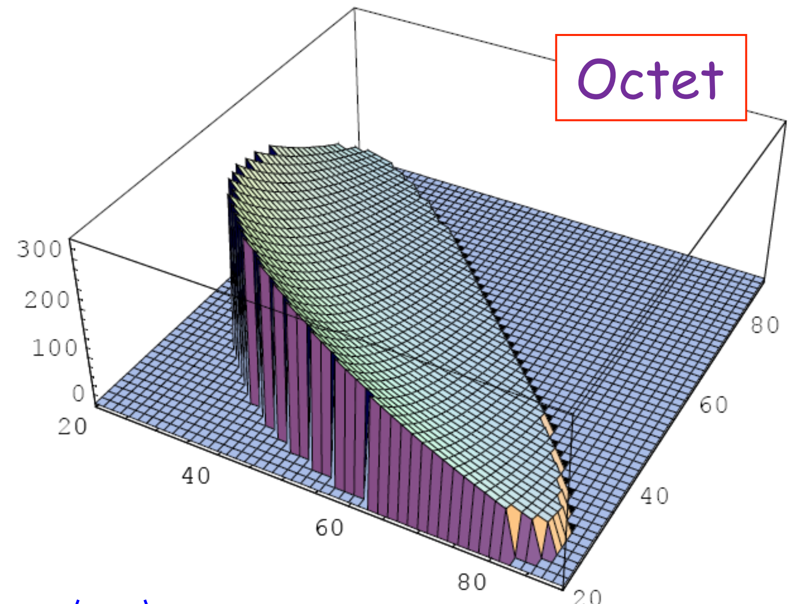
All other two-loop diagrams give a single pole !

Nayak, Qiu, Sterman, 2007

Numerical enhancement from NNLO

- ❑ **LO hard parts with color factor:**





$$\frac{\pi^2\alpha_s^2 v^2}{\varepsilon^2} \Rightarrow \langle O_8 \rangle$$

- ❑ **Matrix elements:**

$$d\sigma^{\rm tot}_{e^+e^-\to H+X}(p_H) \sim d\hat{\sigma}_{e^+e^-\to Q\bar{Q}[S_1]+Q'(\beta_S)}(p_H)\,\langle {}^3\mathcal{S}_1^H\rangle$$
$$+\, d\hat{\sigma}_{e^+e^-\to Q\bar{Q}[S_8]+Q'(\beta_S)}(p_H)\,\frac{\langle {}^3\mathcal{S}_8^H\rangle}{\beta_S^4}$$

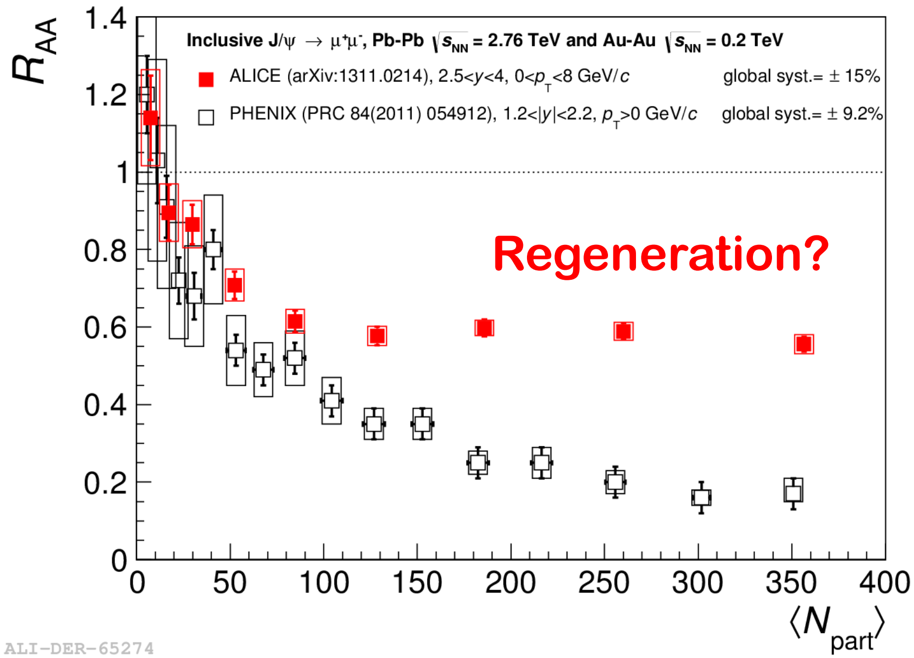
Two terms are equally important if $\beta_s : 0.3$

