J/ψ PRODUCTION AND SUPPRESSION IN NUCLEAR COLLISIONS

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Acknowledgment:

We thank O. Drapier and C. Lourenco for help on NA50 data.

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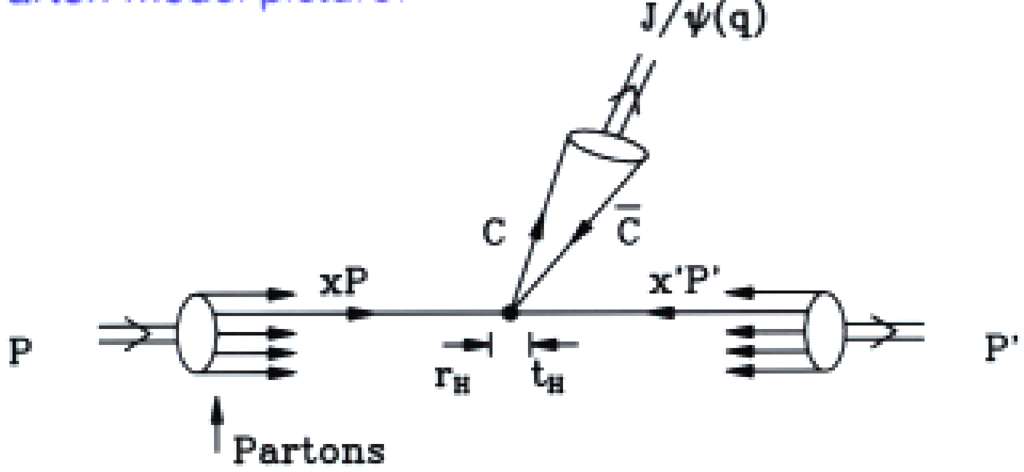
*Research done with James P. Vary and Xiaofei Zhang

1. Hadronic Production of J/ψ Mesons

- Process: $A(P) + B(P') \longrightarrow \mathrm{J}/\psi(q) + X$
- Parton model picture:



- Energy exchange: $> 2M_c \sim 3$ GeV
- $c\bar{c}$ produced at a short-distance: $r_H \leq \frac{1}{2M_c} \sim \frac{1}{15}$ fm
  $\Rightarrow$ J/ψ is unlikely to be formed at $\frac{1}{15}$ fm
- Time dilation:
  $\Rightarrow$ Spectators are "frozen" during the hard collision
  $\Rightarrow$ Their interactions are suppressed: $\left[\frac{1/R^2}{(2M_c)^2+q_T^2}\right]$
- Cross section is factorized:

$$\sigma_{\mathrm{J}/\psi} \approx \sum_{a,b} \int dx \phi_{a/A}(x) \int dx' \phi_{b/B}(x') \hat{\sigma}_{ab\to \mathrm{J}/\psi}(x, x')$$

- The debate is on the transition from the pre-J/ψ partonic states ($c\bar{c}$ pair plus coherent partons) to J/ψ mesons

EXISTING PRODUCTION MODELS:

- Non-relativistic QCD (NRQCD) Model:
  - All colored and uncolored pre-J/ψ partonic states can become color-singlet J/ψ mesons
  - Transition probabilities are proportional to non-perturbative local matrix elements
  - Factorized cross section:

$$\hat{\sigma}_{ab\to J/\psi} \approx \sum_{[O]} \hat{\sigma}_{ab\to[O]}(m_{c\bar{c}}, k_i = 0)\langle O_{J/\psi}(0)\rangle$$

  - Approximation: $k_i \ll m_{c\bar{c}}$ (velocity expansion)
- Color Evaporation Model:
  - All $c\bar{c}$ pairs with invariant mass less than open charm threshold ($m_{c\bar{c}} < m_{D\bar{D}}$) can become J/$\psi$ mesons
  - Transition probability from a $c\bar{c}$ pair to a J/ψ meson is independent of the pair's color and its invariant mass
  - Factorized cross section:

$$\hat{\sigma}_{ab\to J/\psi} \approx F_{c\bar{c}\to J/\psi} \int_{4M_c^2}^{4M_D^2} dm_{c\bar{c}}^2 \, \frac{d\hat{\sigma}_{ab\to c\bar{c}}(m_{c\bar{c}})}{dm_{c\bar{c}}^2}$$

  - Approximation: $F_{c\bar{c}\to J/\psi}$ is a constant

NRQCD MODEL VS. CDF DATA*

- Prompt J/ψ not from χ_c decay. NRQCD predictions with the normalization adjusted to fit the data (solid). Color singlet channel with (dotted) and without (dashed) gluon fragmentation.

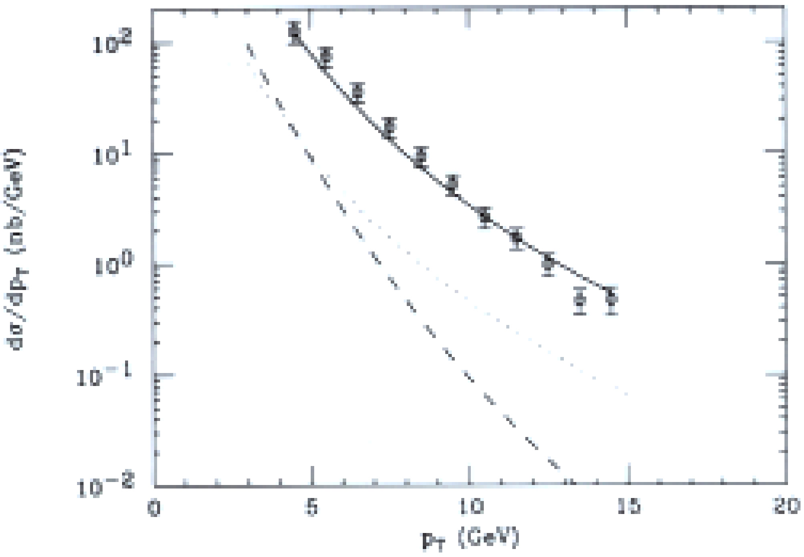


Figure 1

- Prompt ψ' as a function of p_T:

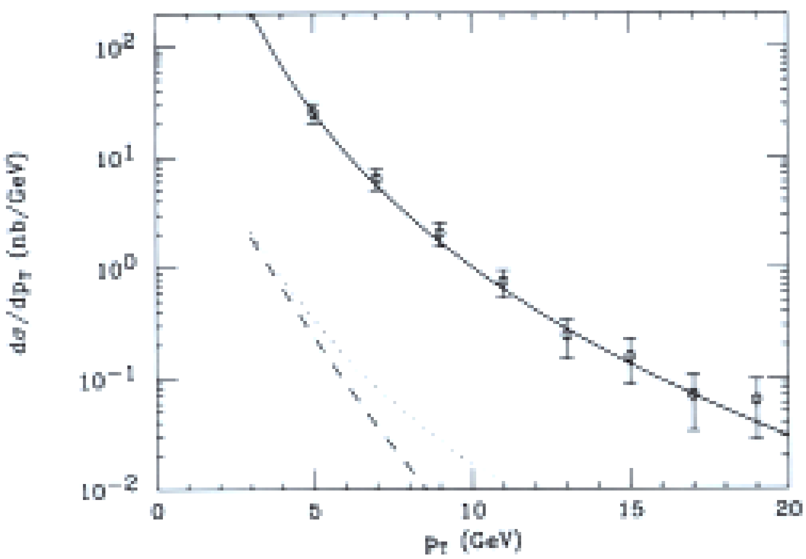
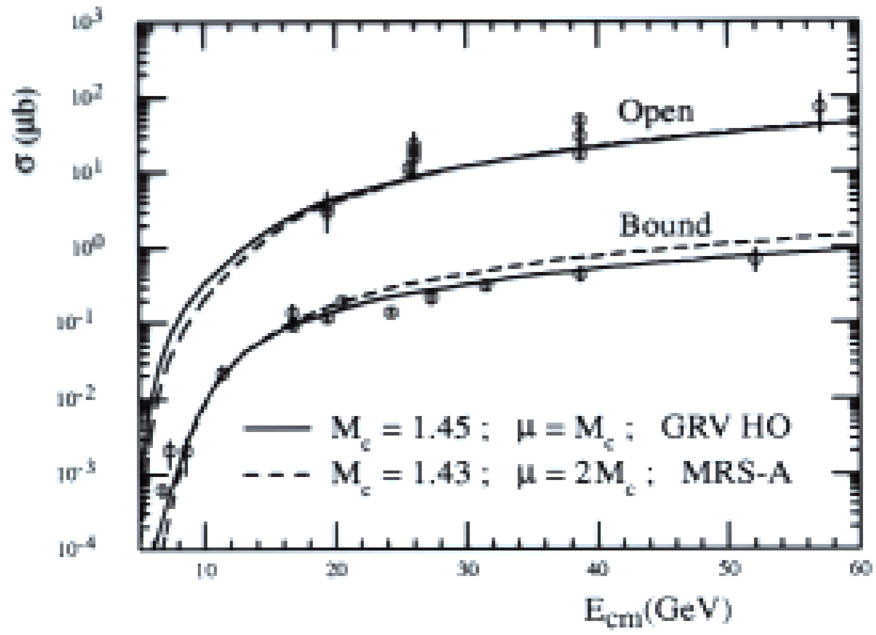


Figure 3

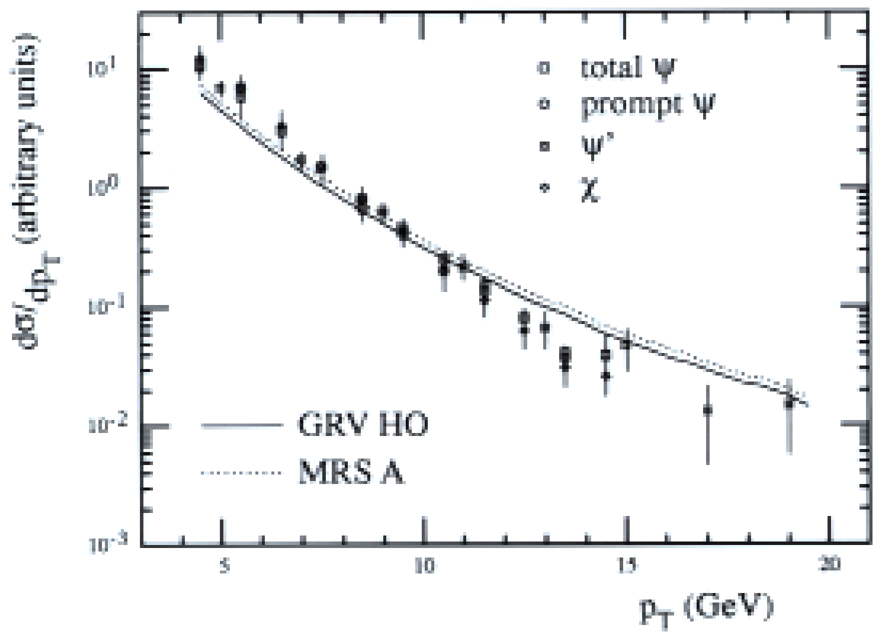
*E. Braaten et al. Annu. Rev. Nucl. Part. Sci. 46, 197 (1996)

Color Evaporation Model vs. Data*

- Charm hadroproduction as a function of collision energy.



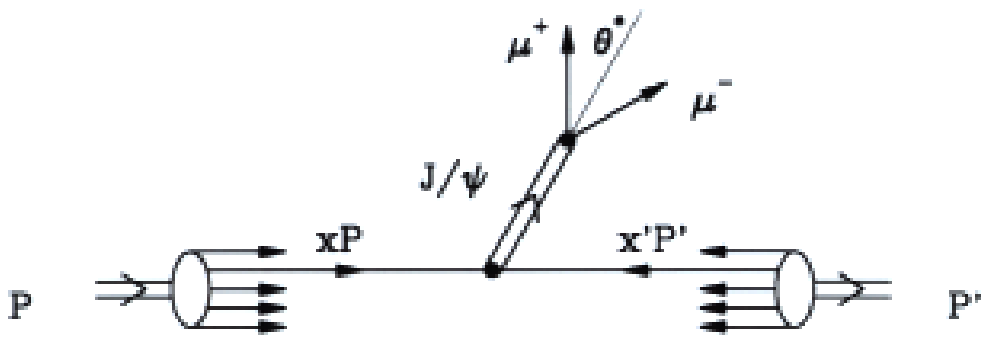
- Charmonia production as a function of p_T:



*J.F. Amundson et al. Phys. Lett. B390, 323 (1997)

Can Polarization Distinguishes Two Models?

