RIKEN/BNL Research Center Workshop

Saturation, the Color Glass Condensate and Glasma: What have we learned from RHIC?

BNL, May 10-12, 2010

Understanding J/ψ Production in pp, dA, AA Collisions

Jianwei Qiu

Brookhaven National Laboratory

Based on work done with Kang, Nayak, Sterman, and etc.

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Understanding J/ψ Production in pp, dA, AA Collisions (in 30 minutes)

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Outline

- Does J/ψ have anything to do with CGC?
- The two intrinsic scales
- Production mechanism?
  - Successes and surprises
- Transverse momentum broadening
- Summary and outlook

Quark mass

- **Quark masses:**

Flavor	Mass
u	$1.5 - 4.5$ MeV
d	$5.0 - 8.5$ MeV
s	$80 - 155$ MeV
c	$1.0 - 1.4$ GeV
b	$4.0 - 4.5$ GeV
t	174.3 ± 5.1 GeV

Light quarks

$\Lambda_{\rm QCD}$

$Q_s(x \sim 1/\sqrt{s})$

Heavy quarks

$\alpha_s\left(m_Q\right) \ll 1$

Quark masses span a wide kinematical range:

$$\frac{m_t}{m_u} \sim 10^4$$

- **Heavy quark is heavy if** $Q_s(x \sim 1/\sqrt{s}) \ll m_Q$
- **Heavy quark is "light" if** $Q_s(x \sim 1/\sqrt{s}) \gtrsim m_Q$

Good probes for a dense medium

- **Basic requirements:**
  - Can be cleanly measured experimentally
  - Can be reliably calculated theoretically
- **Necessary conditions:**
  - Sensitive to the scales and properties of the strongly interacting matter – low momentum scale (a few hundred MeV)
  - Large momentum transfer to ensure pQCD calculation

    → a hard probe sensitive to low momentum physics
- **Potentially good probes:**
  - Have two observed scales (one hard and one soft)
  - Have one observed hard scale and a steeply falling distribution

Heavy quarkonium has two intrinsic scales

❑ Heavy quark mass:

Heavy quark pairs are produced at a distance scale much less than fm

$$\Delta r \sim \frac{1}{2m_Q} \leq 0.1 \text{ fm} \quad \text{(for a charm-quark pair)}$$

$$\leq 0.025 \text{ fm} \quad \text{(for a b-quark pair)}$$

PQCD is "expected" to work for the production of heavy quarks

❑ Quarkonium's nonperturbative binding:

$$\frac{\left|M^2 - 4m_Q^2\right|}{4m_Q^2} \ll 1$$

for both charm and bottom quarkonia

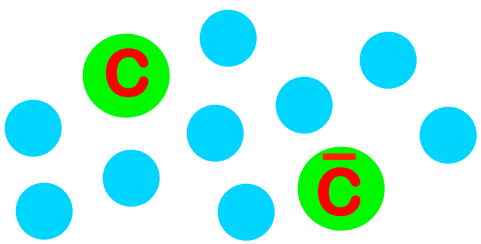
The transition from a heavy quark pair to a quarkonium is Not perturbatively calculable

J/ψ Suppression in QGP

- **Heavy quarkonium provides a non-relativistic system**
  – controlled approximation: potential model, EFT, …

Charm: $\frac{v^2}{c^2} \sim \frac{k_Q^2}{m_Q^2} \sim \frac{\left|M^2 - 4m_c^2\right|}{4m_c^2} \sim 0.3$ **Bottom:** $\frac{v^2}{c^2} \sim 0.1$

- **Color screening in QGP suppresses the formation of J/ψ**



Potential: $V_{Q\bar{Q}}(r) \Rightarrow V_{Q\bar{Q}}(r,T)$

Wave function: $\Phi_{Q\bar{Q}}(r) \Rightarrow \Phi_{Q\bar{Q}}(r,T)$

J/ψ formation rate $\propto \left|\Phi_{Q\bar{Q}}(r,T)\right|^2$

J/ψ suppression ⇔ medium properties

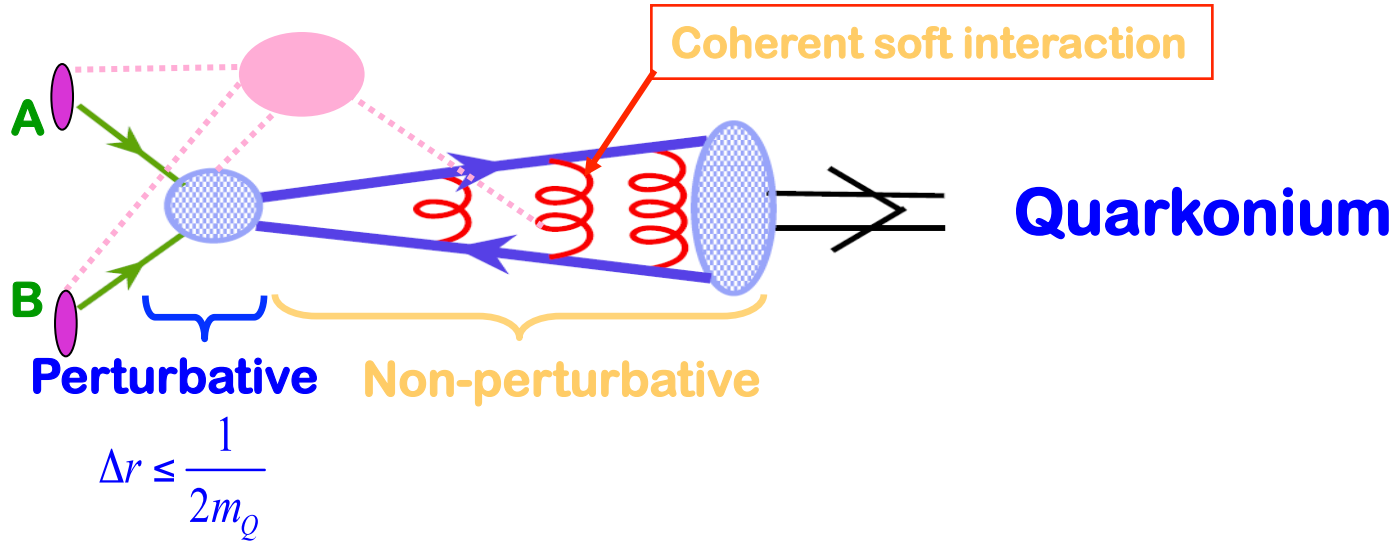
Matsui & Satz (1986)

- **Calibration:**

Do we understand the production mechanism of J/ψ well enough to calibrate the production rate and extract the information on QGP?

The basic production mechanism

- Production of an off-shell heavy quark pair:



- Approximation: on-shell heavy quark pair + hadronization

$$\sigma_{AB\to J/\psi} = \sum_{\text{states}} \int d\Gamma_{Q\bar{Q}} \left[\frac{d\hat{\sigma}(Q^2)}{d\Gamma_{Q\bar{Q}}}\right] F_{\text{states}(Q\bar{Q})\to J/\psi}(p_Q, p_{\bar{Q}}, P_{J/\psi})$$

Different models ⇔ Different assumptions/treatments on how the heavy quark pair becomes a quarkonium?

Color Singlet Model

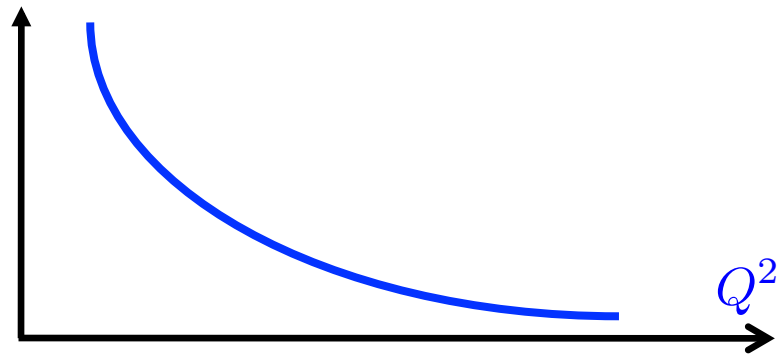
❑ Assumption:

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

❖ Only pairs with right quantum number can become quarkonia

$$\sigma_{AB\to J/\psi} = \sum_{\text{states}} \int d\Gamma_{Q\bar{Q}} \left[\frac{d\hat{\sigma}(Q^2)}{d\Gamma_{Q\bar{Q}}}\right] F_{\text{states}(Q\bar{Q})\to J/\psi}(p_Q, p_{\bar{Q}}, P_{J/\psi})$$

❖ Steep falling: $F(Q^2)$



→ $\hat{\sigma}(Q^2 \approx 4m_c^2)$

→ $\int dQ^2 F(Q^2) \propto |\psi(0)|^2$ – fixed by decay

→ $\sigma_{AB\to J/\psi} \propto \hat{\sigma}(Q^2 \approx 4m_c^2)\ |\psi(0)|^2$

No free parameter!

Color Evaporation Model

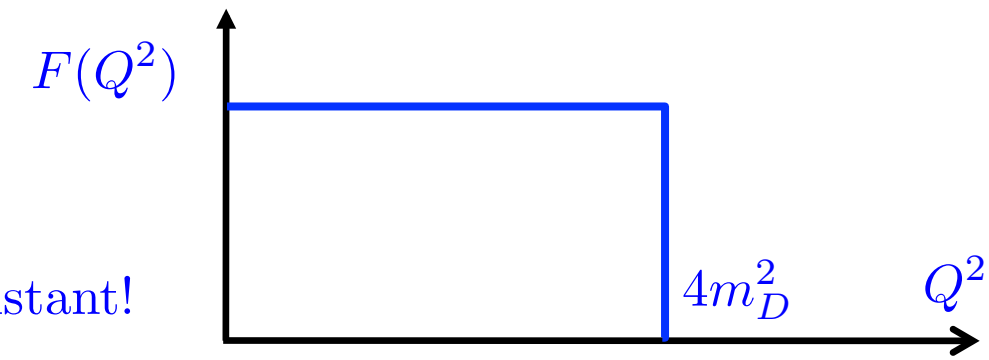
Fritsch (1977), Halzen (1977), ...

❑ Approximation:

❖ All colored or color singlet pairs with invariant mass less then open charm threshold could become bound quarkonia

$$\sigma_{AB\to J/\psi} = \sum_{\text{states}} \int d\Gamma_{Q\bar{Q}} \left[\frac{d\hat{\sigma}(Q^2)}{d\Gamma_{Q\bar{Q}}}\right] F_{\text{states}(Q\bar{Q})\to J/\psi}(p_Q, p_{\bar{Q}}, P_{J/\psi})$$

❖ Threshold:



➡ $F(Q^2)$ – Constant!