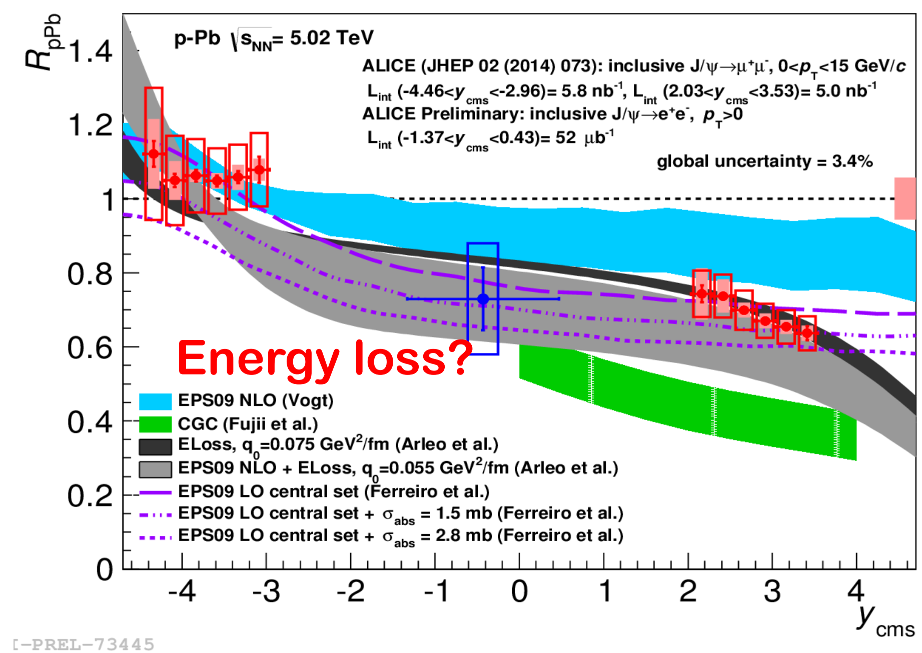
Nayak, Qiu, Sterman, 2007

Same feature for heavy quark fragmentation

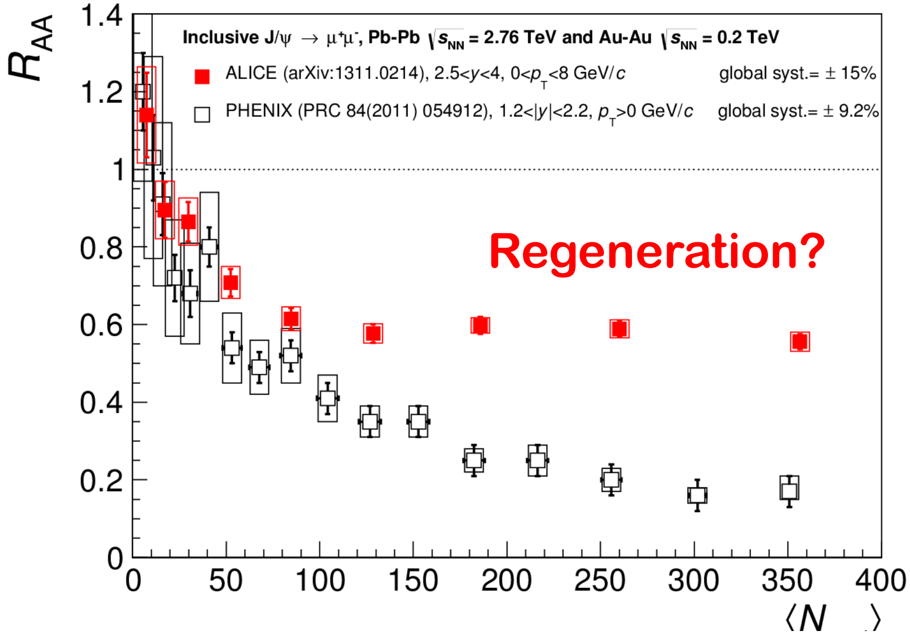
Kang, et al. 2007

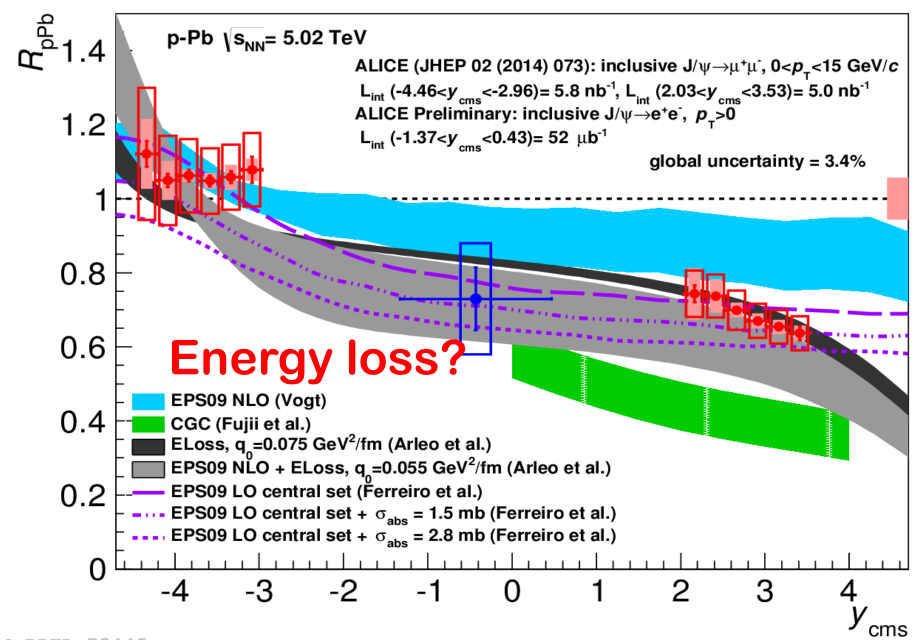
Heavy quarkonium – puzzles

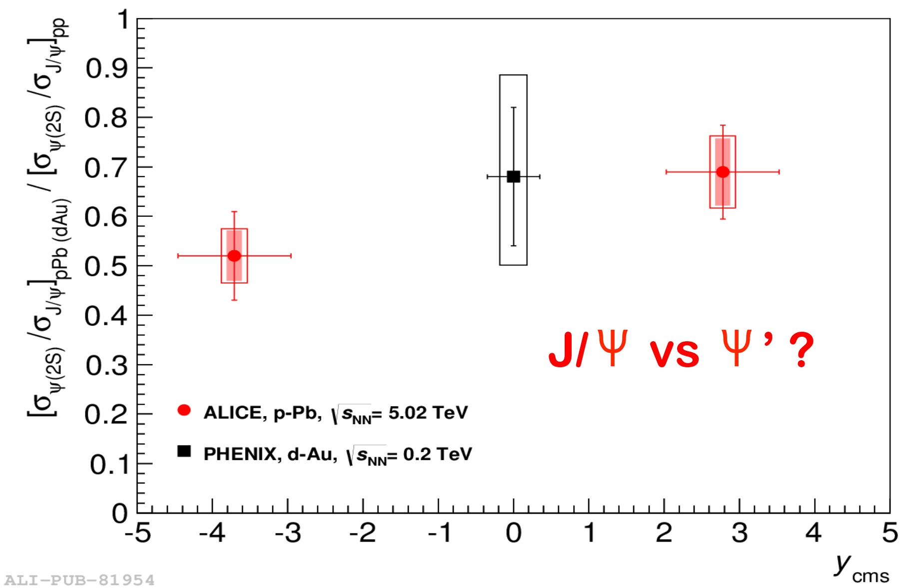


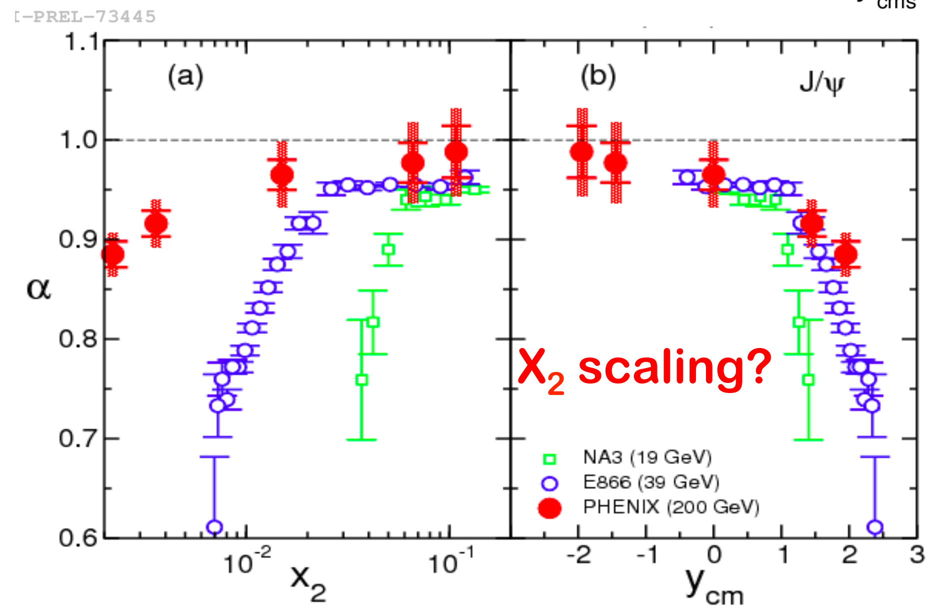


Heavy quarkonium – puzzles

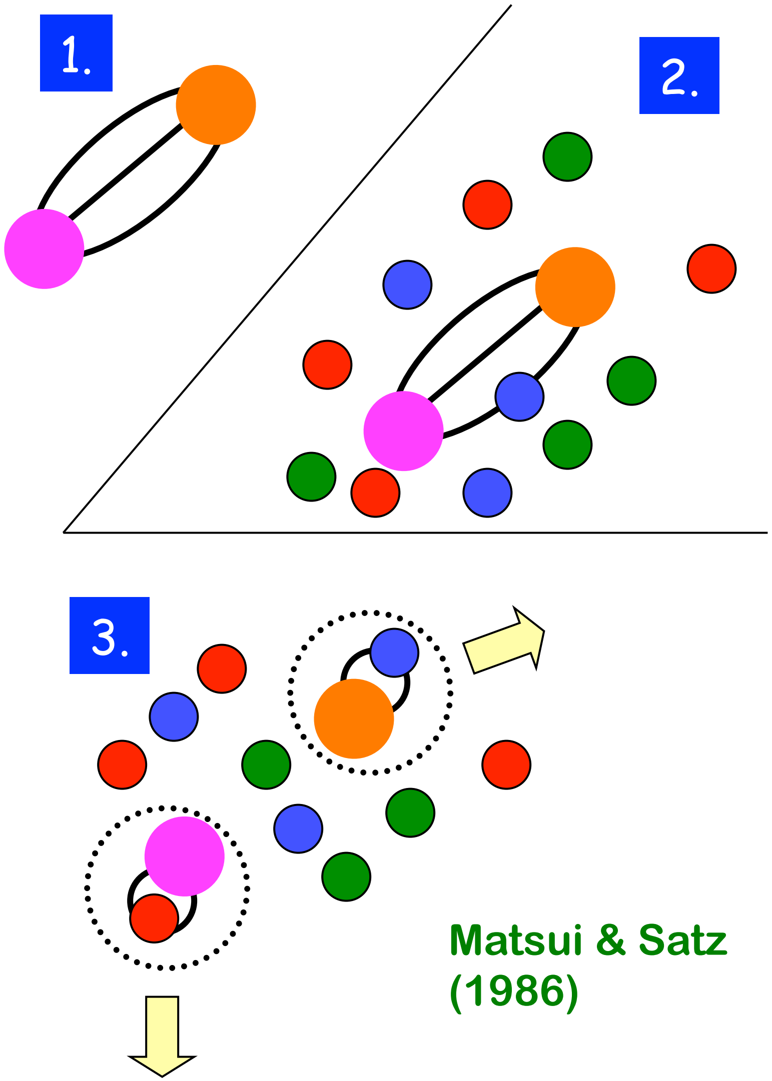






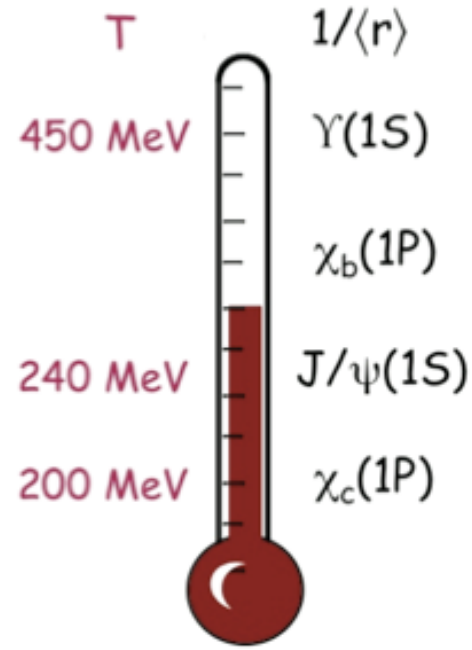


Melting a quarkonium in QGP – deconfinement



Matsui & Satz (1986)

QGP Thermometer



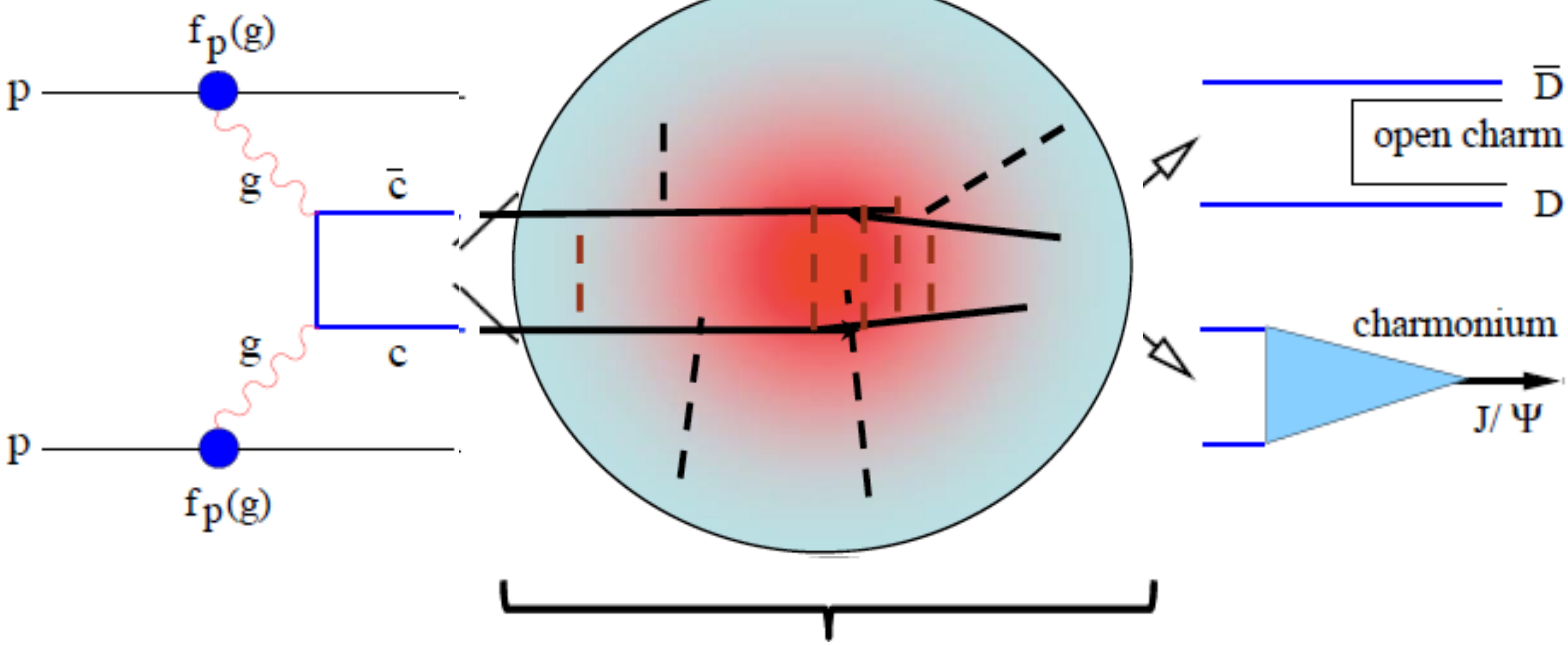
A. Mocsy, P. Petreczky, and MS, 1302.2180

See suppression at SPS, RHIC, and the LHC

But, Time dependent quarkonia formation!