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



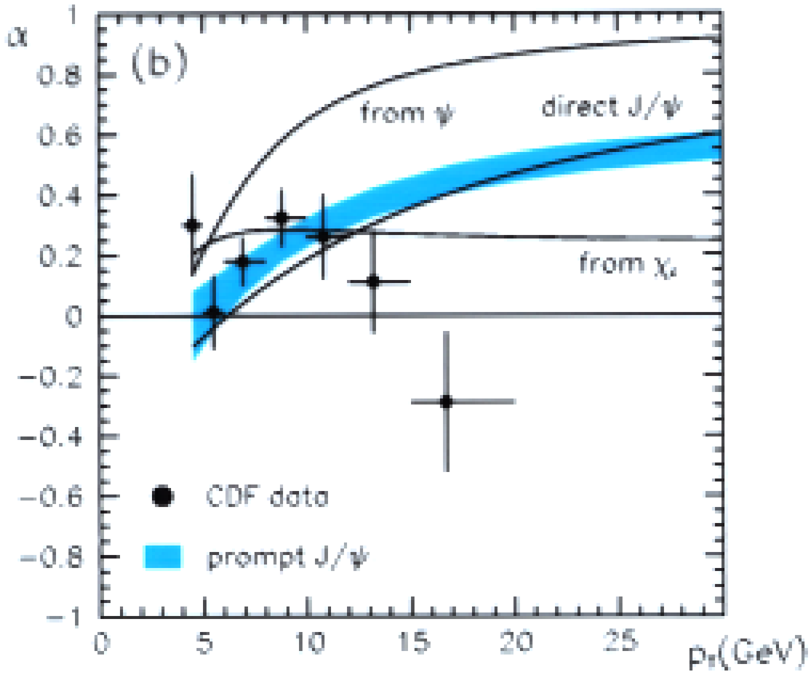
- Normalized distribution:

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

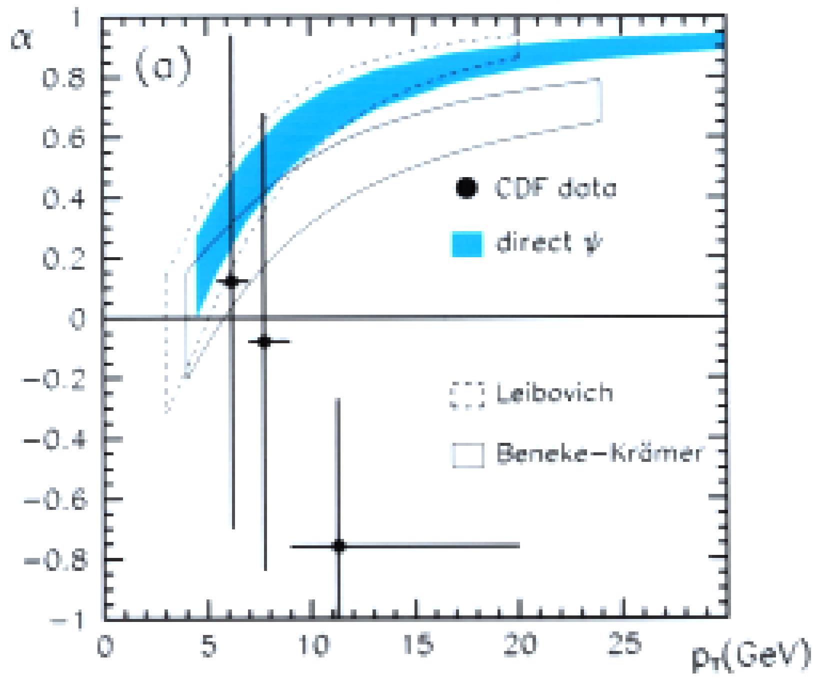
$$\alpha = \begin{cases} +1 & \text{fully transverse} \\ 0 & \text{unpolarized} \\ -1 & \text{fully longitudinal} \end{cases}$$

NRQCD Model vs. CDF Data on Polarization*

- J/ψ polarization as a function of p_T:



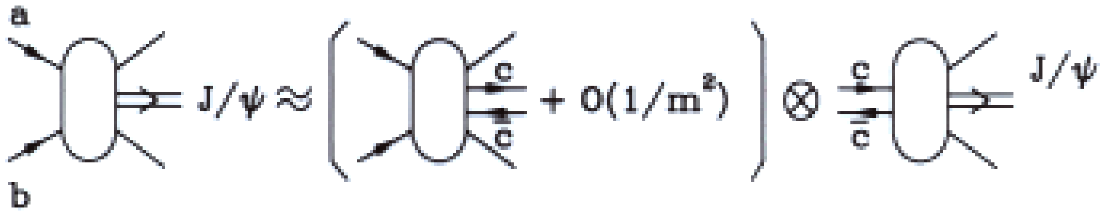
- ψ' polarization as a function of p_T:



*E. Braaten et al. Phys. Rev. D62, 094005 (2000)

QCD Factorization for Hadronic J/ψ Production *

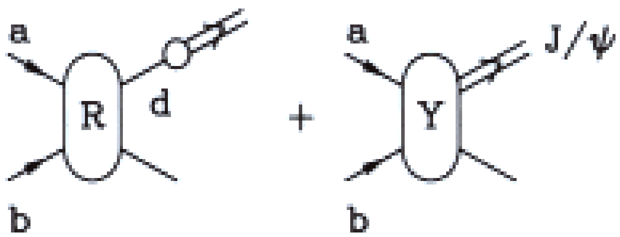
- Total hadronic J/ψ cross section:



$$\sigma_{AB\to J/\psi} \approx \sum_{[c\bar{c}]} \int dm^2_{c\bar{c}} \left[\frac{d\sigma_{AB\to[c\bar{c}]}}{dm^2_{c\bar{c}}} + O\left(\frac{1/R^2}{m^2_{c\bar{c}}}\right) \right]$$

$$\times\, F_{[c\bar{c}]\to J/\psi}(m^2_{c\bar{c}})$$

- Hadronic J/ψ production at large q_T:



$$\frac{d\hat{\sigma}_{ab\to J/\psi}}{dq_T^2\,dy} = \frac{d\hat{\sigma}^{(R)}_{ab\to J/\psi}}{dq_T^2\,dy} + \frac{d\hat{\sigma}^{(Y)}_{ab\to J/\psi}}{dq_T^2\,dy}$$