➡ $$\sigma_{AB\to J/\psi} \approx f_{J/\psi} \int_{4m_c^2}^{4m_D^2} dQ^2 \left[\frac{d\sigma(Q^2)}{dQ^2}\right]$$

One constant per quarkonium state

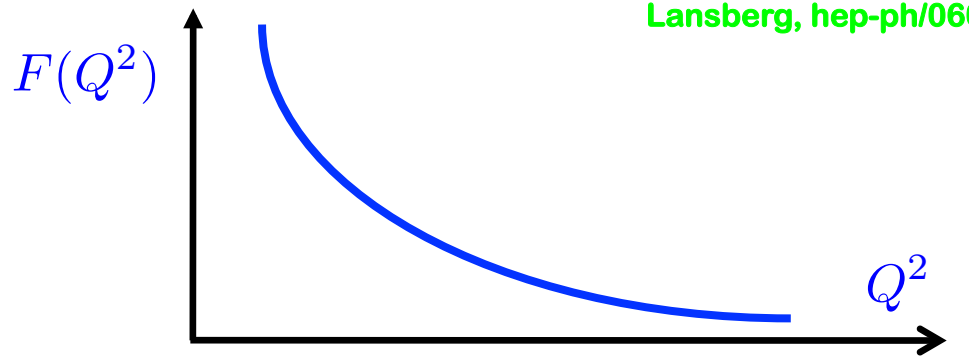
NRQCD Model

Bodwin, Braaten, Lepage, PRD, 1995
Brambilla, et al. hep-ph/0412158
Lansberg, hep-ph/0602091, …

❑ Approximation:

- ❖ Steeply falling:
- ❖ v-expansion:

$$v_{c\bar{c}}^2 \approx \frac{Q^2 - 4m_c^2}{4m_c^2}$$



$$\sigma_{AB\to J/\psi} = \sum_{\text{states}} \int d\Gamma_{Q\bar{Q}} \left[\frac{d\hat{\sigma}(Q^2)}{d\Gamma_{Q\bar{Q}}}\right] F_{\text{states}(Q\bar{Q})\to J/\psi}(p_Q, p_{\bar{Q}}, P_{J/\psi})$$

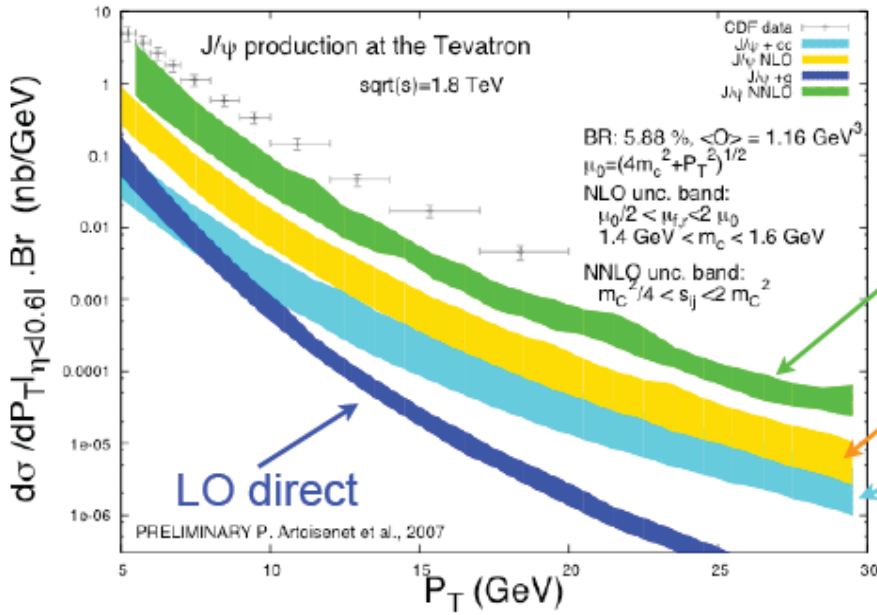
$$\longrightarrow \quad \sigma_{AB\to \mathrm{J}/\psi}(M_{\mathrm{J}/\psi}) = \sum_n \sigma_{[\mathcal{O}_n]}(4m_c^2 = M_{\mathrm{J}/\psi})\ \langle \mathcal{O}_n(0)\rangle$$

$$\langle \mathcal{O}(0)\rangle \propto \int dQ^2\ v_{c\bar{c}}^2\ F(Q^2) \quad \longleftarrow \quad \text{universal}$$

Infinite number of parameters!

Predictive power $\longleftrightarrow$ truncation in v-expansion

CSM: Huge high order corrections



Color-singlet contribution for J/ψ and Upsilon production at Tevatron

NNLO

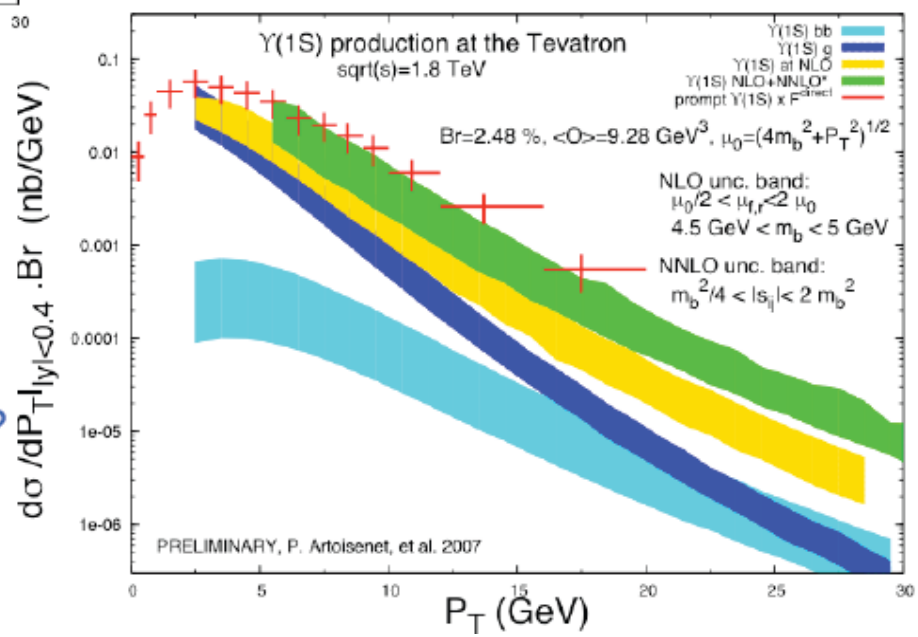
NLO

LO associate

P. Artoisenet, F. Maltoni, et.al. 2007

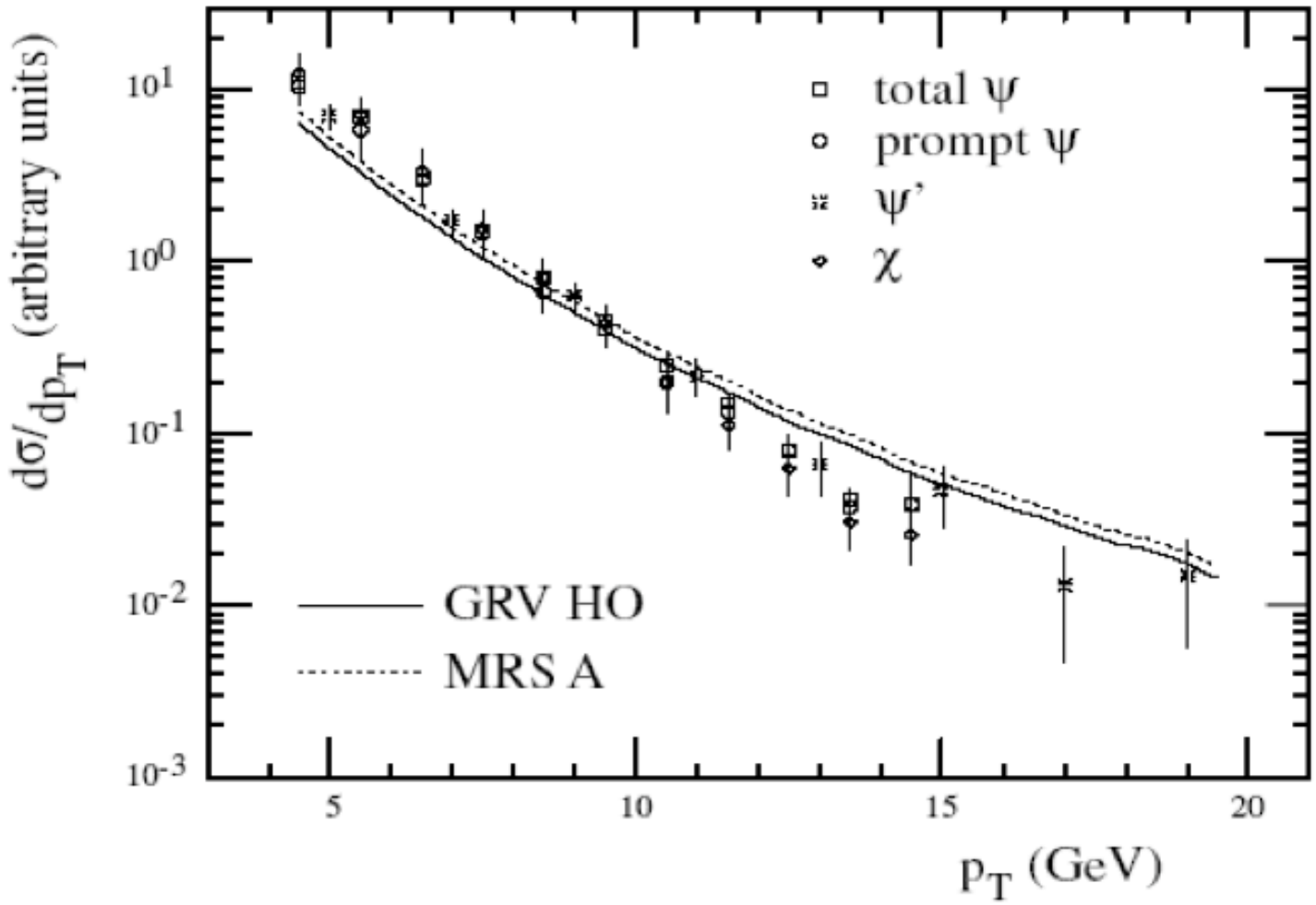
Large uncertainty band
⇒strong scale dependence

Large NLO, NNLO contribution
⇒ how perturbative series converge?