Production in A+A collisions

Gossiaux and Katz



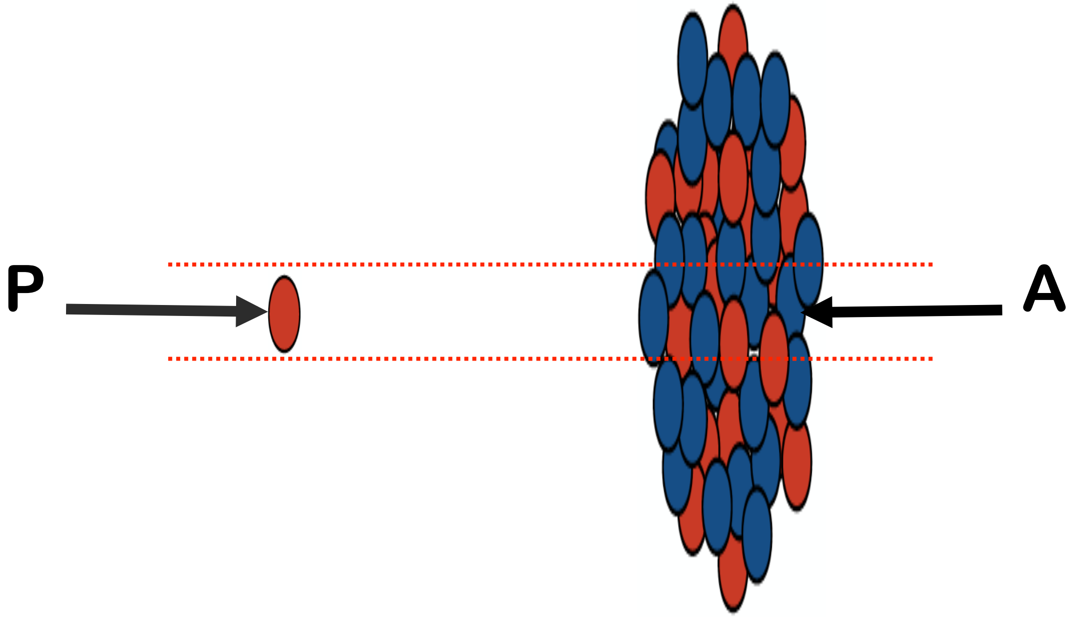
Very complicate QFT at finite T!

Need a full time-dependent, dynamical model of QGP with heavy quarks!

Many model approaches are available, …,
But, not to be discussed here!

Production in p(d)+A collisions

❑ Proton (deuteron) – Nucleus Collisions:



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

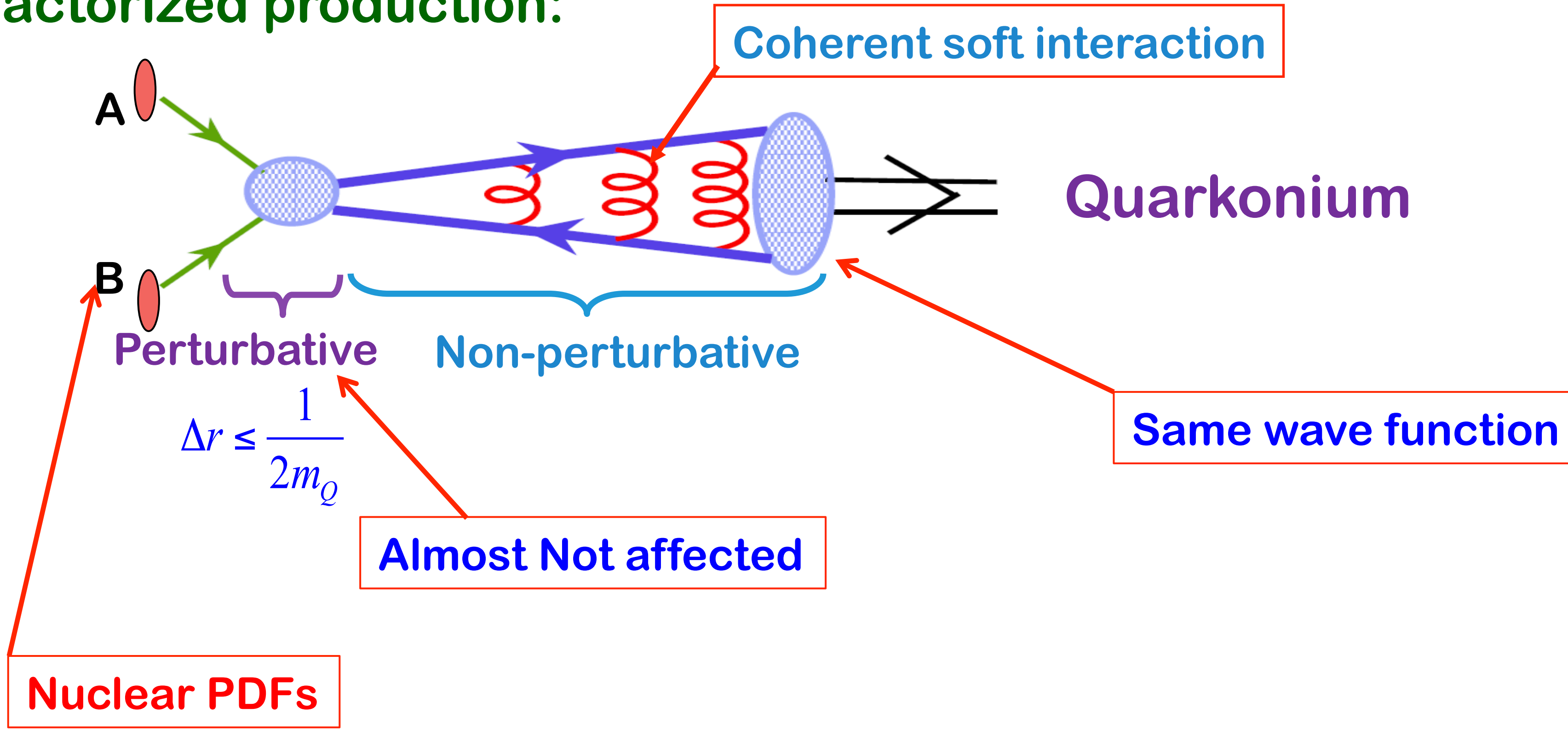
✧ Nuclei as potential filters of production mechanisms

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

Nucleus is not a simple superposition of nucleons!

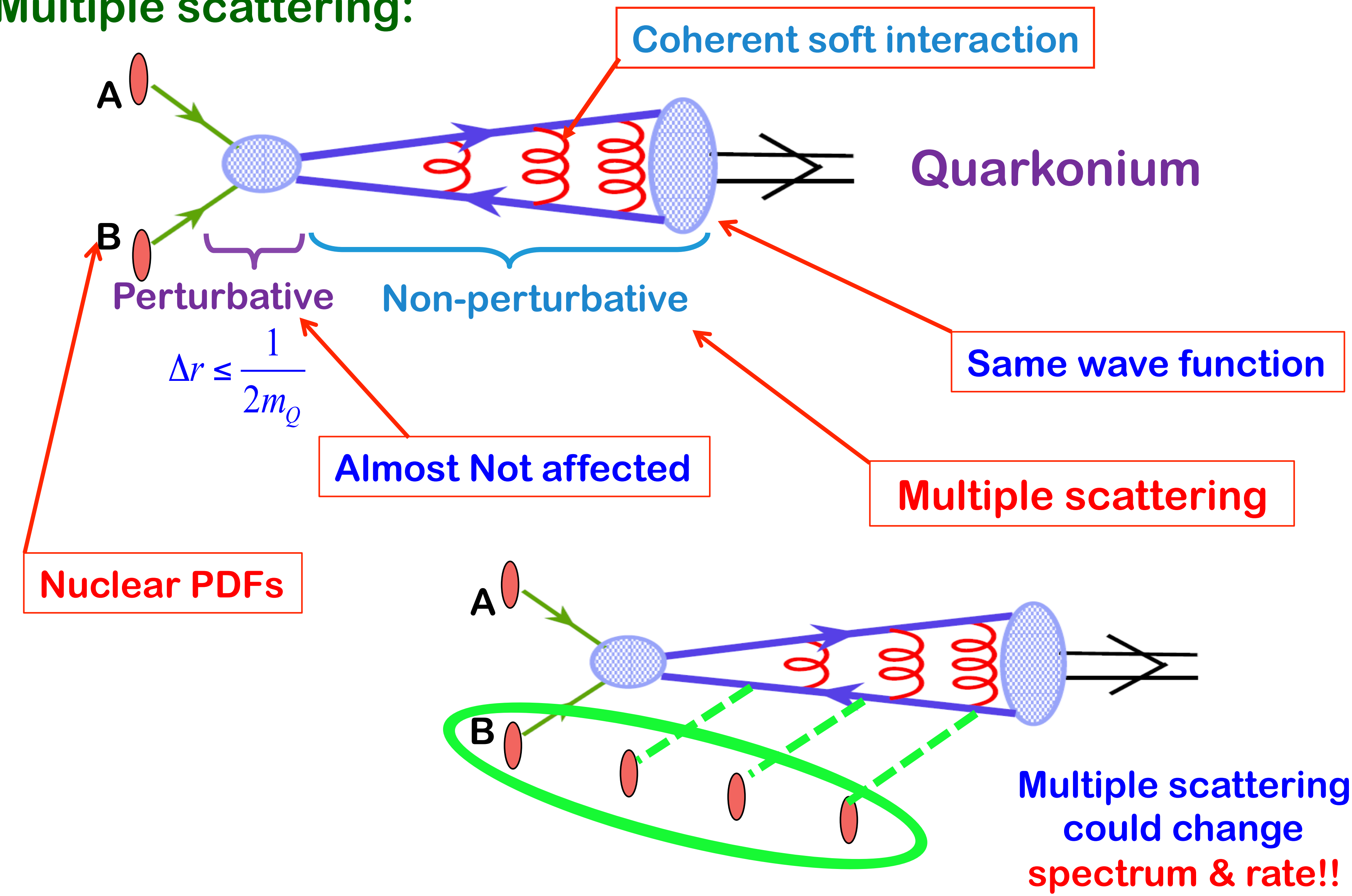
Production in p(d)+A collisions

- Factorized production:



Production in p(d)+A collisions

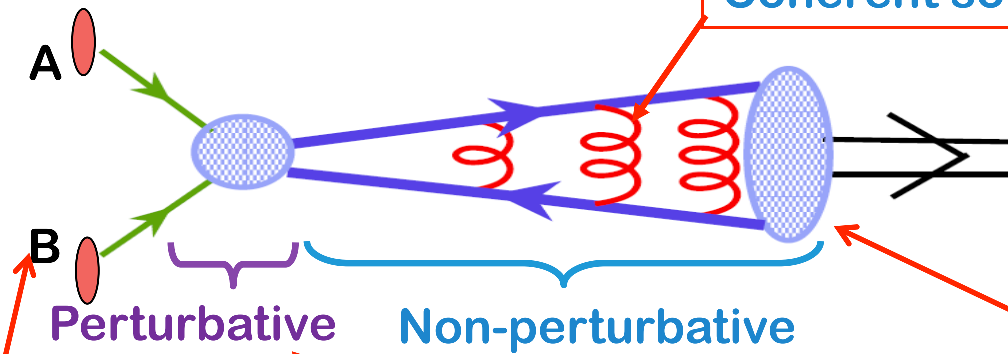
- ❑ **Multiple scattering:**



Production in p(d)+A collisions

- ❑ **Multiple scattering:**

Coherent soft interaction



Quarkonium

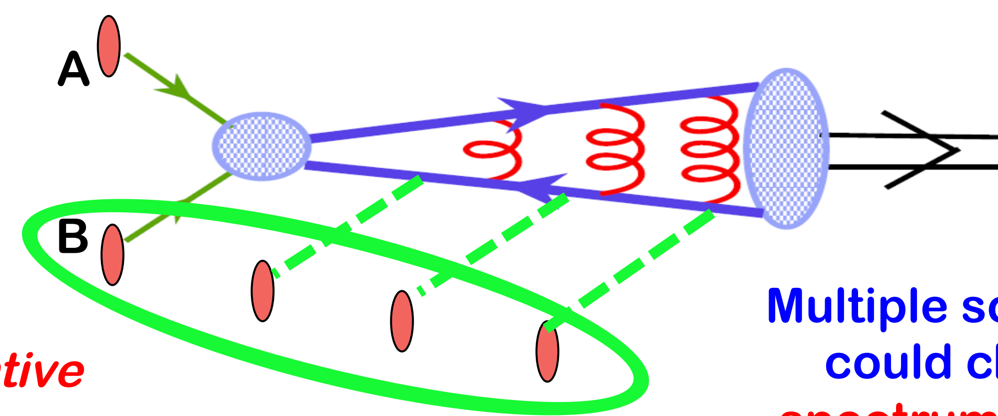
Same wave function

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

Almost Not affected

Multiple scattering

Nuclear PDFs

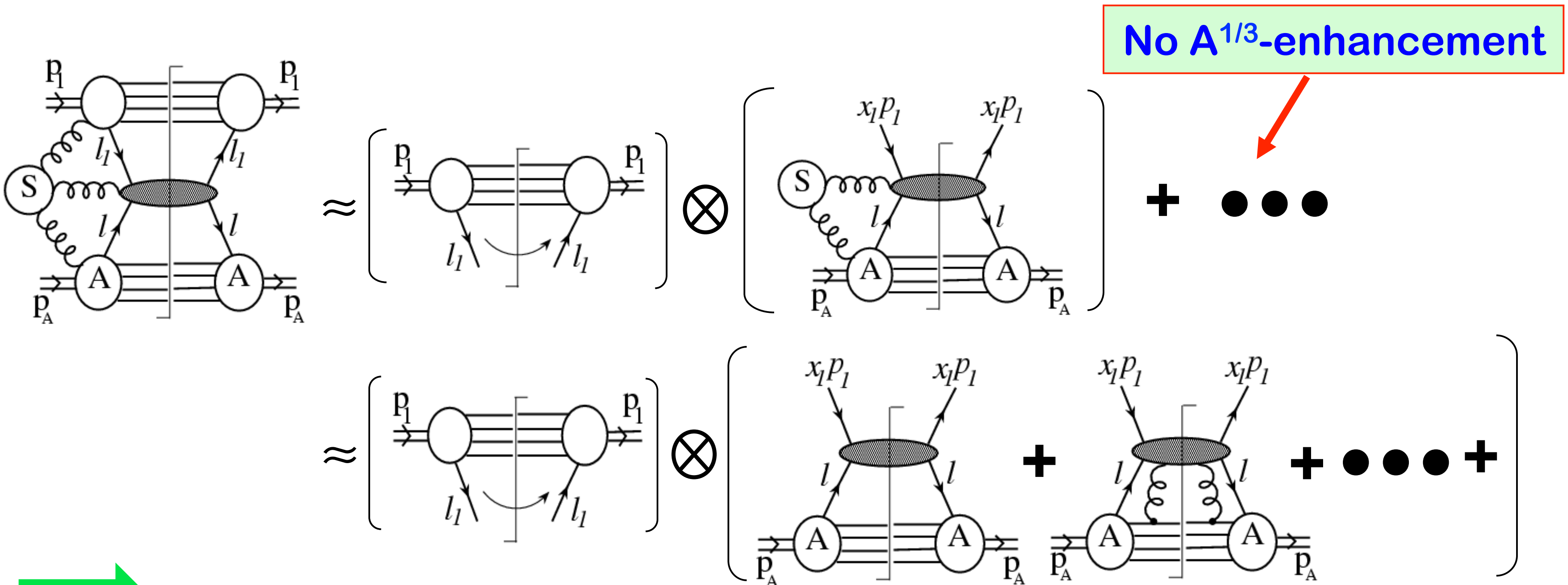


Can multiple scattering interfere with nonperturbative formation of quarkonia?

Multiple scattering could change spectrum & rate!!

Breaking of factorization in hadronic 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

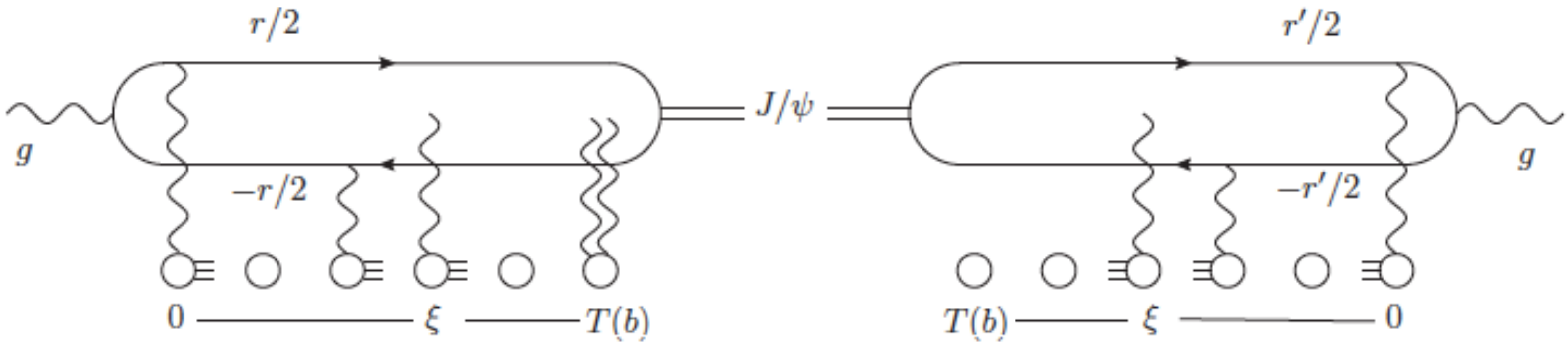
✧ P_T spectrum: Factorization argument similar to SIDIS