  - $\hat{\sigma}^{(R)}$ resums large $\ln(q_T^2/m^2_{c\bar{c}})$ to all orders in α_s
  - $\hat{\sigma}^{(Y)}$ = J/ψ produced at a distance scale $\sim 1/q_T$

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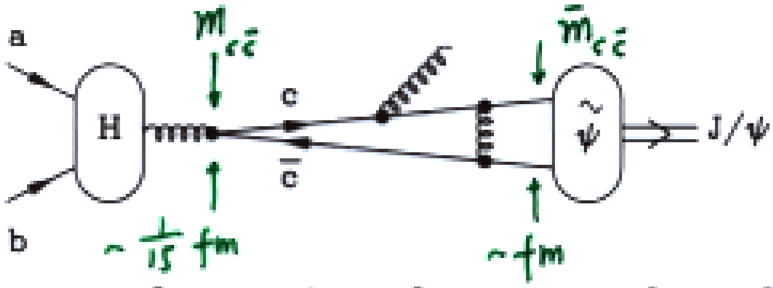
*J.-W. Qiu and G. Sterman, in preperation

TRANSITION PROBABILITY: $F_{[c\bar{c}]\to J/\psi}(m^2_{c\bar{c}})$



$$F_{[c\bar{c}]\to J/\psi}(m^2_{c\bar{c}}) \propto \int d\bar{m}^2_{c\bar{c}}\, K_{[c\bar{c}]}(m^2_{c\bar{c}}, \bar{m}^2_{c\bar{c}})\, |\tilde{\psi}(k)|^2$$

with $\bar{m}^2_{c\bar{c}} = 4M_c^2 + k^2$

- If J/ψ mesons are formed without gluon radiation following the production of the $c\bar{c}$ pairs,
  $F_{[c\bar{c}]\to J/\psi}(m^2_{c\bar{c}}) \propto |\tilde{\psi}(k)|^2$ with $m^2_{c\bar{c}} = 4M_c^2 + k^2$
  Narrow width of J/ψ wave function leads to a good velocity expansion and the NRQCD Model

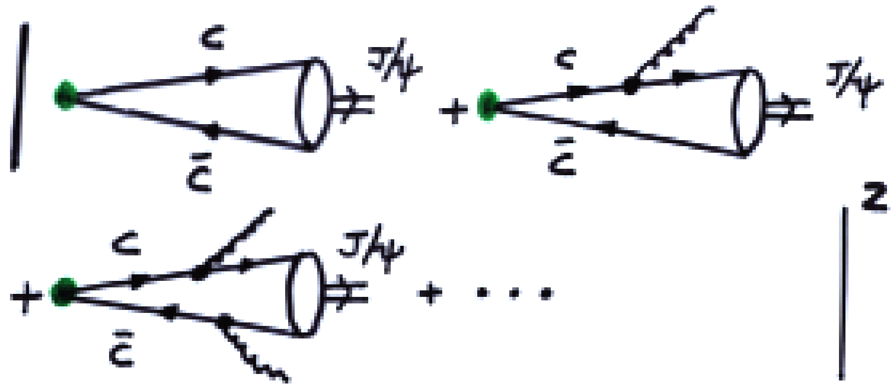
- Leading power terms in NRQCD Model $\Longleftrightarrow$ assume
  $F_{[c\bar{c}]\to J/\psi}(m^2_{c\bar{c}}) \approx \langle O_{[c\bar{c}]\to J/\psi}(0)\rangle\, \delta(1 - \frac{M^2_{J/\psi}}{m^2_{c\bar{c}}})$
  $\Rightarrow F$ with $m_{c\bar{c}} > M_{J/\psi}$ are strongly suppressed!

- Beyond leading power terms, NRQCD formalism breaks down for J/ψ total cross section due to the spectator interactions

- Color evaporation model $\Longleftrightarrow$ assume
  $F_{[c\bar{c}]\to J/\psi}(m^2_{c\bar{c}}) \approx$ Constant $\times\, \theta(m^2_{D\bar{D}} - m^2_{c\bar{c}})$
  independent of color and invariant mass of the pair
  $\Rightarrow F$ with $m_{c\bar{c}} > M_{J/\psi}$ are Not suppressed!

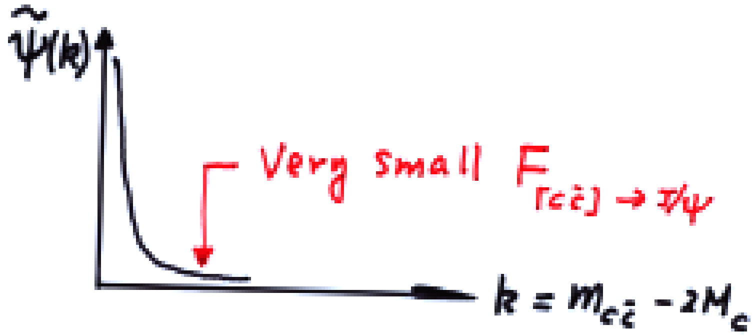
- QCD Factorization:

$F_{[c\bar{c}]\to J/\psi}(m_{c\bar{c}}^2) \propto$



When $m_{c\bar{c}}^2 > 4M_c^2$,

- Without radiation:
- With radiation:

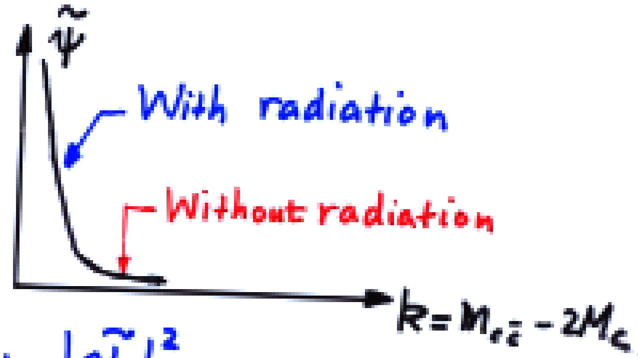


— Heavy quark mass suppresses radiation

— Radiation reduces invariant mass

$\bar{m}_{c\bar{c}}^2 < m_{c\bar{c}}^2$

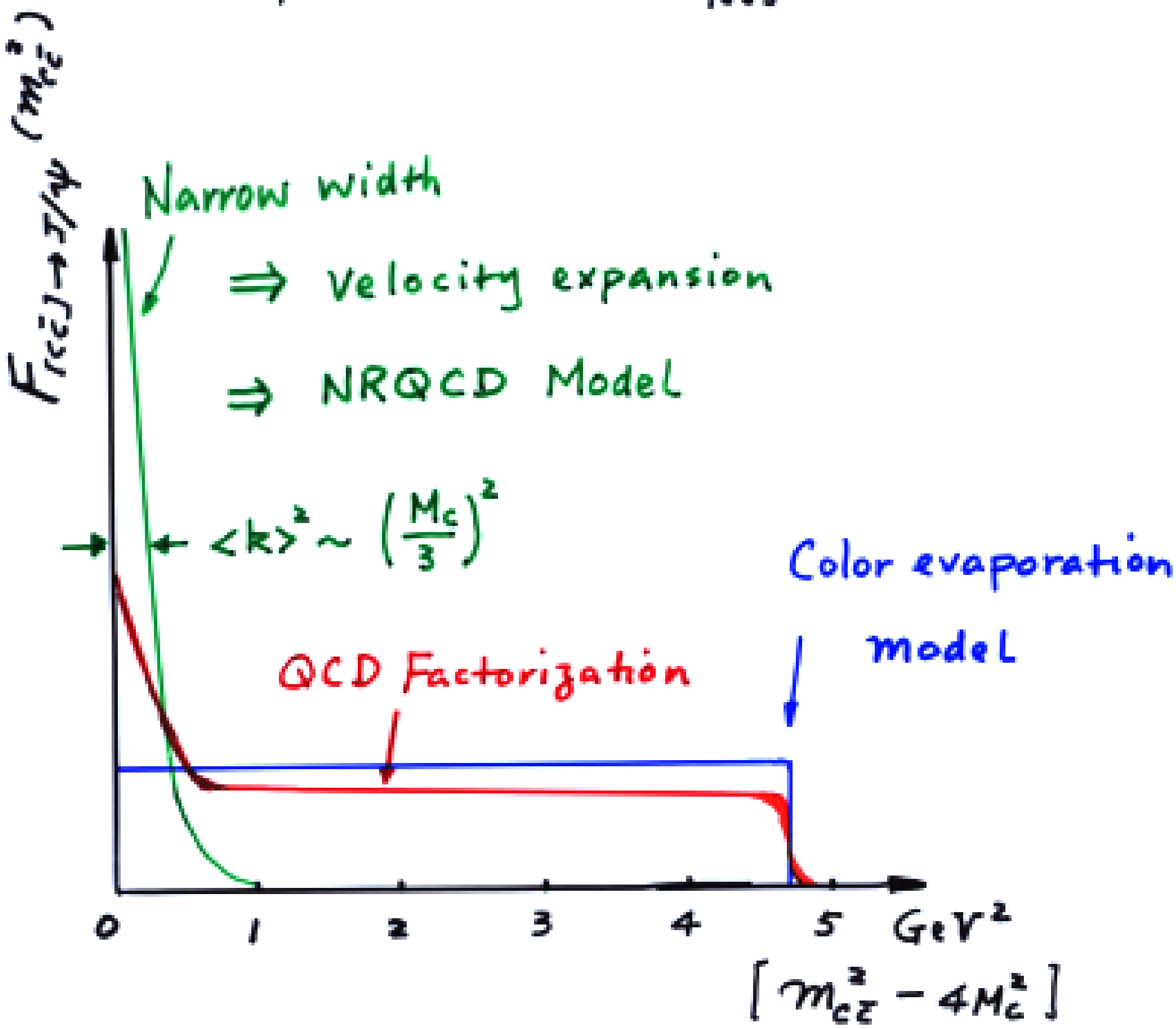
⇒ Smaller invariant mass enhances the $F_{[c\bar{c}]\to J/\psi}(m_{c\bar{c}}^2)$ due to $|\tilde{\psi}|^2$.



⇒ Transition probability is between the approximations of NRQCD and Color Evaporation Model.

- Transition probability:

$$F_{[c\bar{c}]\to J/\psi}(m_{c\bar{c}}^2) \propto \int d\bar{m}_{c\bar{c}}^2 \, K_{[c\bar{c}]}(m_{c\bar{c}}^2, \bar{m}_{c\bar{c}}^2) \, |\tilde{\Psi}(k)|^2$$



Why both NRQCD and Color Evaporation Model Work well for CDF data ?

* When $Q_T \gtrsim M_{J/\psi}$ ($\sqrt{s} \gg Q_T$), $\frac{d\sigma_{AB\to c\bar{c}}}{dm_{c\bar{c}}^2} \sim \text{Constant}$

  for $m_{c\bar{c}}^2 \in [4M_c^2, 4M_D^2]$.

$$\Rightarrow \sigma_{AB\to J/\psi} \approx \int dm_{c\bar{c}}^2 \left(\frac{d\sigma_{AB\to c\bar{c}}}{dm_{c\bar{c}}^2}\right) * F_{c\bar{c}\to J/\psi}(m_{c\bar{c}}^2)$$

$$\approx \frac{d\sigma_{AB\to c\bar{c}}}{dm_{c\bar{c}}^2} \cdot \underbrace{\int dm_{c\bar{c}}^2 F_{c\bar{c}\to J/\psi}(m_{c\bar{c}}^2)}_{\sim \text{Constant}}$$

↑ insensitive to the shape of $F_{c\bar{c}\to J/\psi}(m_{c\bar{c}}^2)$.

* However, three production mechanisms should predict different nuclear effect, because the interactions with nuclear medium are sensitive to the formation from a pre-J/ψ partonic state to a physical J/ψ.