CEM: OK for inclusive production

- Good for total cross section, ok for P_T distribution:

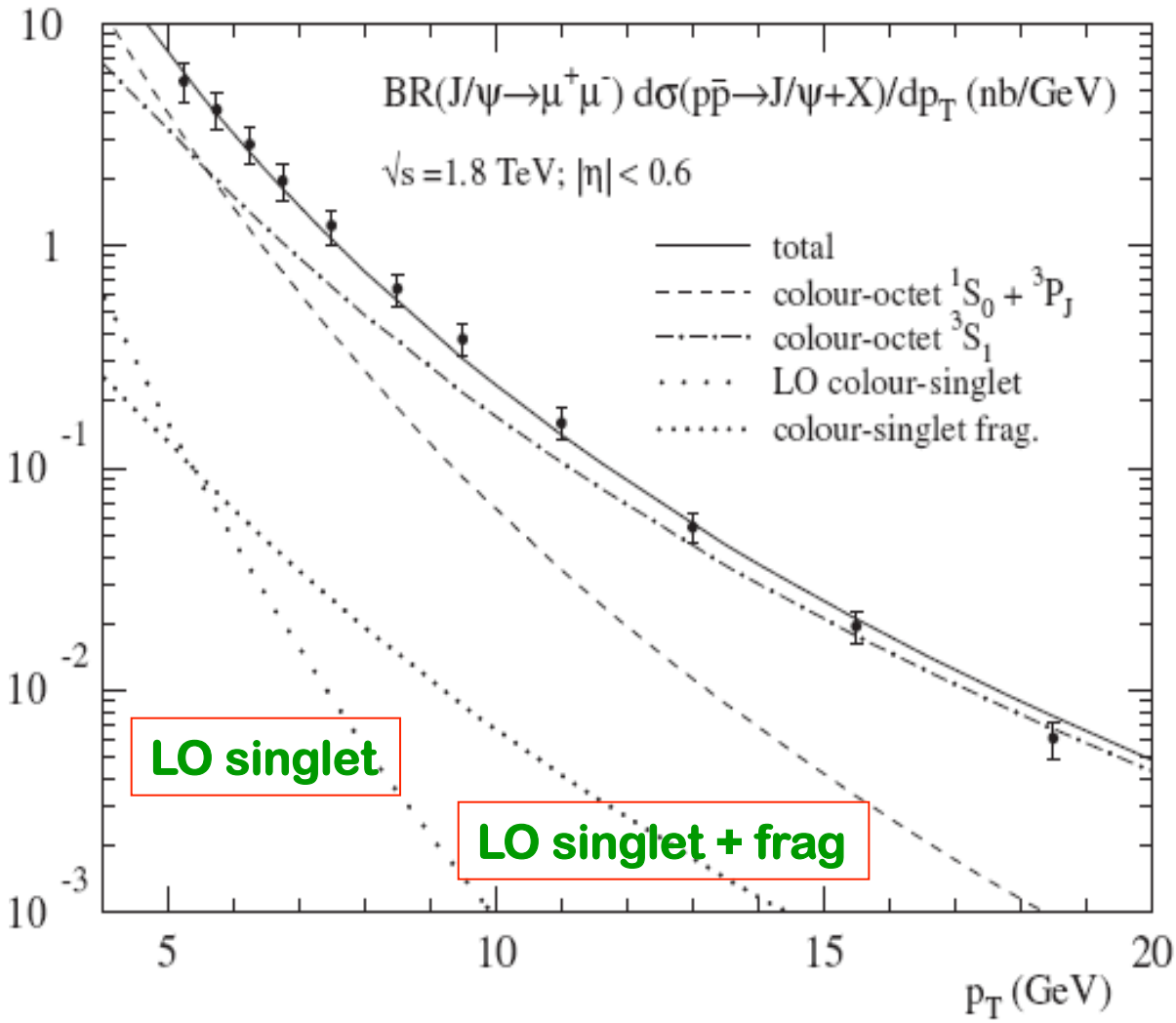


Amundson et al, PLB 1997

NRQCD Model: Best fit to Tevatron data

M. Kramer, 2001

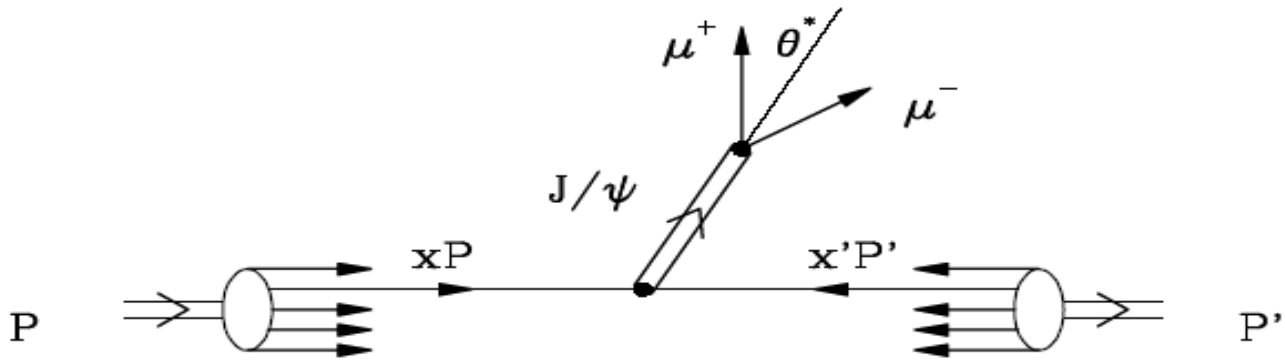
- Unpolarized J/ψ at the Tevatron:



NRQCD model gave the best description of P_T distribution of various inclusive heavy quarkonium production at Tevatron, with matrix elements fixed by data

Polarization of quarkonium at Tevatron

- Measure angular distribution of $\mu^+\mu^-$ in J/ψ decay



- Normalized distribution:

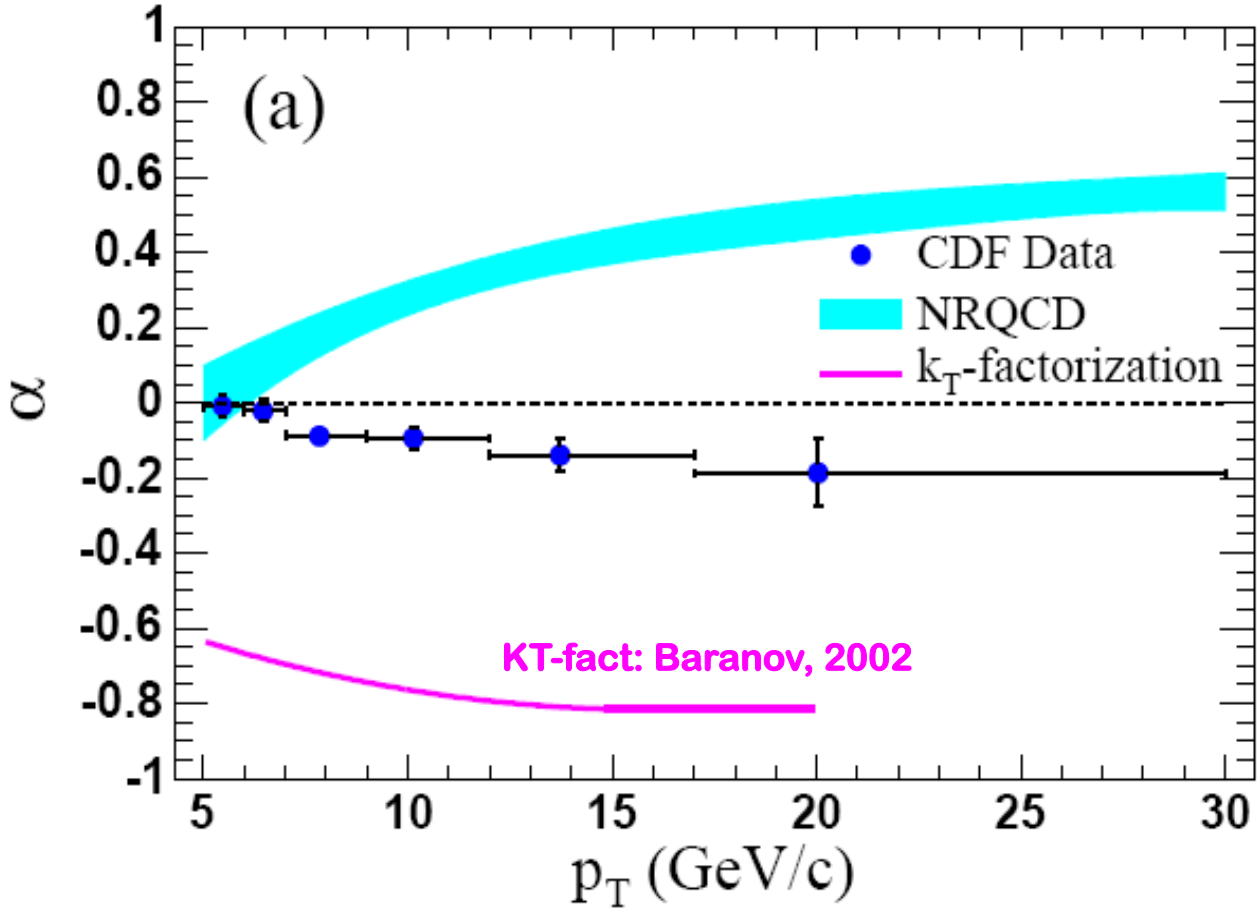
$$I(\cos\theta^*) = \frac{3}{2(\alpha+3)}\,(1+\alpha\cos\theta^*)$$

$$\alpha = \begin{cases} +1 & \text{fully transverse} \\ 0 & \text{unpolarized} \\ -1 & \text{fully longitudinal} \end{cases}$$

Surprises from polarization measurements

❑ Transverse polarization at high p_T?