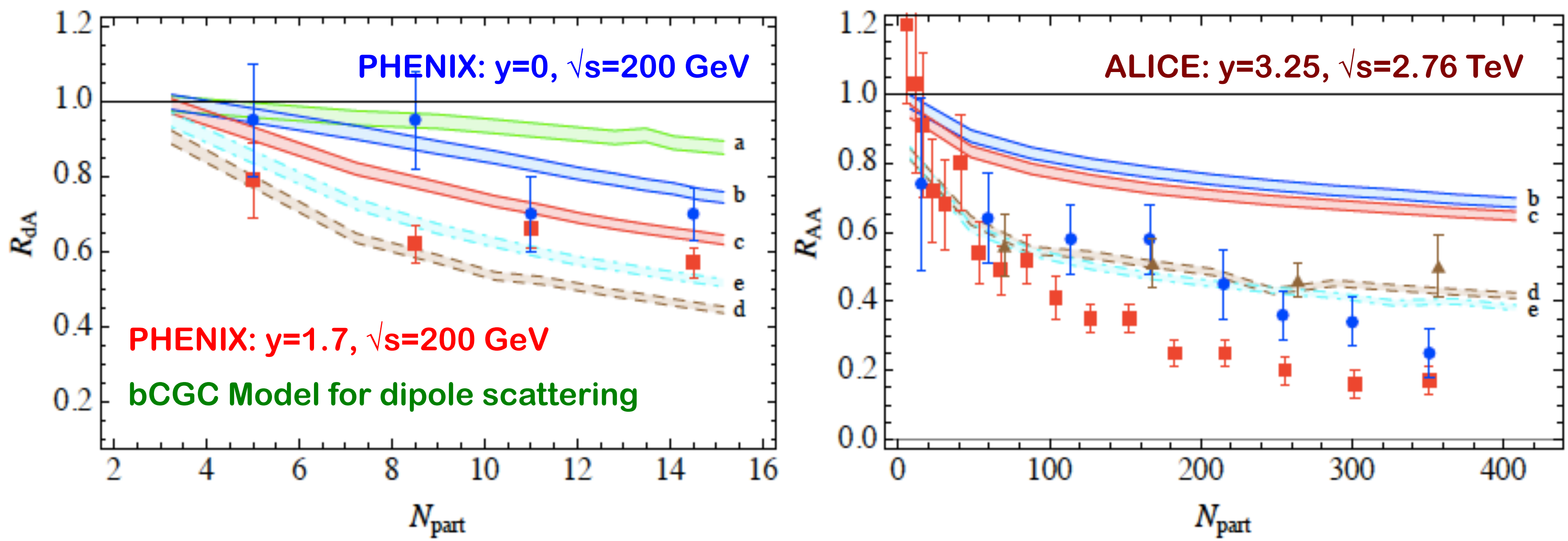
TMD or collinear – low P_T to high P_T

Multiple scattering in cold nuclear matter

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

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



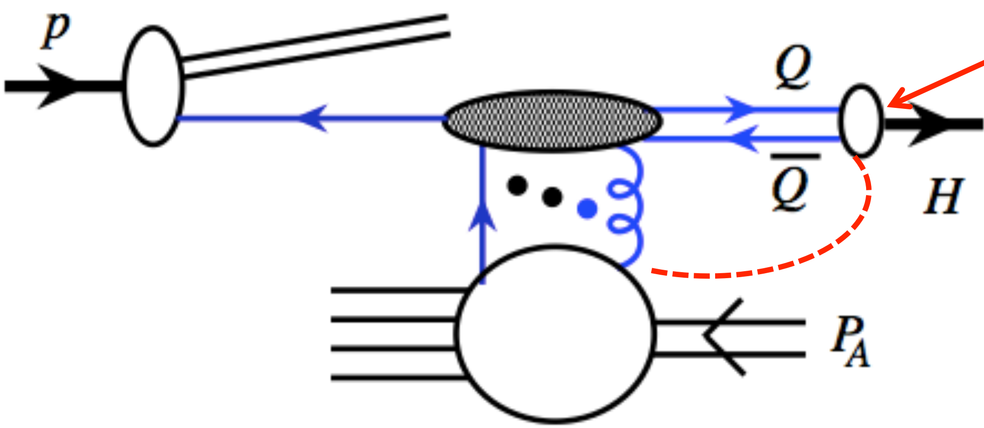


OK for pA, but, far off for AA – J/ψ melting in QGP (MS 1986)?

Production with multiple scattering

Brodsky and Mueller, PLB 1988

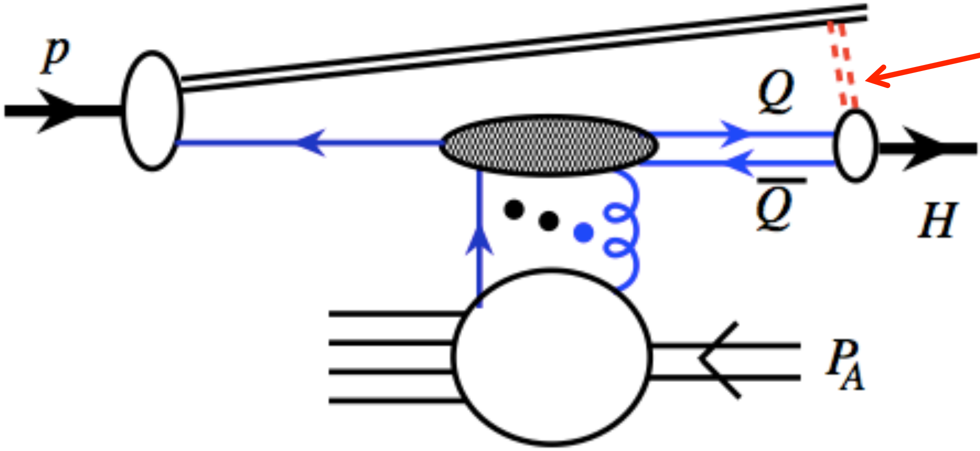
- ❑ *Backward* production in p(d)+A collisions:



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:



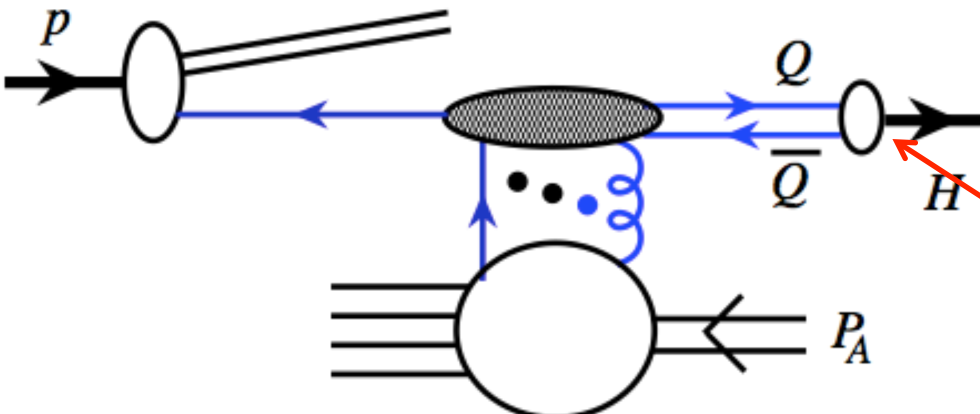
Co-mover interaction

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

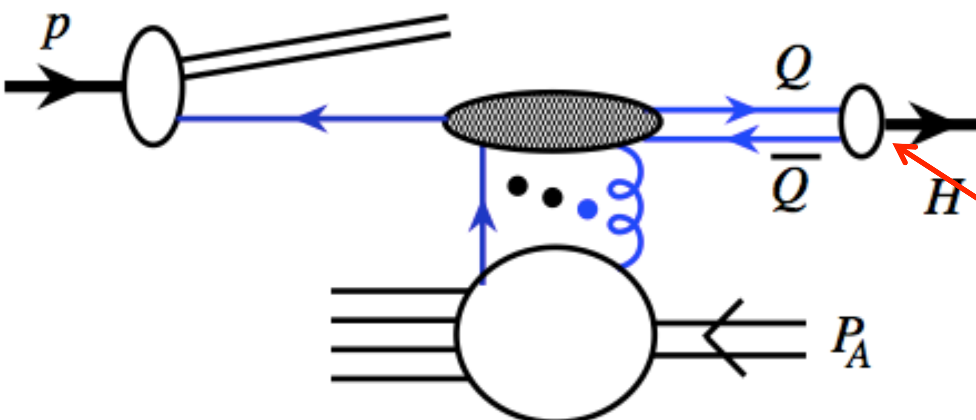
Non-perturbative formation of J/Ψ is far outside of nucleus

✧ 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

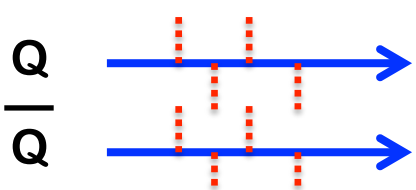
Non-perturbative formation of J/Ψ is far outside of nucleus

✧ 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



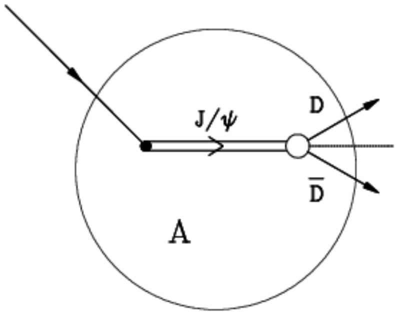
Soft multiple scattering – "random walk"

➡ Momentum imbalance – larger invariant mass

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

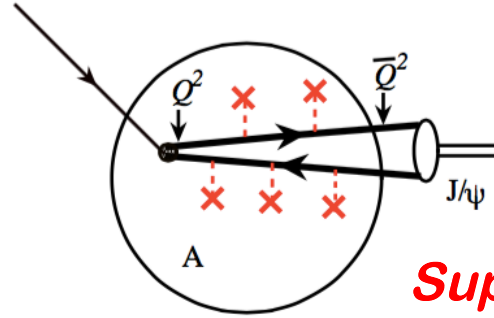
Suppression in total production rate

Glauber model



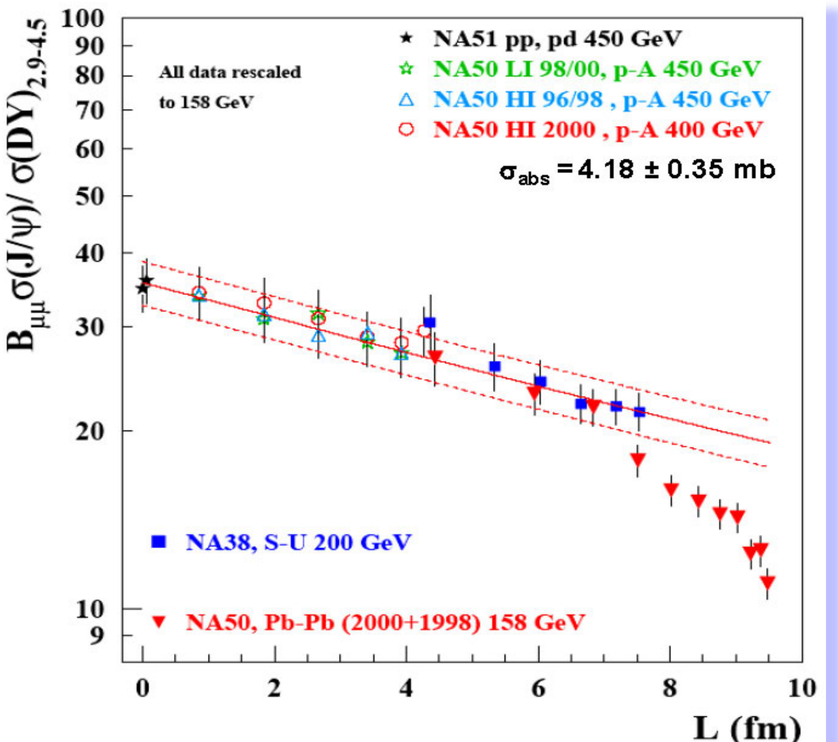
$$\frac{1}{AB}\,\frac{\sigma_{AB}}{\sigma_{NN}}$$
$$\approx e^{-\rho_0\,\sigma_{\rm abs}\,L_{AB}}$$