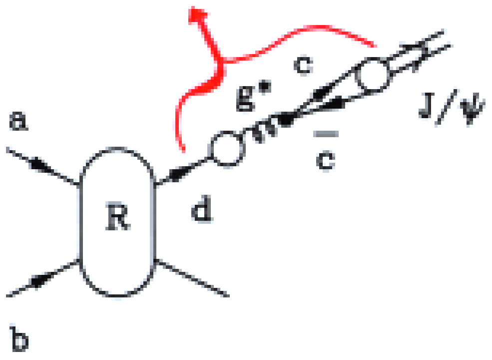
UNDERSTANDING THE J/ψ POLARIZATION*

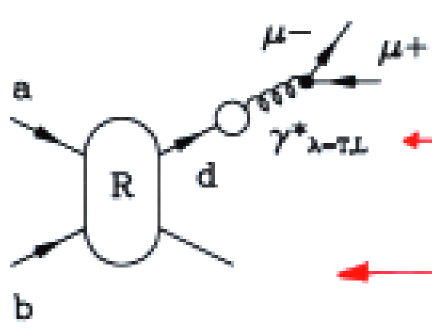
- When $q_T^2 \gg M_{J/\psi}^2$, reliable QCD calculations require to resum the large logarithms, $\ln^n(q_T^2/M_{J/\psi}^2)$
- Logarithms are resummed into fragmentation functions

$$\frac{d\hat{\sigma}^{(R)}_{ab\to J/\psi}}{dq_T^2\,dy} = \frac{d\hat{\sigma}_{ab\to d}}{dp_{d_T}^2\,dy}(\vec{p}_d = \frac{\vec{q}}{z}) \otimes D_{d\to J/\psi}(z)$$

- Due to heavy quark mass, we can approximate

$$D_{d\to J/\psi}(z) \propto D_{d\to g^*}(z; m_{c\bar{c}}) \otimes \bar{F}_{[c\bar{c}]\to J/\psi}(z', m_{c\bar{c}})$$





← Virtual γ of invariant mass Q

- Virtual gluon, immediately decays into a $c\bar{c}$ pair, is more likely to be longitudinally polarized when $q_T \gg m_{c\bar{c}}$
- Use inclusive Drell-Yan process as an example

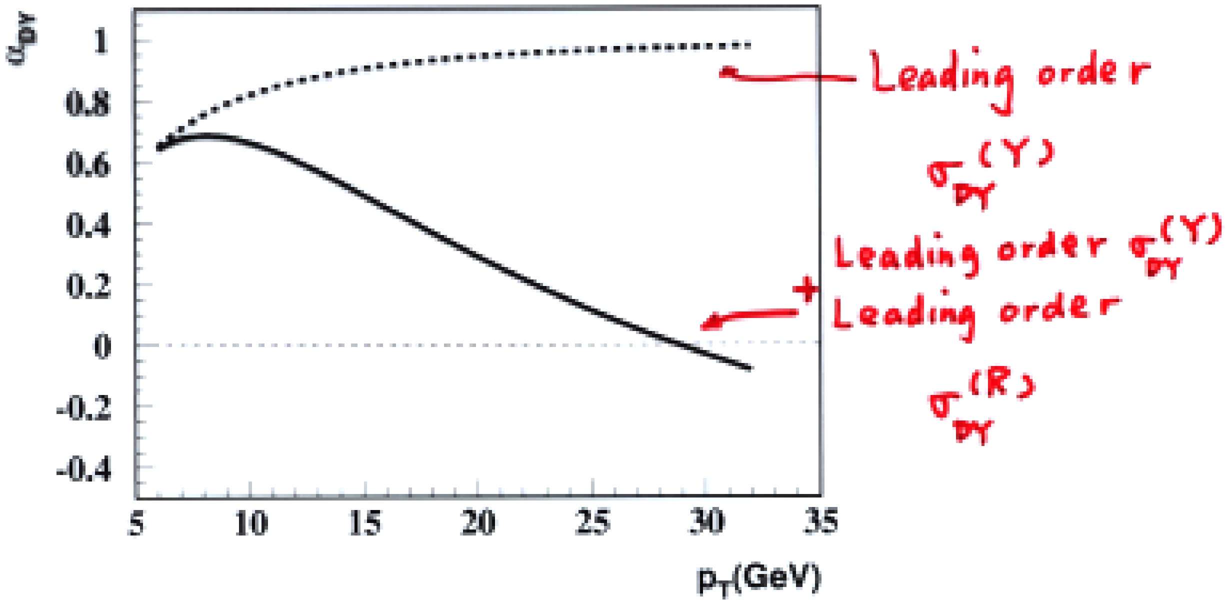
$$\alpha = \frac{\frac{d\sigma_{AB\to\gamma_T^*}}{dq_T^2\,dy} - \frac{d\sigma_{AB\to\gamma_L^*}}{dq_T^2\,dy}}{\frac{d\sigma_{AB\to\gamma_T^*}}{dq_T^2\,dy} + \frac{d\sigma_{AB\to\gamma_L^*}}{dq_T^2\,dy}}$$

$$\sigma_{AB\to\gamma_\lambda^*} = \sigma^{(R)}_{AB\to\gamma_\lambda^*} + \sigma^{(Y)}_{AB\to\gamma_\lambda^*}$$

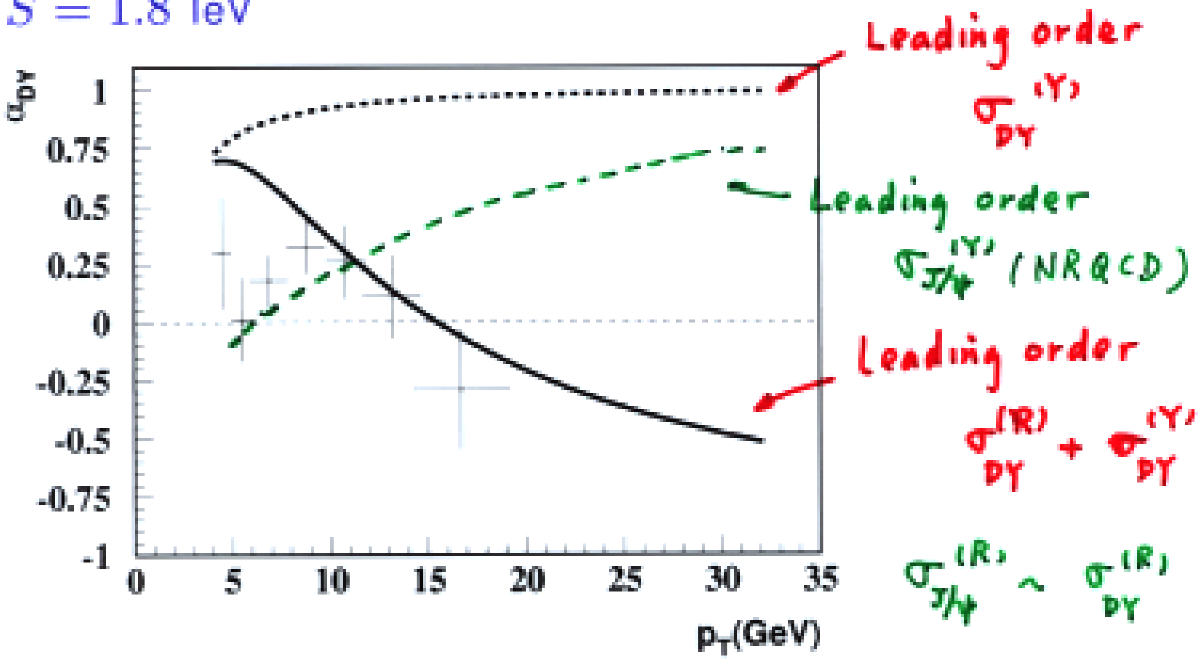
*Jianwei Qiu and Xiaofei Zhang, hep-ph/0101004