NRQCD: Cho & Wise, Beneke & Rothstein, 1995, …

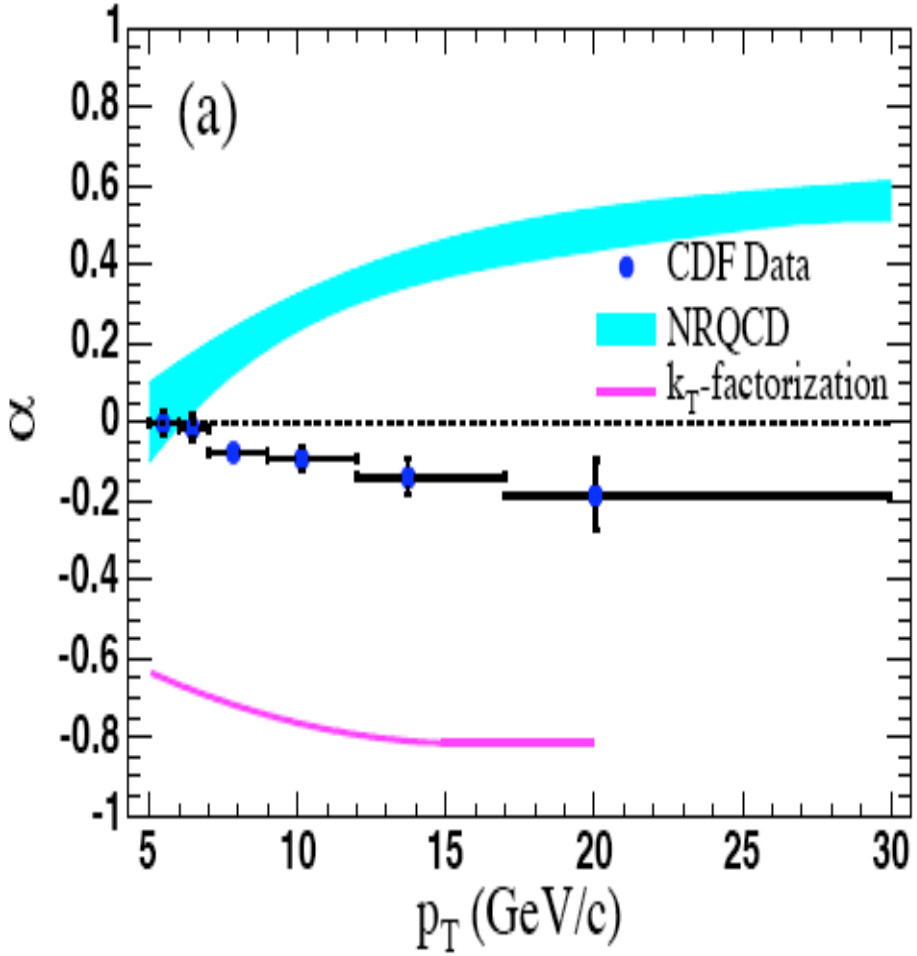


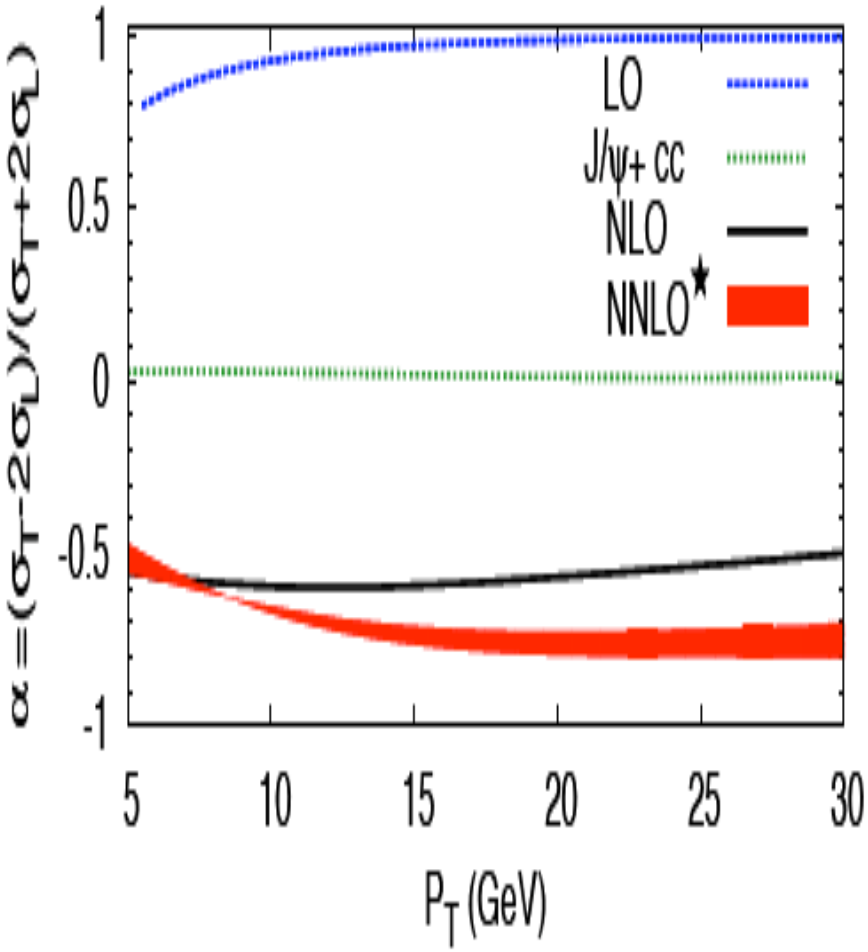
$$\alpha = \frac{\sigma_T - \sigma_L}{\sigma_T + \sigma_L}$$

CDF Collaboration, PRL 2007

NRQCD vs Color Singlet Model

- J/psi polarization:



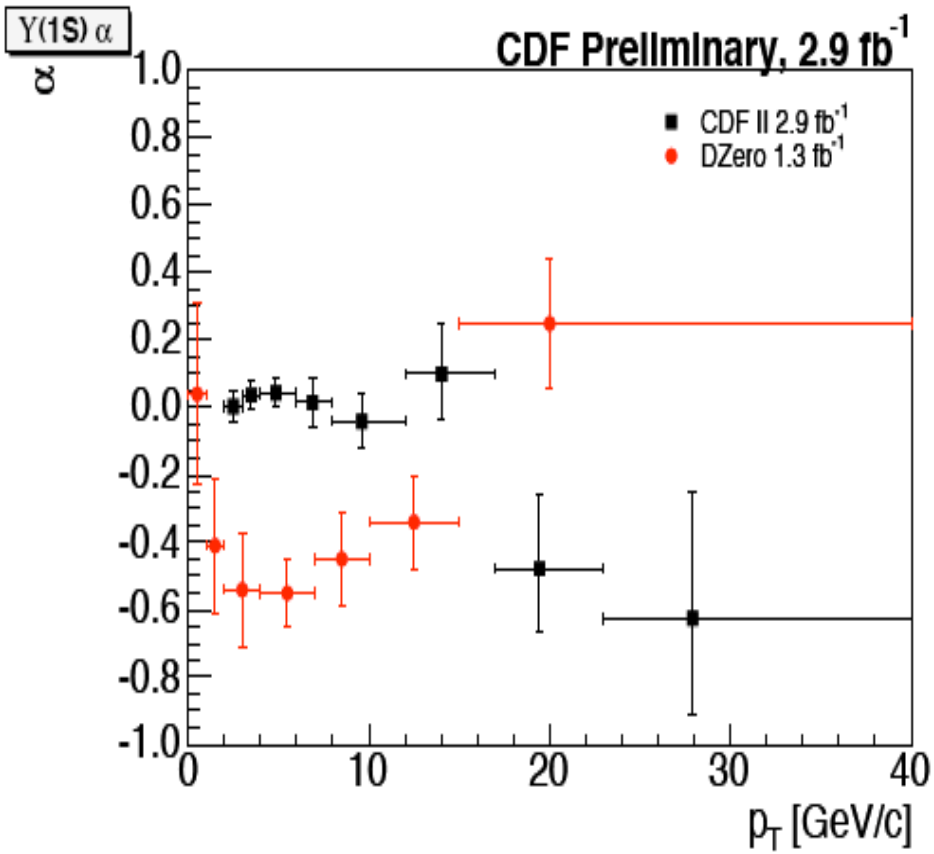


Lansberg, 2009

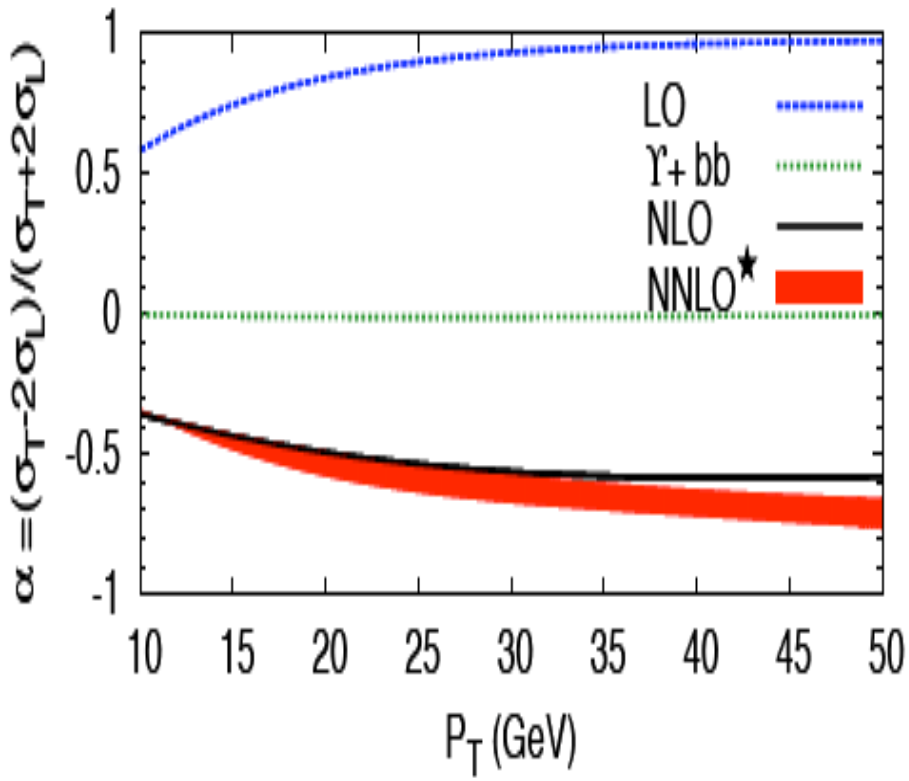
Role of higher order contribution?

Upsilon polarization

- Inconsistency between D0 and CDF:



Singlet model



- Octet contribution?

P. Artoisenet, et al. 2008

Heavy quarkonium associated production

- **Inclusive J/ψ + charm production:**

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

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

NRQCD-LO: ~ 0.07 pb

Kiselev, et al 1994,
Cho, Leibovich, 1996
Yuan, Qiao, Chao, 1997
…
Zhang, Chao, 2007 (NLO)

- **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 ?

Questions

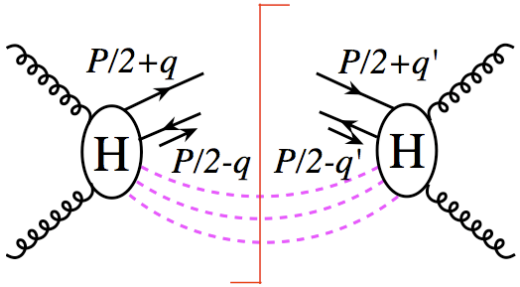
- Why the high order correction in CSM is so large? How many orders should we calculate?

- Why the CSM predicts the longitudinally polarized J/psi?

- Why NRQCD model predicts wrong polarization and "wrong rate" for association production?

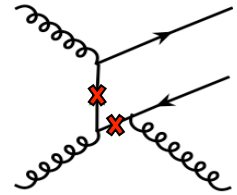
Why high orders in CSM are so large?