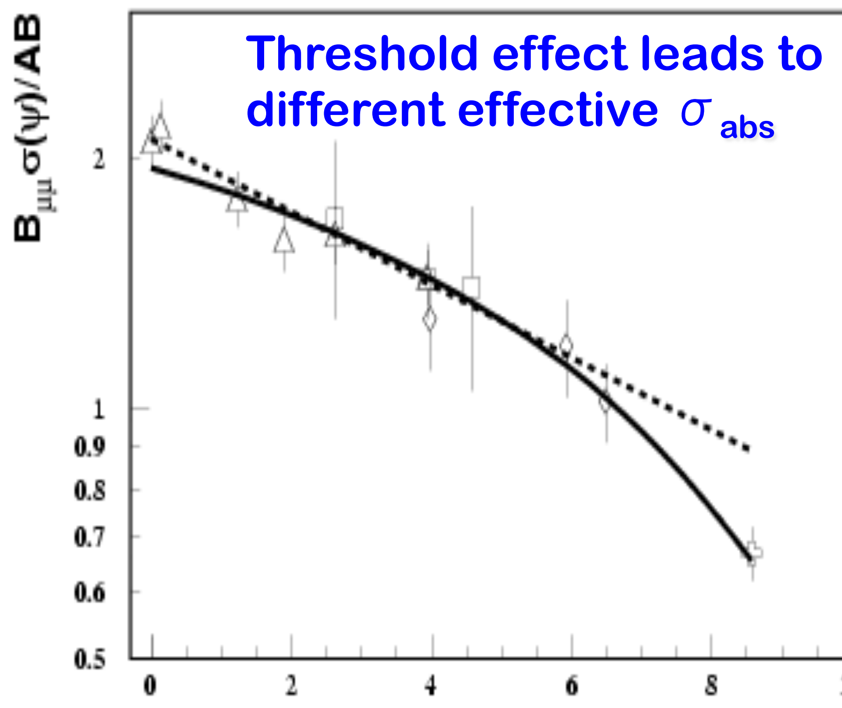
Multiple scattering of the pair



$$\overline{Q}^2 = Q^2 + \varepsilon\, L_{AB}$$
$$\varepsilon \sim \hat{q} \sim \langle \Delta q_T^2 \rangle$$

Suppression of J/ψ



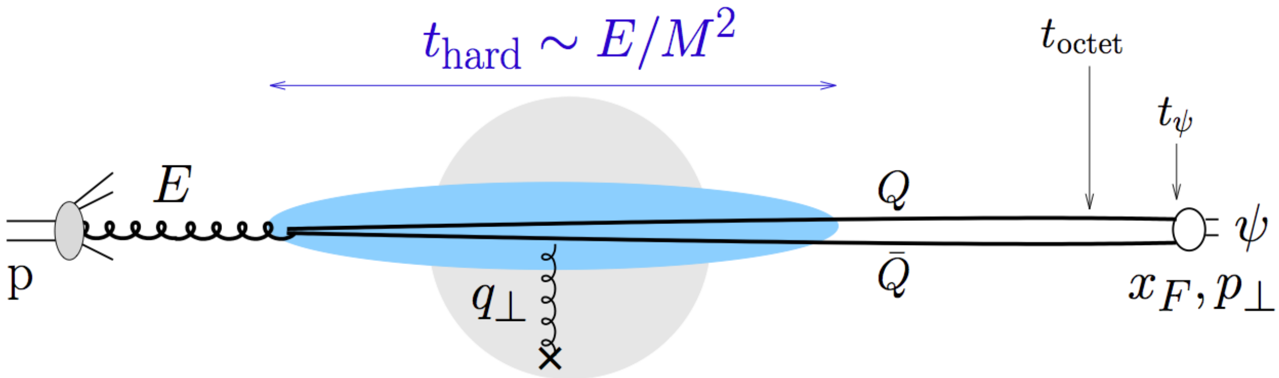


Qiu, Vary, Zhang, PRL 2002

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

❑ Picture + assumptions:

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



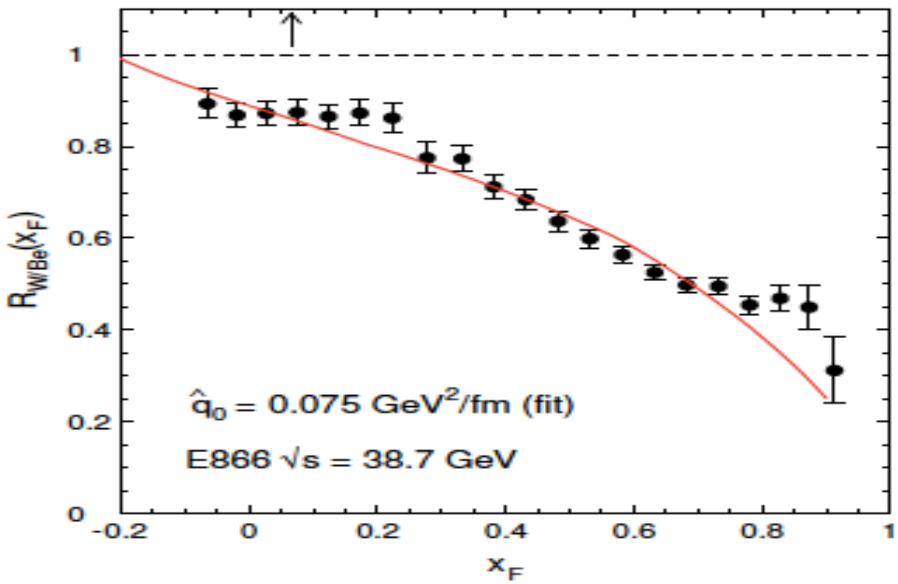
- Color neutralization happens on long time scales: $t_{\rm octet} \gg t_{\rm hard}$
- Medium rescatterings do not resolve the octet $c\bar{c}$ pair
- Hadronization happens outside of the nucleus: $t_\psi \gtrsim L$
- $c\bar{c}$ pair produced by gluon fusion

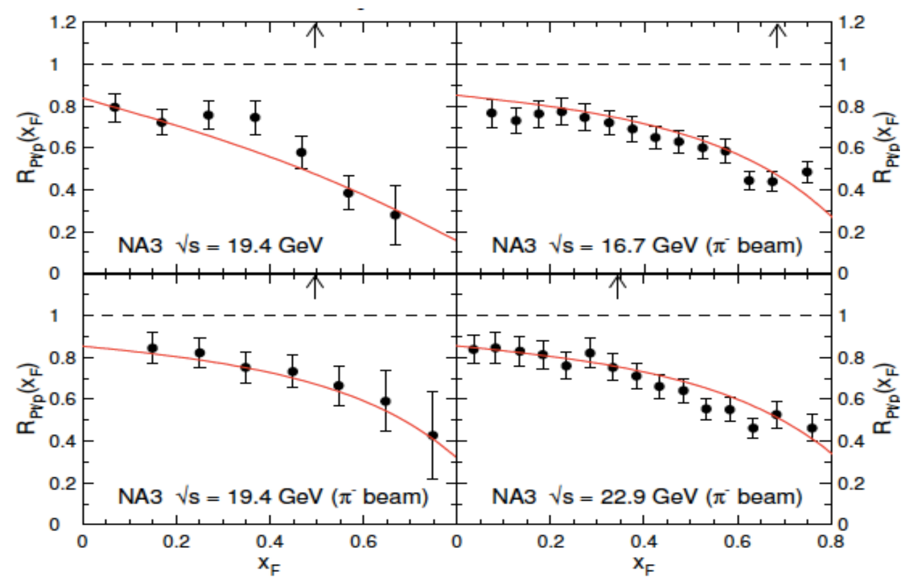
❑ Model energy loss:

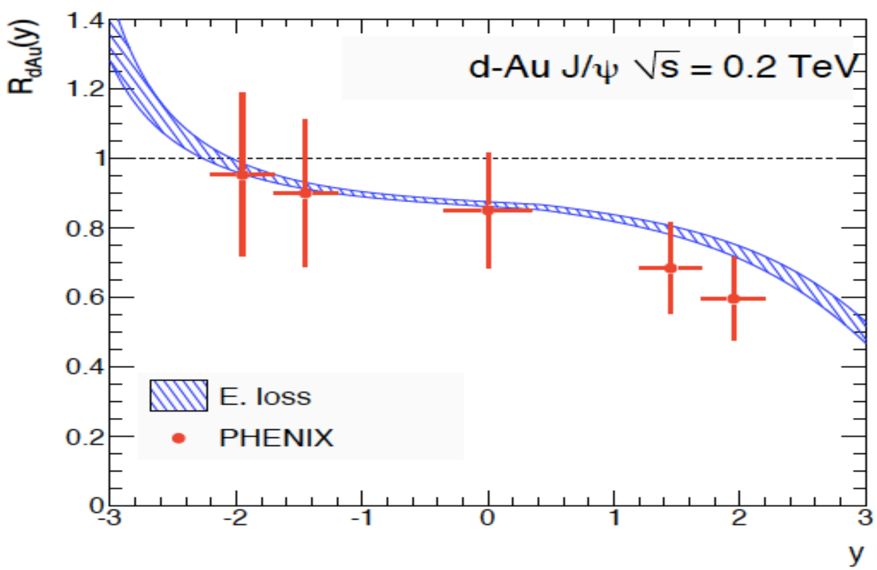
$$\frac{1}{A}\frac{d\sigma_{pA}}{dE}(E,\sqrt{s}) = \int_0^{\varepsilon_{\max}} d\varepsilon\, \mathcal{P}(\varepsilon, E)\, \frac{d\sigma_{pp}}{dE}(E+\varepsilon,\sqrt{s}) \qquad \hat{q}(x) \sim \hat{q}_0 \left(\frac{10^{-2}}{x}\right)^{0.3}$$