DRELL-YAN POLARIZATION α_{DY}*

- Drell-Yan α_{DY} at $Q = 5$ GeV and $\sqrt{S} = 1.8$ TeV with (solid) and without (dashed) resummation: $\sigma^{(R)}$.



- CDF data on $\alpha_{J/\psi}$ along with Drell-Yan α_{DY} at $Q = 3.1$ GeV and $\sqrt{S} = 1.8$ TeV



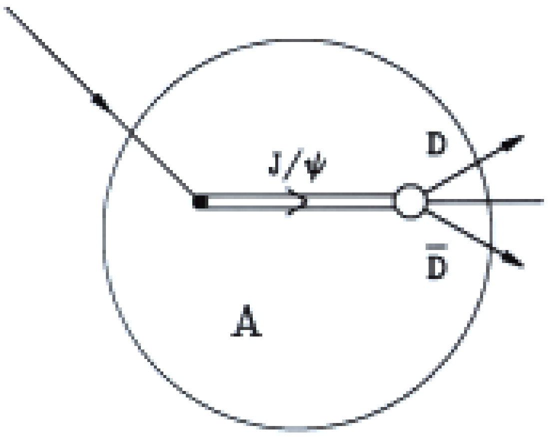
*J.-W. Qiu, R. Rodriguez, and X.-F. Zhang, in preparation

2. J/ψ SUPPRESSION WITHOUT QGP

- Multiple scattering in nuclear medium breaks J/ψ

  $\Rightarrow$ J/ψ suppression

- The ordinary nuclear absorption

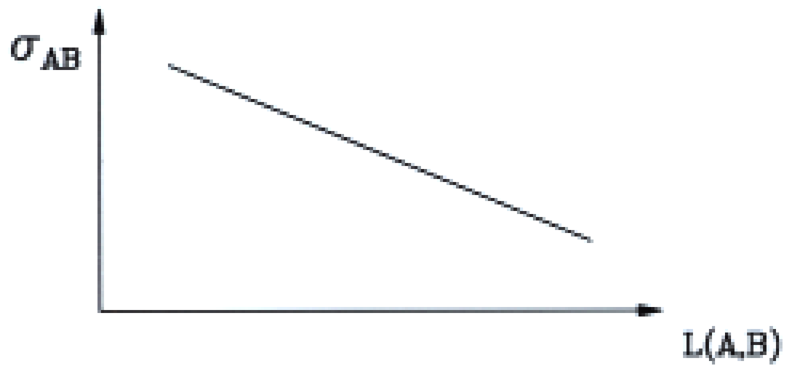


- J/ψ color singlet
- J/ψ-Nucleon absorption $\sigma_{\rm abs}^{J/\psi-N} \sim 3$ mb
- Same $\sigma_{\rm abs}$ along the path

$\Rightarrow$ Glauber Model:

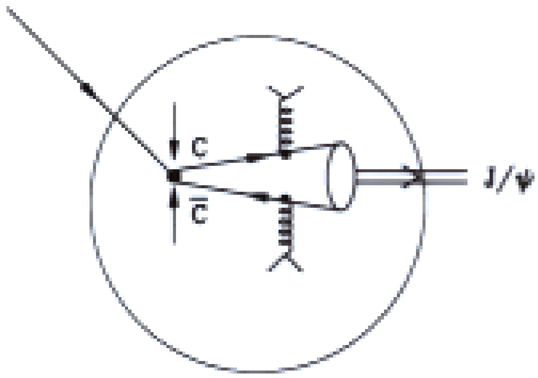
$$\sigma_{AB} \approx AB\,\sigma_{NN}\, e^{-\rho_0\, \sigma_{\rm abs}^{J/\psi-N}\, L_{AB}}$$

$\Rightarrow$ Expect a straight line on a semi-log plot vs. the effective medium length L_{AB}



- Need $\sigma_{\rm abs} \sim 7$ mb to fit most data, but Pb-Pb data.

New Suppression Mechanism

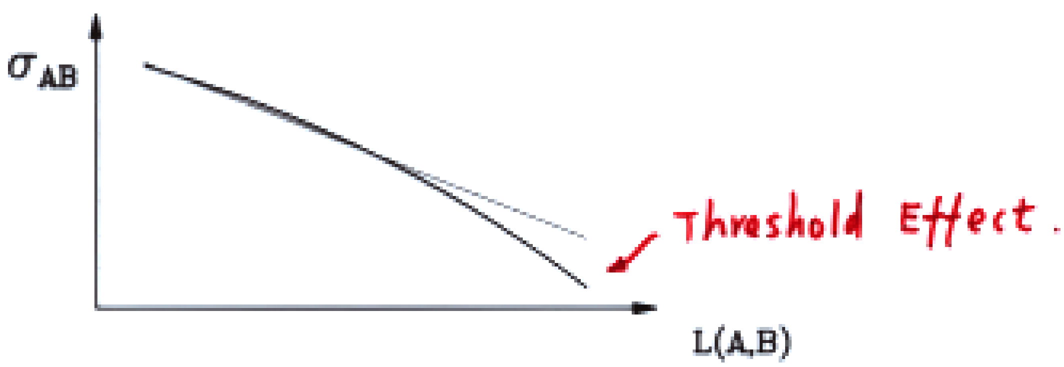


- J/ψ are not produced at the point of hard collision
  $\Rightarrow$ partonic $c\bar{c}$ states going through medium