❑ NR projection operator for s=1 state:



$$\mathcal{P}(P, q \to 0, s=1) = \frac{1}{\sqrt{2m_Q}} \gamma_\mu \epsilon^\mu_\lambda(P) \left[\gamma \cdot \frac{P}{2} + m_Q \right]$$

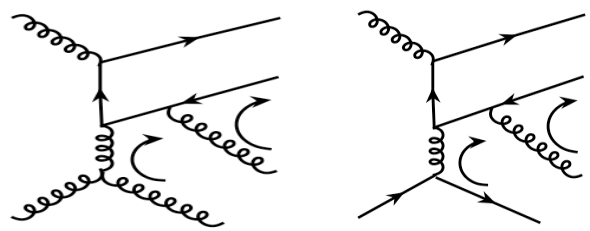
Leading order in α_s $\Longrightarrow$



$$\sim \mathcal{O}\left(\frac{1}{P_T^8}\right)$$

Next-to-leading order: Artoisenet et al. 2007

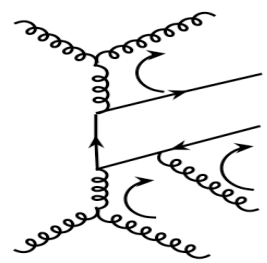
Claim – leading diagrams:



> 10 times LO

Next-to-next-to leading order: Artoisenet et al. 2008

Claim – leading contribution:



> 10 times NLO

$(1/P_T)^n$ vs $(\alpha_s)^n$ expansion

Kang, Qiu and Sterman, 2010

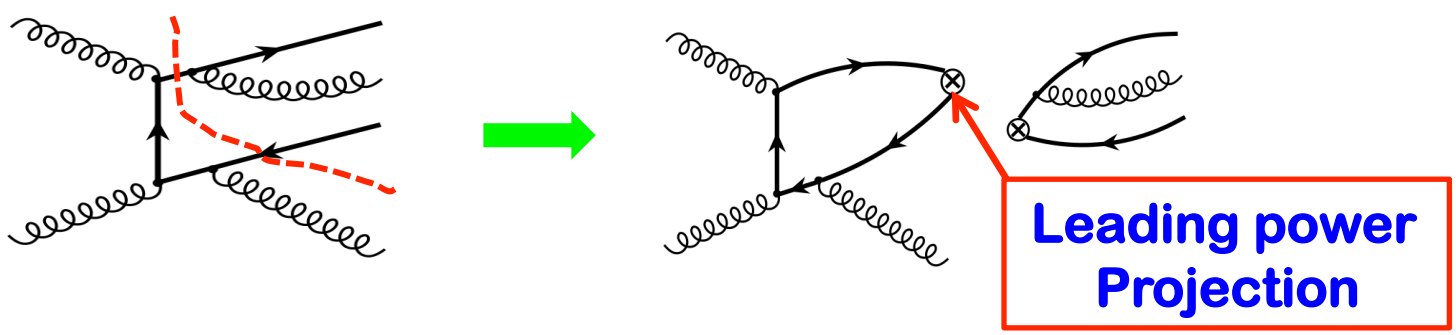
- The s=1 NR projection operator:

$$\mathcal{P}(P, q \to 0, s=1) = \frac{1}{\sqrt{2m_Q}} \gamma_\mu \epsilon^\mu_\lambda(P) \left[\gamma \cdot \frac{P}{2} + m_Q \right]$$

Picks up contributions that vanish as $m_Q \longrightarrow 0$

- $(\alpha_s)^n$ expansion does not pick up leading power in $(1/P_T)^n$

LO is $(1/P_T)^8$ ⟷ NLO gives $(1/P_T)^6$



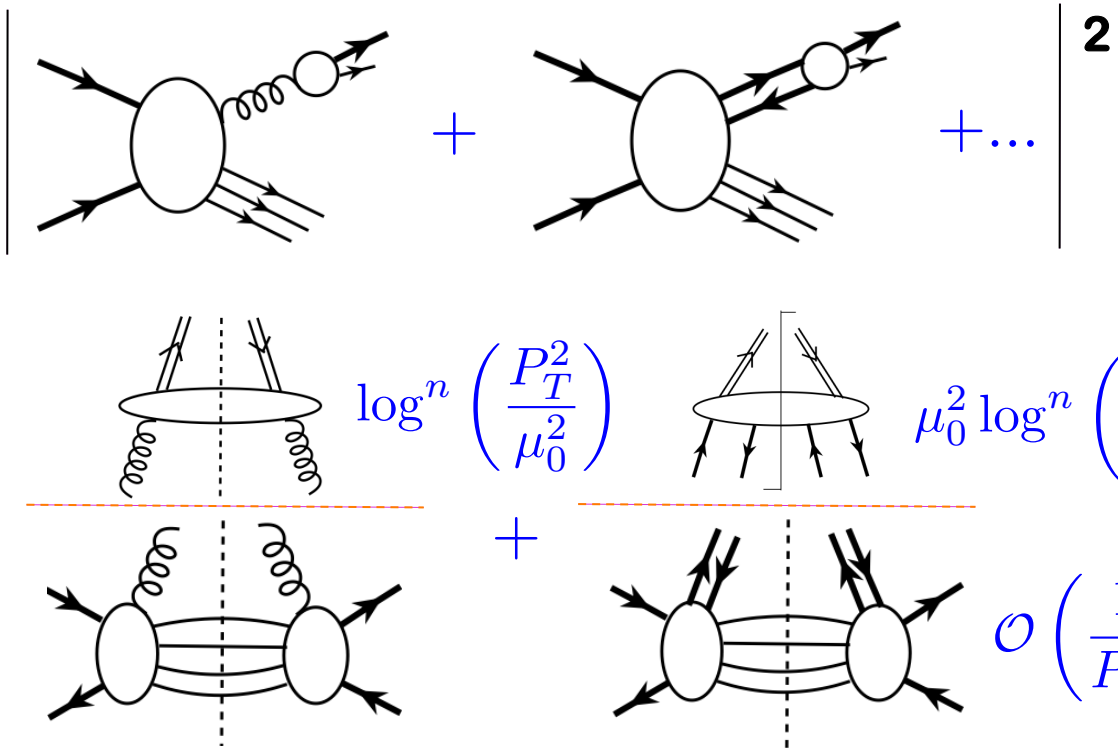
➡ $(1/P_T)^n$ – power expansion before $(\alpha_s)^n$ – expansion

PQCD factorization formalism

❑ Expansion in m_Q/P_T:

Kang, Qiu and Sterman, 2010

$$E\frac{d\sigma_{J/\psi}}{d^3P}:$$

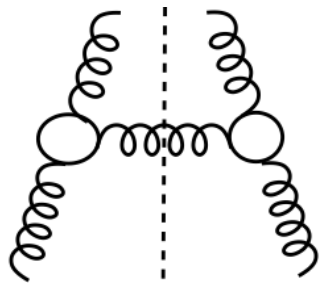


- ❖ **Leading power in 1/P:** ⟷ **much smaller FFs**
  - **– color, symmetry, high orders**
- ❖ **Subleading power in $1/P_T$:** ⟷ **much larger FFs**

PQCD evolution

❑ Single parton:

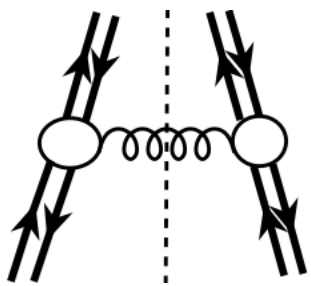
Kang, Qiu and Sterman, 2010



Same as normal DGLAP
Difference from input distribution

$$D_{g\to J/\psi}(z,\mu_0,m_Q)$$

❑ Heavy quark pair:



Differ from DGLAP – still logarithmic
Spin-color sensitive
Infrared safe evolution
Nonperturbative input distribution

$$\mu^2\frac{\partial}{\partial\mu^2}D_{[Q\bar{Q}(a8)]\to HX}(z,m_Q,\mu) = \int_z^1\frac{dz'}{z'}D_{[Q\bar{Q}(a8)]\to HX}(z',m_Q,\mu)\,\mathcal{K}^{(1)}_{a8\to a8}(z/z',\alpha_s)$$

$$\mathcal{K}^{(1)}_{a8\to a8}(z,\alpha_s) = \frac{\alpha_s}{2\pi}(2C_A)\left(\left[\frac{2z}{1-z}\right]_+ + \frac{1}{4}\delta(1-z)\right)$$

Evolution dominated by octet channels

NRQCD to input distributions

❑ Single parton:

Nayak, Qiu and Sterman, 2005

$$D_{g\to J/\psi}(z,\mu_0,m_Q) \to \sum_{[Q\bar{Q}(c)]} \hat{d}_{g\to[Q\bar{Q}(c)]}(z,\mu_0,m_Q)\langle\mathcal{O}_{[Q\bar{Q}(c)]}(0)\rangle|_{\rm NRQCD}$$

Dominated by transverse polarization

❑ Heavy quark pair:

Kang, Qiu and Sterman, 2010

$$D_{[Q\bar{Q}(\kappa)\to J/\psi}(z,\mu_0,m_Q) \to \sum_{[Q\bar{Q}(c)]} \hat{d}_{[Q\bar{Q}(\kappa)\to[Q\bar{Q}(c)]}(z,\mu_0,m_Q)\langle\mathcal{O}_{[Q\bar{Q}(c)]}(0)\rangle|_{\rm NRQCD}$$

Dominated by longitudinal polarization

This NRQCD factorization has not been proved!