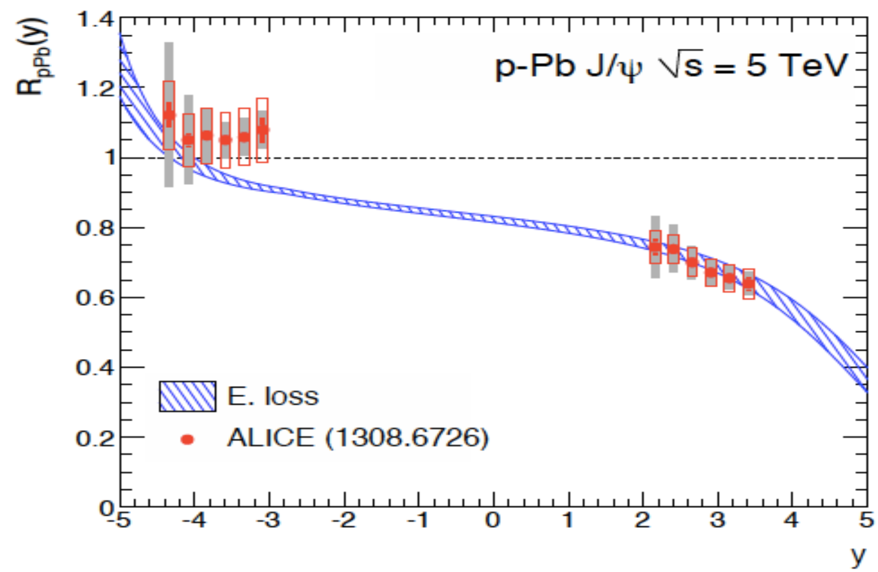
$\mathcal{P}(\varepsilon, E)$: **Quenching weight ~ scaling function of** $\sqrt{\hat{q}L}/M_\perp \times E$

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









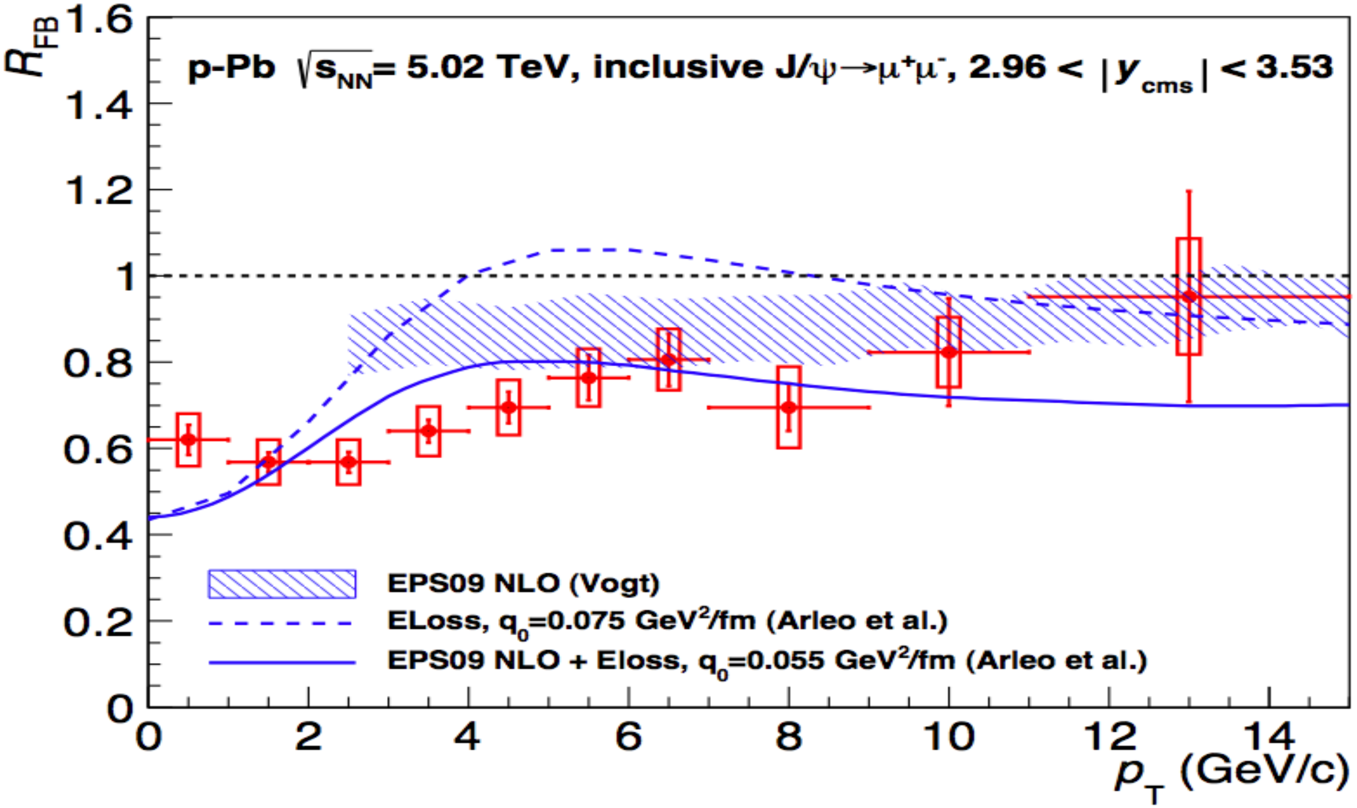
A-dependence in P_T in p+A

- **Model:**

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

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

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



Quarkonium pT distribution

- Quarkonium production is dominated by low p_T region
- Low p_T distribution at collider energies:

  determined mainly by gluon shower of incoming partons

  – initial-state effect

  Qiu, Zhang, PRL, 2001
- Final-state interactions suppress the formation of J/ψ:

  Also modify the p_T spectrum – move low pT to high pT – broadening

  – Final-state effect
- Broadening:
  - Sensitive to the medium properties
  - Perturbatively calculable

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

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

- R_{pA} at low q_T:

Guo, Qiu, Zhang, PRL, PRD 2002

$$R(A, q_T) \equiv \frac{1}{A} \frac{d\sigma^{hA}}{dQ^2 \, dq_T^2} \bigg/ \frac{d\sigma^{hN}}{dQ^2 \, dq_T^2} \equiv A^{\alpha(A, q_T) - 1} \approx 1 + \frac{\Delta \langle q_T^2 \rangle}{A^{1/3} \langle q_T^2 \rangle_{hN}} \left[-1 + \frac{q_T^2}{\langle q_T^2 \rangle_{hN}} \right]$$

Quarkonium P_T-broadening in p(d)+A

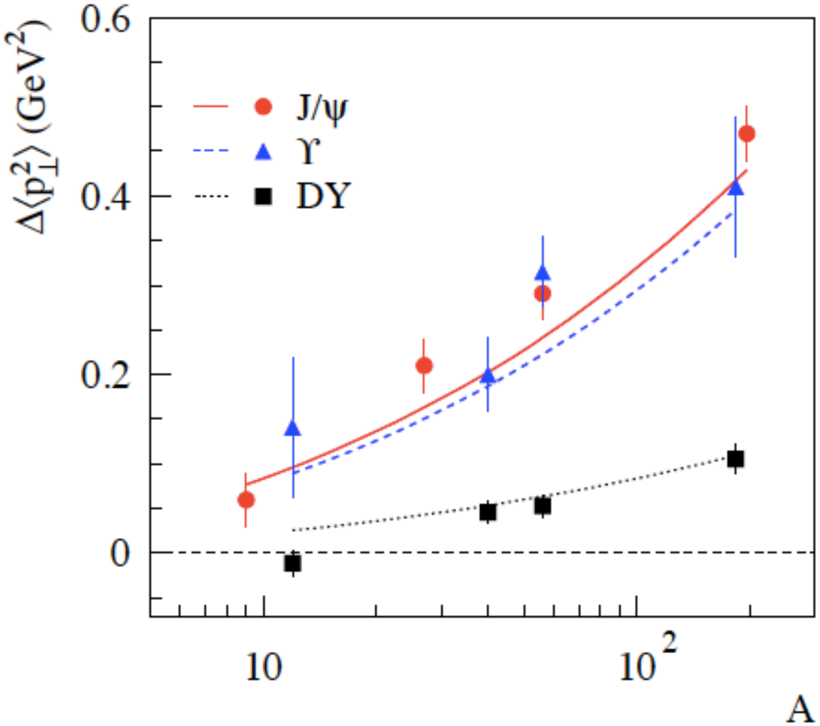
Kang, Qiu, PRD77(2008)

❑ Broadening:

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

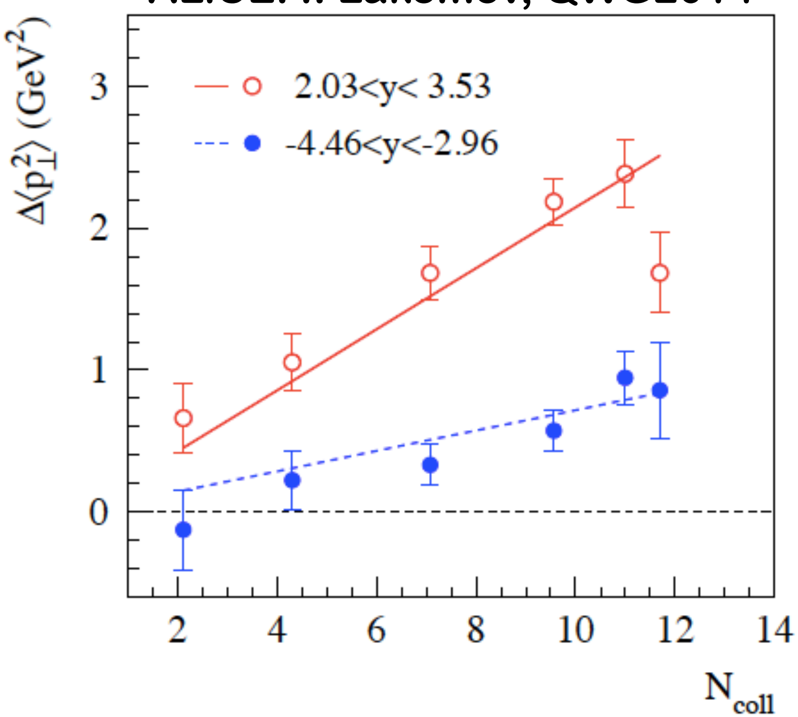
Calculated in both NRQCD and CEM

$$\lambda^2 = \kappa\,\ln(Q)\,x^{-\delta} \propto \hat{q}, \quad \kappa = 3.51\times10^{-3}\ 1/\mathrm{GeV}^2, \quad \delta = 1.71\times10^{-1}$$



$$\left(A^{1/3}-1\right) \rightarrow \left(A^{1/3}-1\right) N_{\mathrm{coll}}/N_{\mathrm{coll}}^{\mathrm{min.bias}}.$$