So far, it works to 2-loop level for single parton case

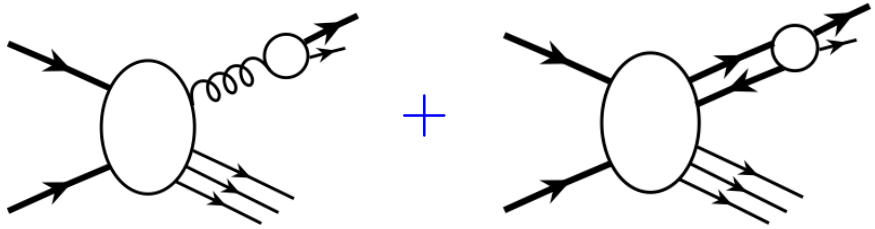
Nayak, Qiu and Sterman, 2005

J/ψ polarization

- **Competition between LP and NLP:**

Kang, Qiu and Sterman, 2010

$$E\frac{d\sigma_{J/\psi}}{d^3P} :$$

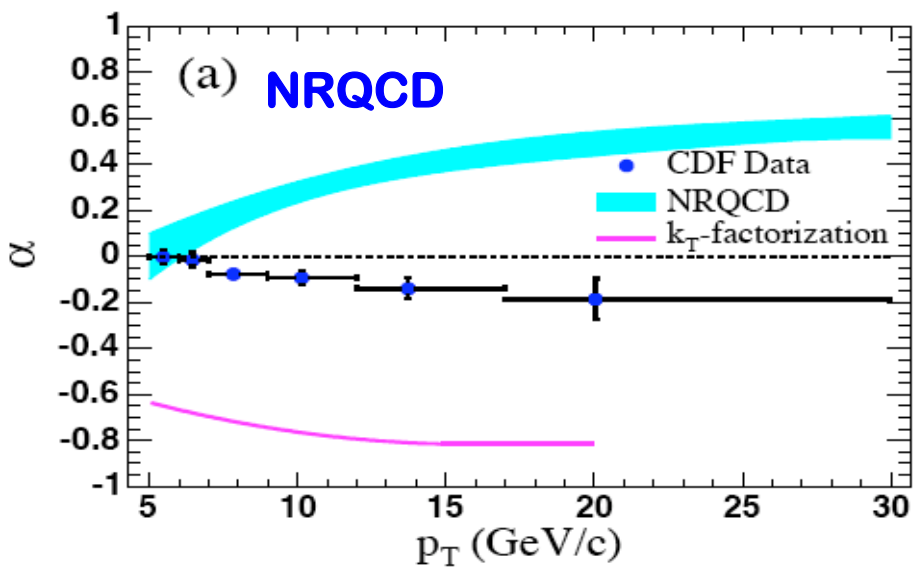


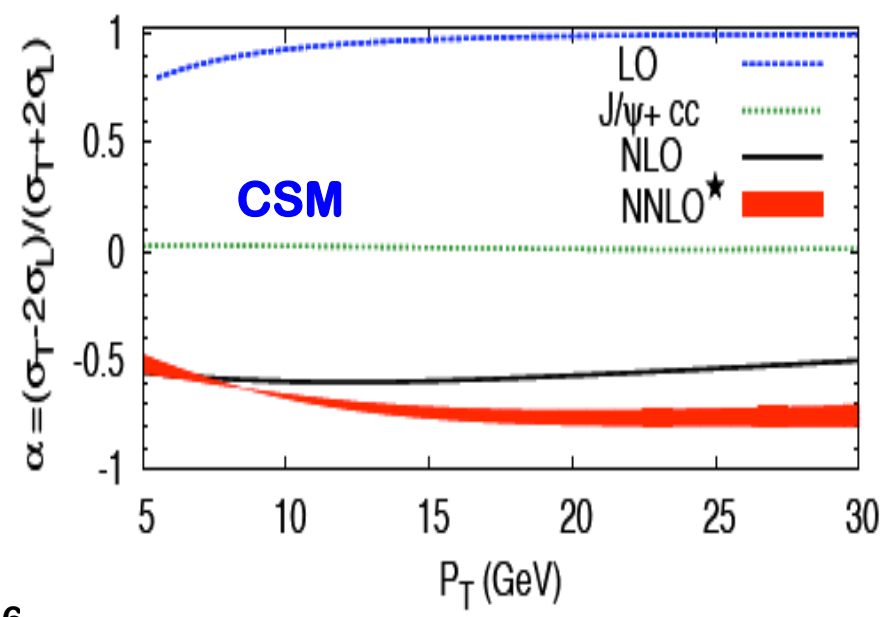
$+$ $+\ldots$

Transverse polarization

Longitudinal polarization

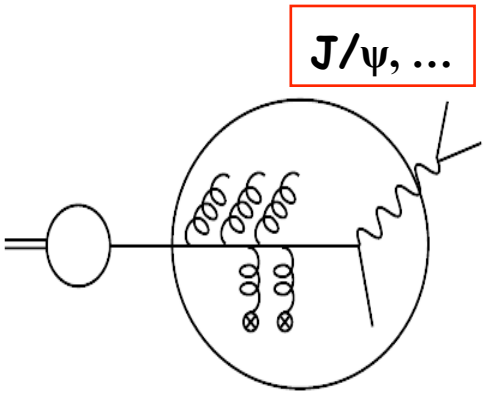
Both dominated By octet channels!



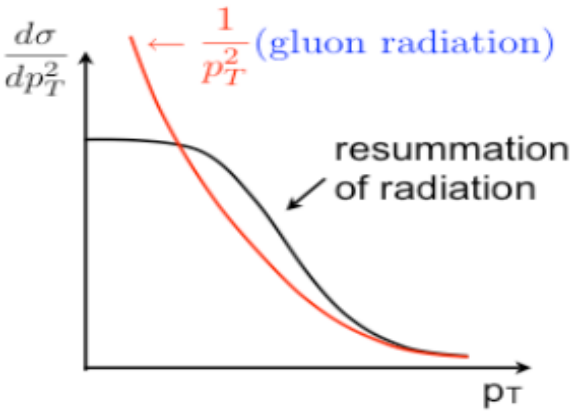


Transverse momentum distribution

- **Multiple scattering in medium:**
  - Each scattering is too soft to calculate perturbatively
  - Resummation + multiple scattering (not yet achieved)



- **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

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

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

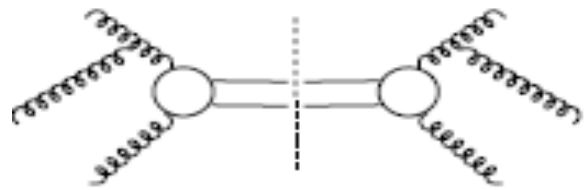
Broadening of heavy quarkonia

Kang, Qiu, PRD77(2008)

❑ Initial-state only:

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

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



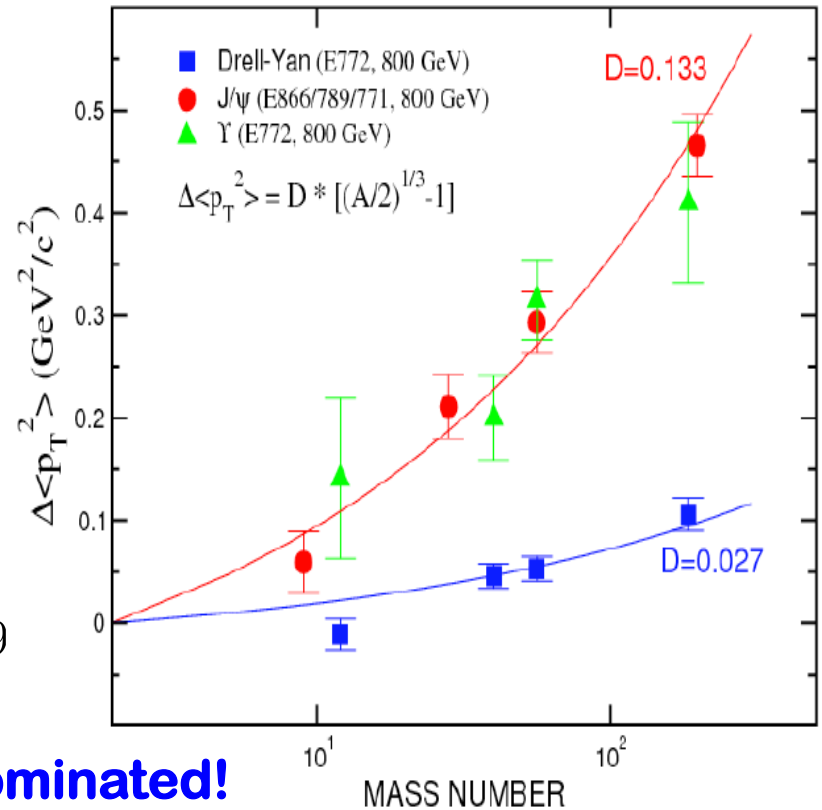
❑ Experimental data from d+A:

Clear $A^{1/3}$ dependence

But, wrong normalization!

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

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



Final-state effect – octet channel dominated!

Only depend on observed quarkonia

J.C.Peng, hep-ph/9912371

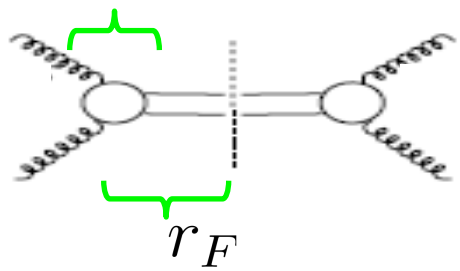
Johnson,et al, 2007

Final-state multiple scattering

Kang, Qiu, PRD77(2008)

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

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



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

  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

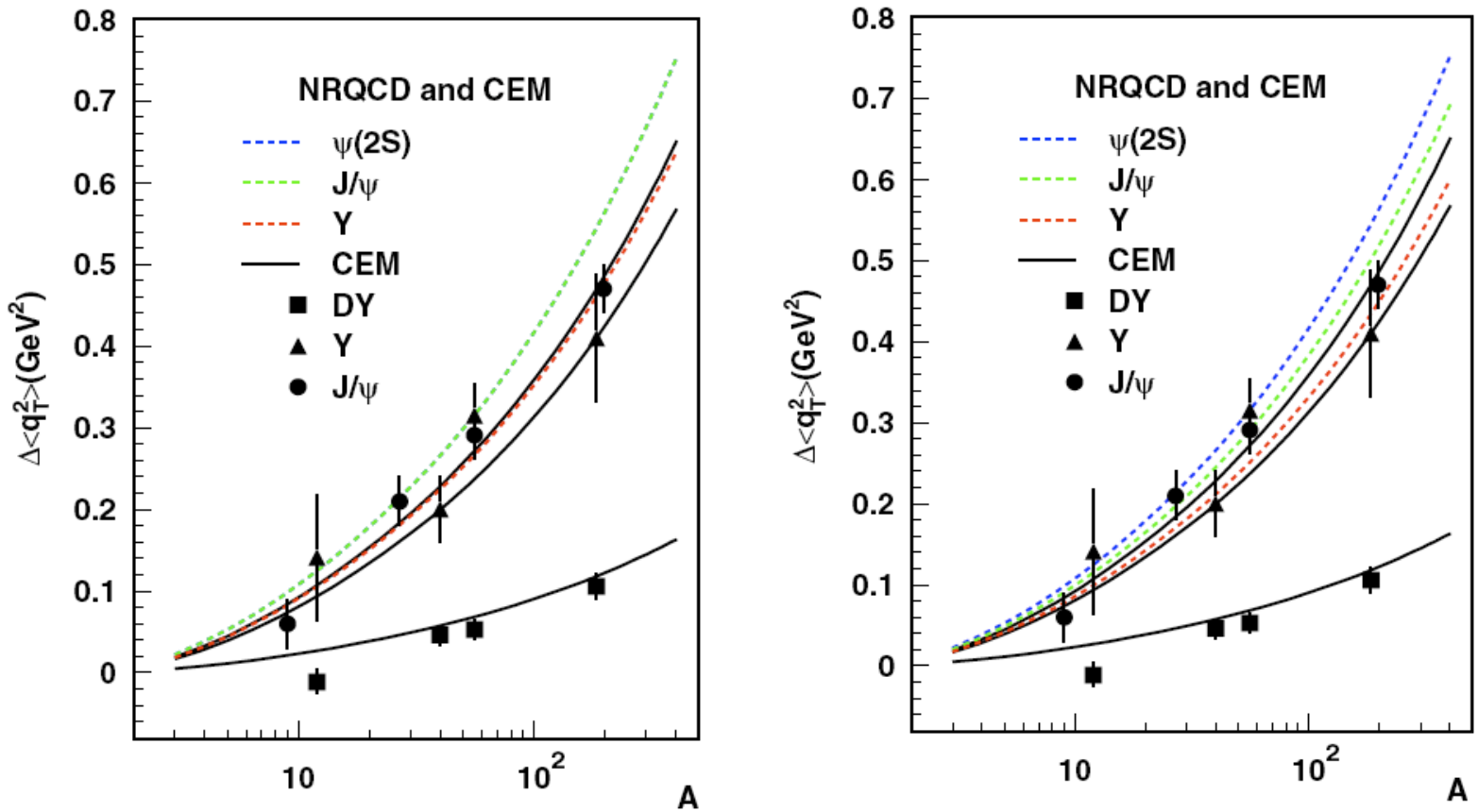
  NRQCD model, color evaporation model, …

Broadening of heavy quarkonia in d+A

Kang, Qiu, PRD77(2008)

- **Final-state effect is important:**

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



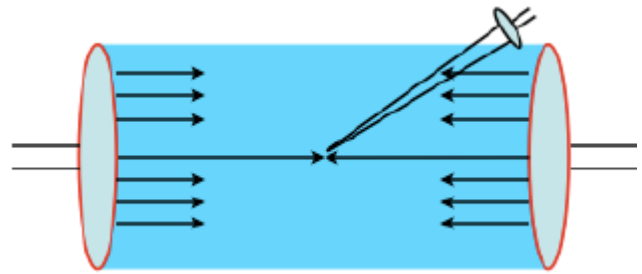
- **Mass – independence, not very sensitive to the feeddown**

Broadening of quarkonia in A+A

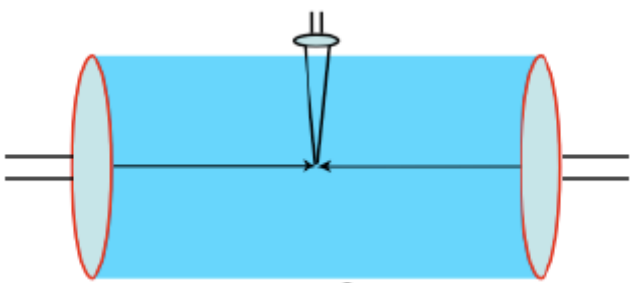
- **If no hot medium was formed:**

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

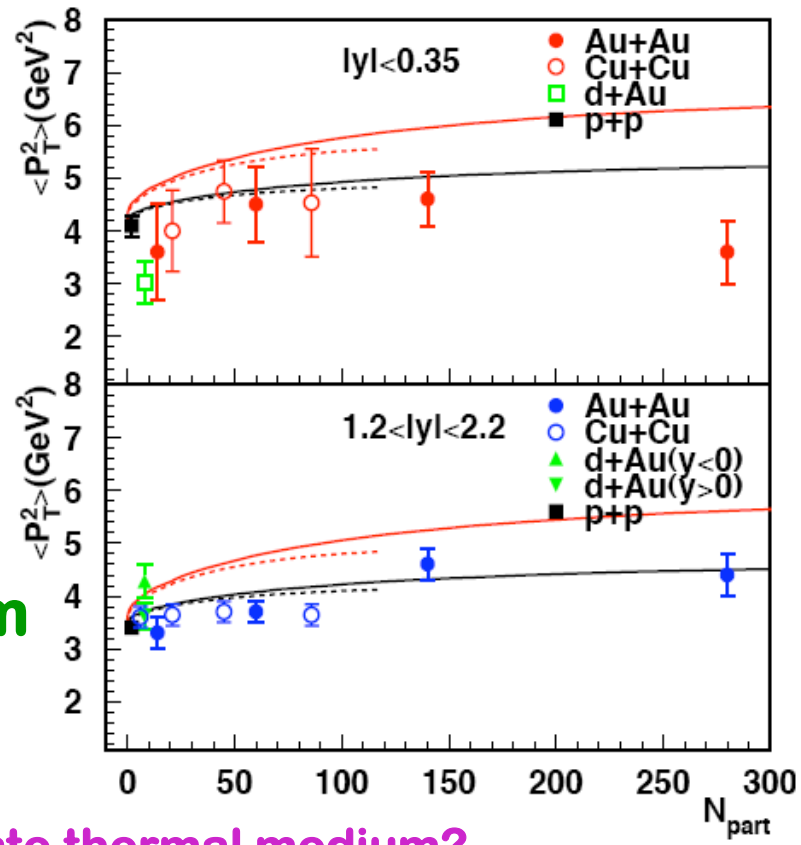
Superposition of pA



- **If hot medium is formed:**



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



Some kind of slow moving medium was produced at RHIC!

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

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

Summary and outlook

- None of the existing factorized production models, including NRQCD model, were proved theoretically
- New pQCD factorization formula: LP + NLP
- Both LP and NLP hard production dominated by octet channels
- Polarization is a result of competition between LP and NLP
- Heavy quarkonium has two intrinsic scales, and could be a good probe to study the formation of bound states in QCD
- Harder to form J/ψ if $m_c \sim Q_s$ ⟶ suppression of J/ψ Tuchin's talk
- Experimental measurements, in particular, the upsilon polarization at LHC, are needed to test the production mechanism!

Thank you!

Backup slices

Color evaporation model (CEM)

- **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:**

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

- **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 $r_F > R_A$

NRQCD model

❑ Cross section:

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

❑ 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:

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

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

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

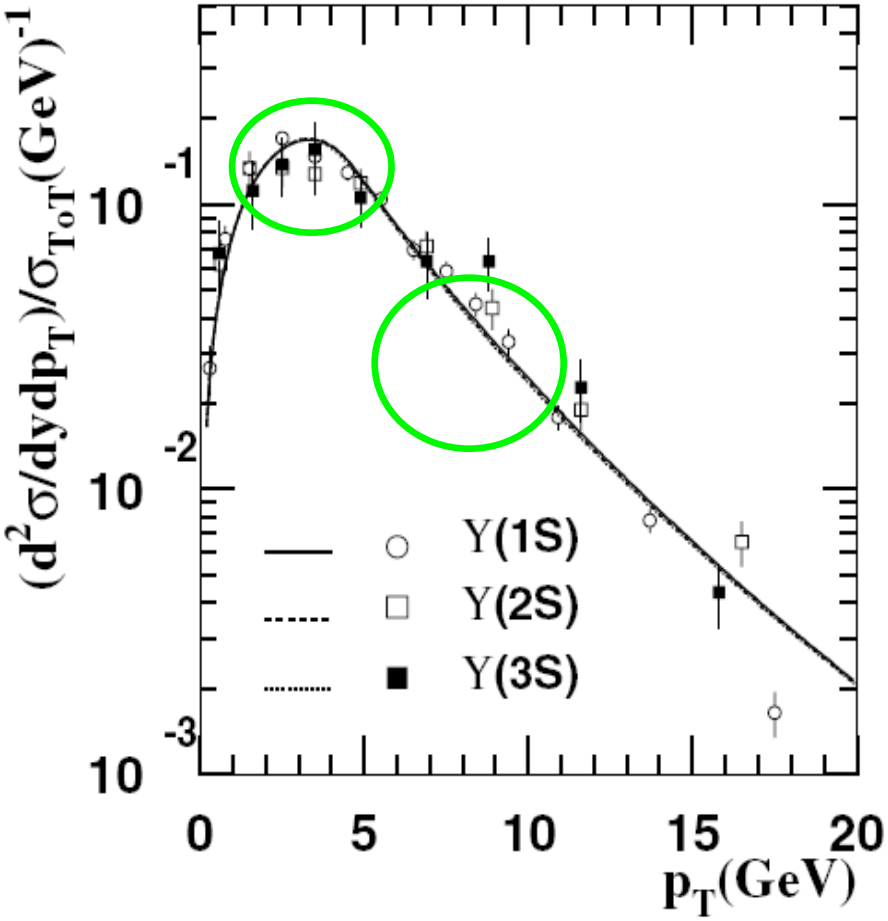
Only color octet channel contributes

❑ Leading features:

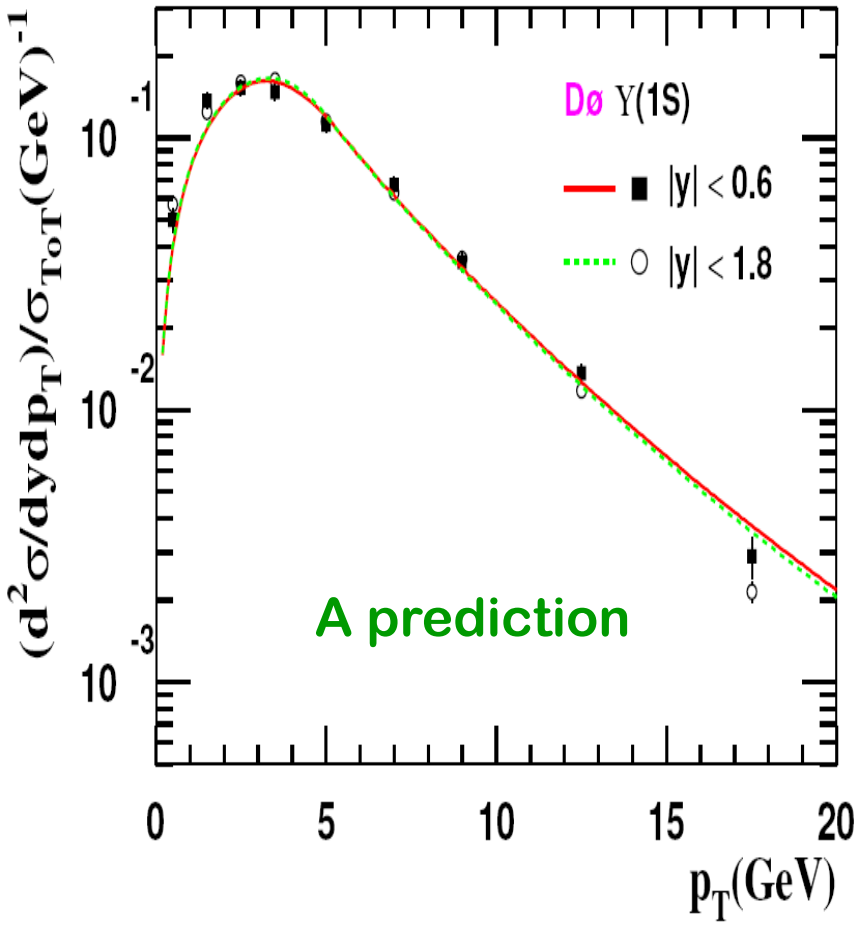
$$\Delta\langle q_T^2\rangle_{\rm HQ}^{\rm NRQCD} \approx \Delta\langle q_T^2\rangle_{\rm HQ}^{\rm CEM} \approx (2C_A/C_F)\Delta\langle q_T^2\rangle_{\rm DY}$$