ALiCE: I. Lakomov, QWG2014



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

❑ Cross section:

Kang, Qiu, PRD77(2008)

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

❑ Broadening:

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

Hard parts:

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

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

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

Only color octet channel contributes

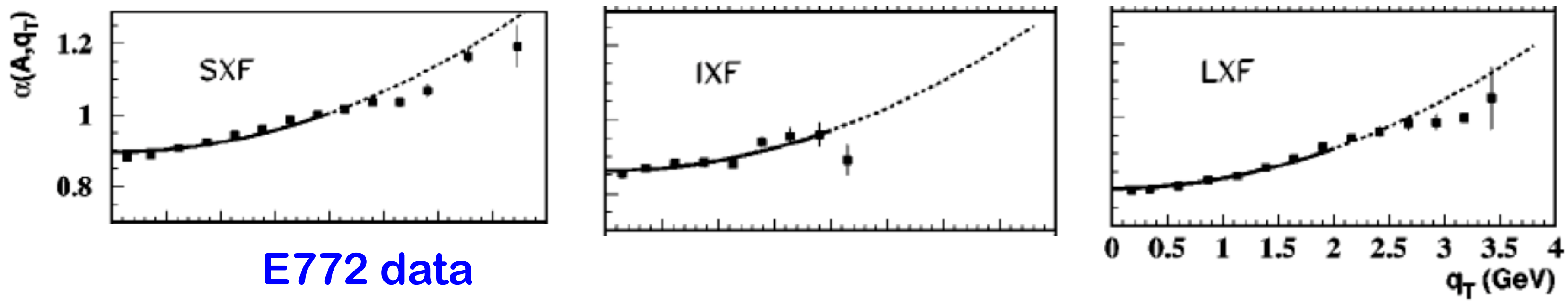
❑ Leading features:

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

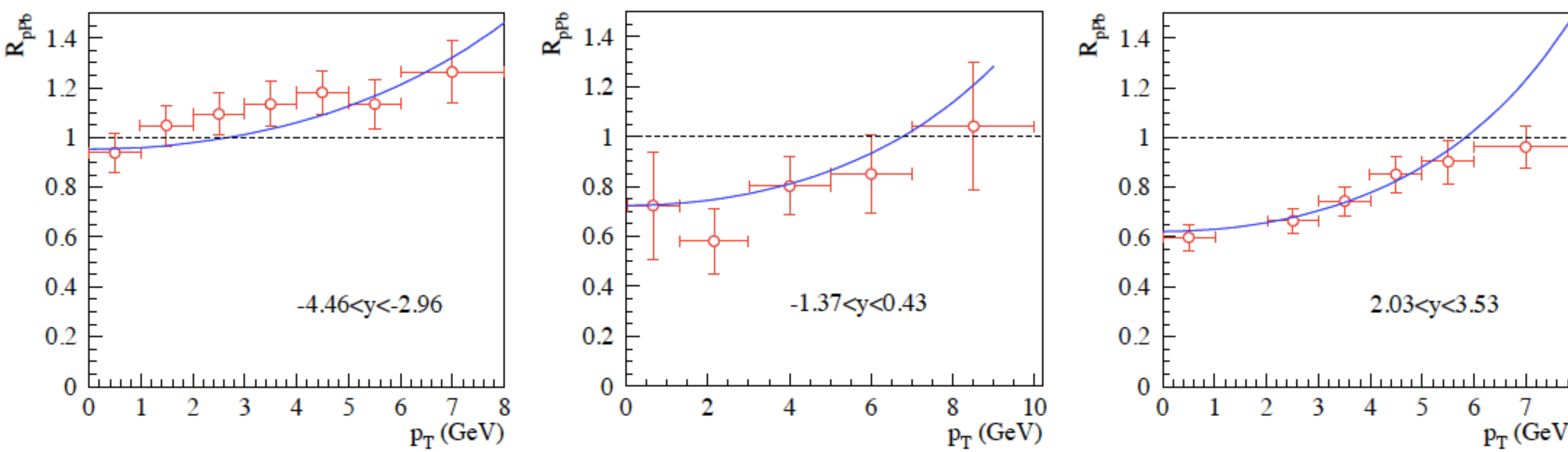
Quarkonium P_T-distribution in p(d)+A

❑ Nuclear modification – low pT region:

$$\frac{d\sigma_{AB}}{dyd^2p_T} \approx \frac{d\sigma_{AB}}{dy}\left[\frac{1}{\pi(\langle p_T^2\rangle_{NN}+\Delta\langle p_T^2\rangle_{AB})}\, e^{-p_T^2/(\langle p_T^2\rangle_{NN}+\Delta\langle p_T^2\rangle_{AB})}\right]$$



E772 data

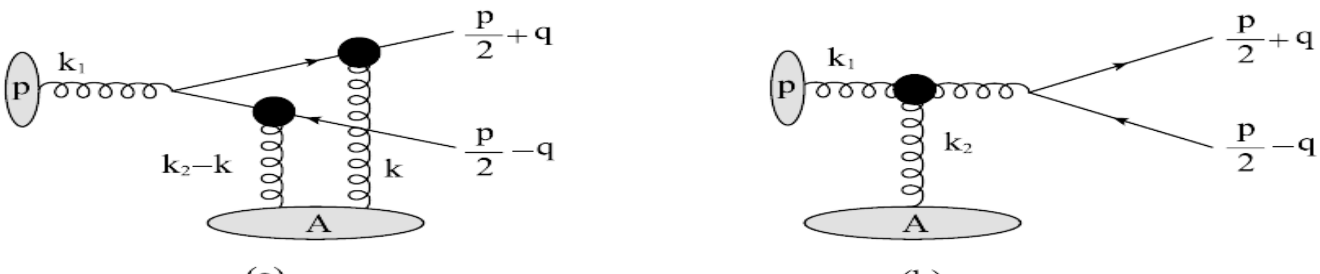


ALICE data

Forward quarkonium production in p(d)+A

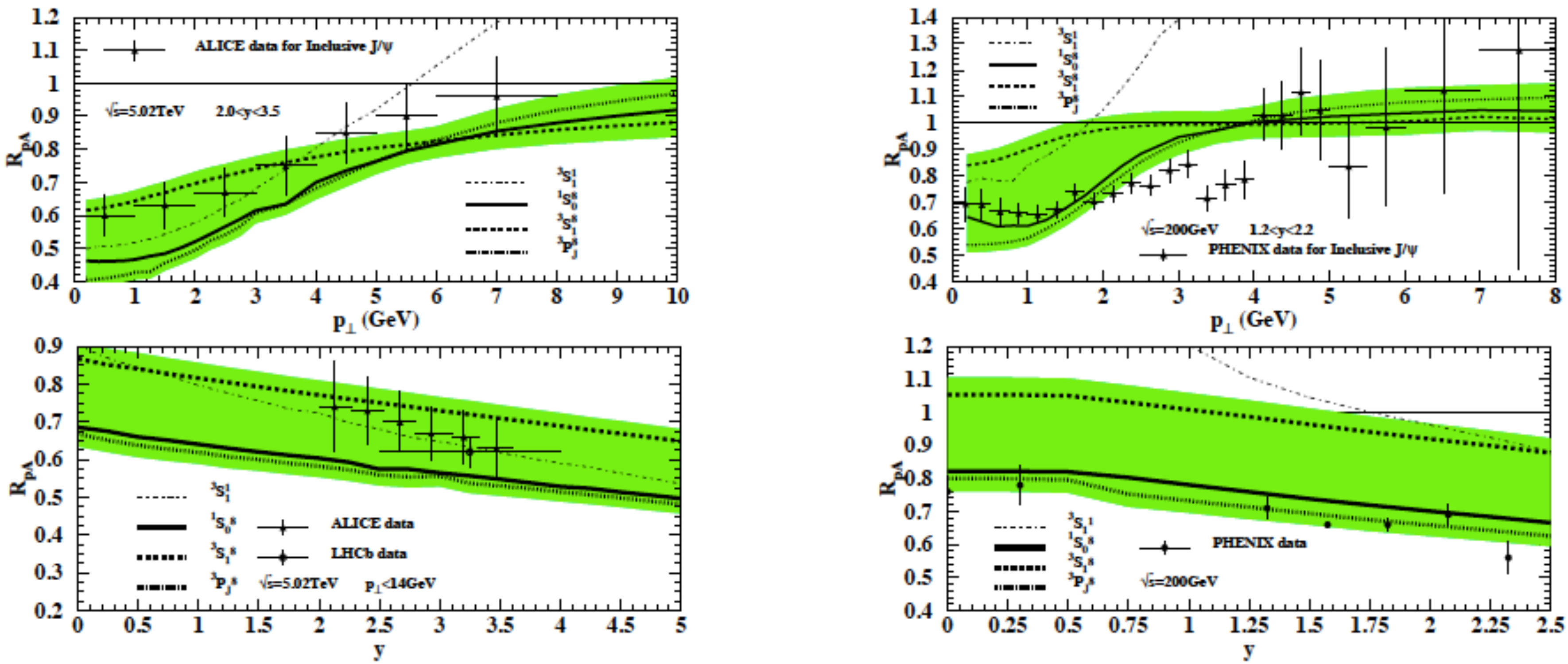
❑ Calculation of multiple scattering:

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



Coherent multiple scattering ➡ **suppression at large y**

Ma et al 1503.07772



Summary

- It has been over 40 years since the discovery of J/Ψ

- When $p_T >> m_Q$ at collider energies, earlier model calculations for the production of heavy quarkonia are not perturbatively stable

  LO in α_s-expansion may not be the LP term in $1/p_T$-expansion

- QCD factorization works for both LP and NLP (α_s for each power)

  - LP dominates: ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ channels
  - NLP dominates: ${}^1S_0^{[8]}$ and ${}^3S_1^{[1]}$ channels
  - From current data: ${}^3P_J^{[8]}$ likely to cancel ${}^3S_1^{[8]}$

    the production dominated by ${}^1S_0^{[8]}$

There are still a lot of unanswered questions related to quarkonium!

- Nuclear medium could be a good "filter" or a fermi-scale detector for studying how a heavy quarkonium is emerged from a pair of heavy quarks

Thank you!

Backup slides