CEM: Resummation of pQCD logs

CDF Run-I



D0 Run-II

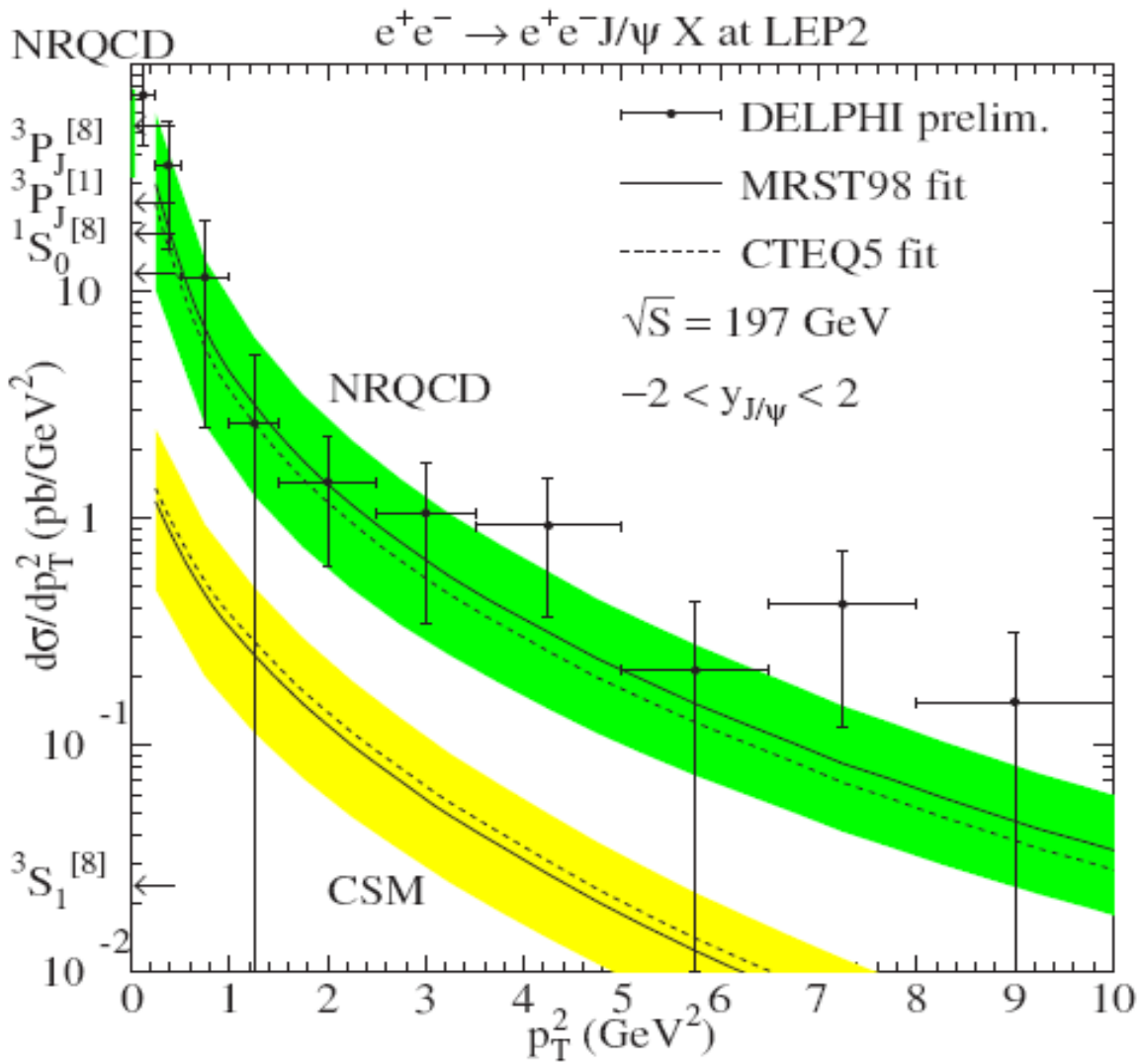


CEM with all order resummation of soft gluon shower

Berger, Qiu, Wang, 2005

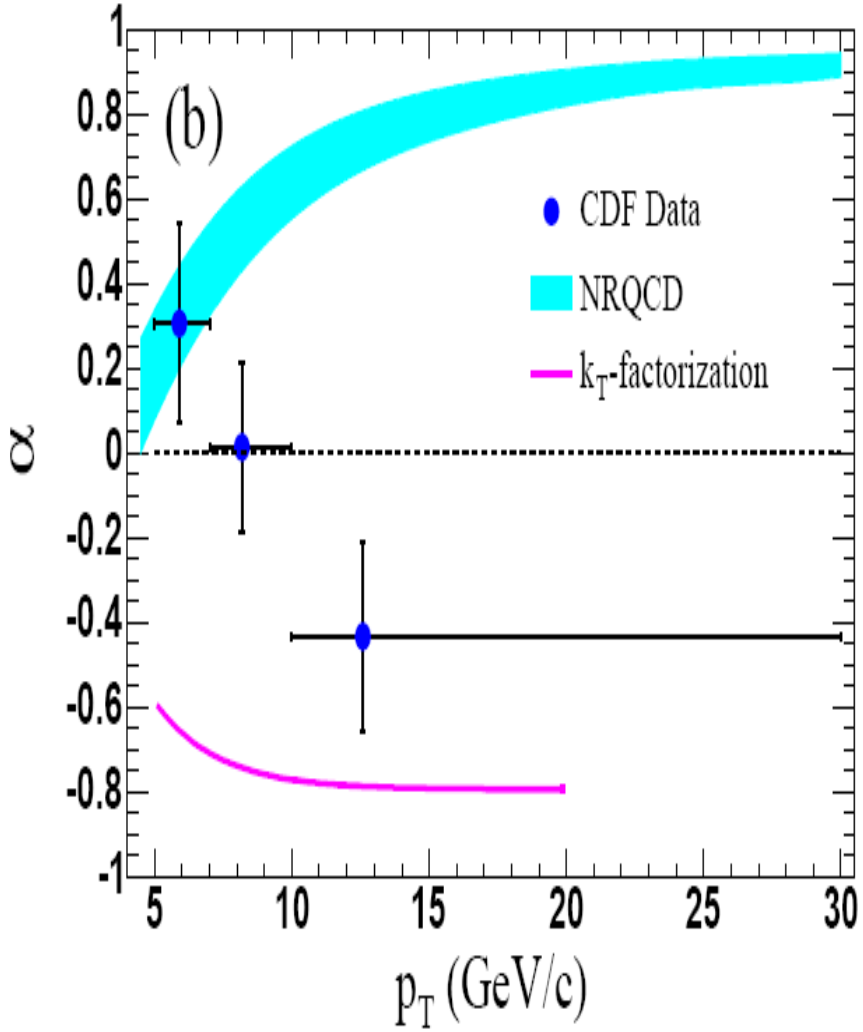
NRQCD Model: J/ψ photo-production

- **LEP data:** $\gamma\gamma \to J/\psi + X$

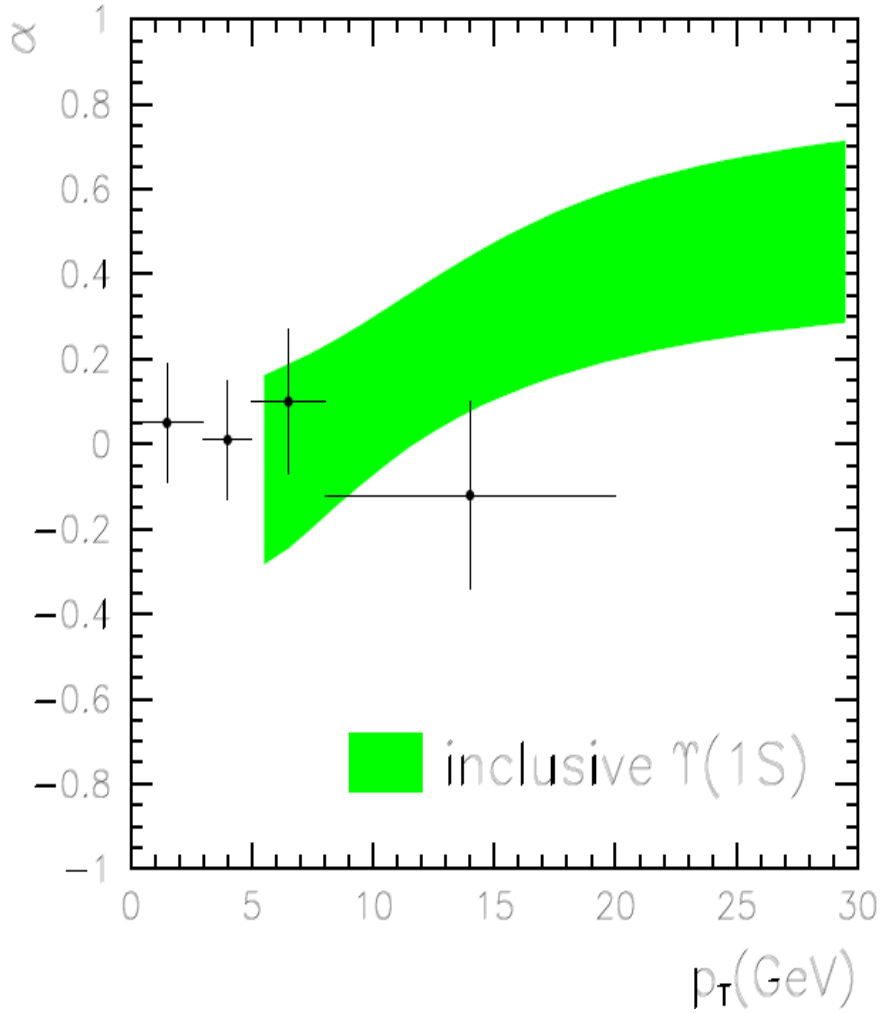


QWG's report

❑ Same problem for other states:



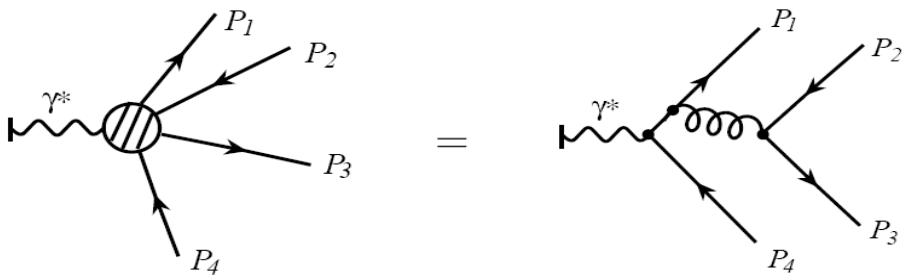
CDF Collaboration, PRL 2007

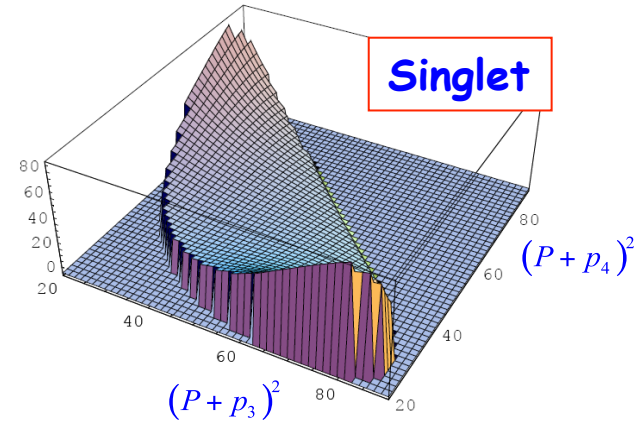


Braaton & Lee, PRD63, 071501 (2001)

Associated production at B-factory

- **Kinematically preferred configuration:**

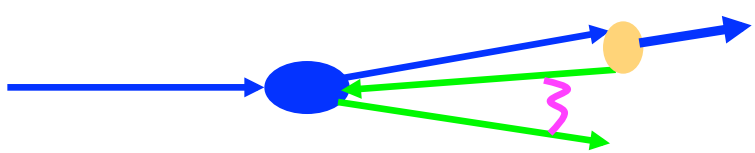




Production rate of a singlet charm quark pair is dominated by the phase space where $s_3=(P_1+P_2+P_3)^2$ or $s_4=(P_1+P_2+P_4)^2$ near its minimum

- **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