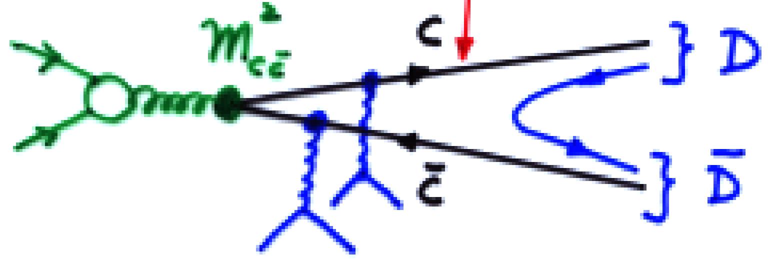
- Multiple scattering with nuclear medium increase the invariant mass of the $c\bar{c}$ pairs
  $\Rightarrow$ push some $c\bar{c}$ pairs over the open charm threshold
  $\Rightarrow$ "suppress" the production of J/ψ (see figure)

- The suppression rate depends on
  - Gain of invariant mass per medium length: ϵ
  - Functional form of the transition probability: $F_{[c\bar{c}]\to J/\psi}(m^2_{c\bar{c}})$
  - Functional form of the $c\bar{c}$ cross section: $\frac{d\sigma_{AB\to c\bar{c}}}{dm^2_{c\bar{c}}}$

- Expect a non-linear behavior on the semi-log plot

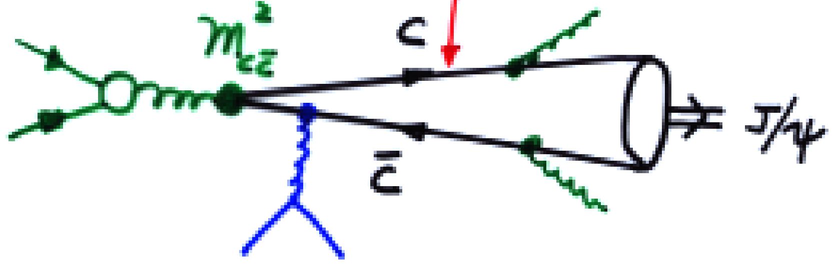


* $\bar{m}_{c\bar{c}}^2 = m_{c\bar{c}}^2 + \varepsilon^2 L > 4M_D^2$



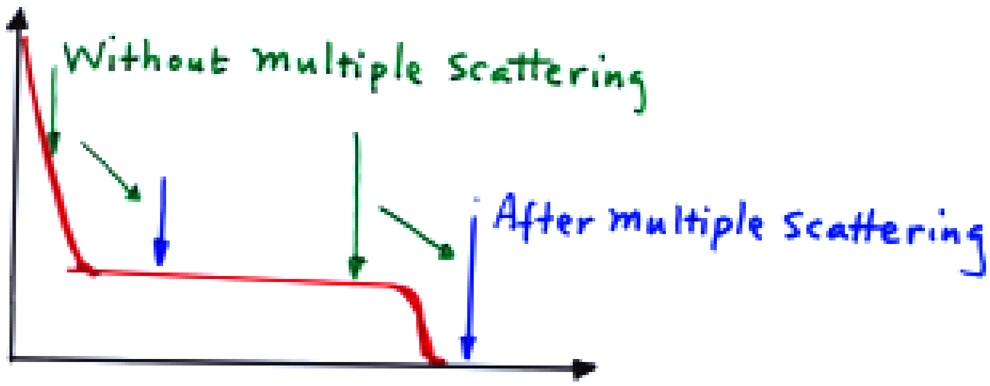
$\Rightarrow$ J/ψ Suppression

* $\bar{m}_{c\bar{c}}^2 < 4M_D^2$



More radiation

- $F_{[c\bar{c}]\to J/\psi}(m_{c\bar{c}}^2) \longrightarrow F_{[c\bar{c}]\to J/\psi}(\bar{m}_{c\bar{c}}^2)$ Smaller F!

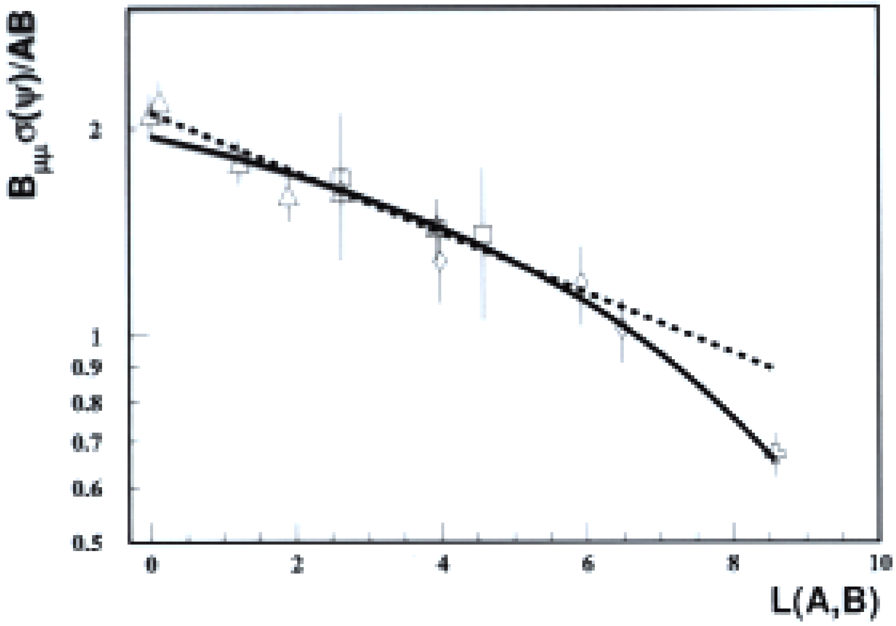


- $\int_{4M_c^2}^{4M_D^2} dm_{c\bar{c}}^2 \longrightarrow \int_{4M_{c\bar{c}}^2}^{4M_D^2 - \varepsilon^2 L} dm_{c\bar{c}}^2$ ← Smaller phase space!

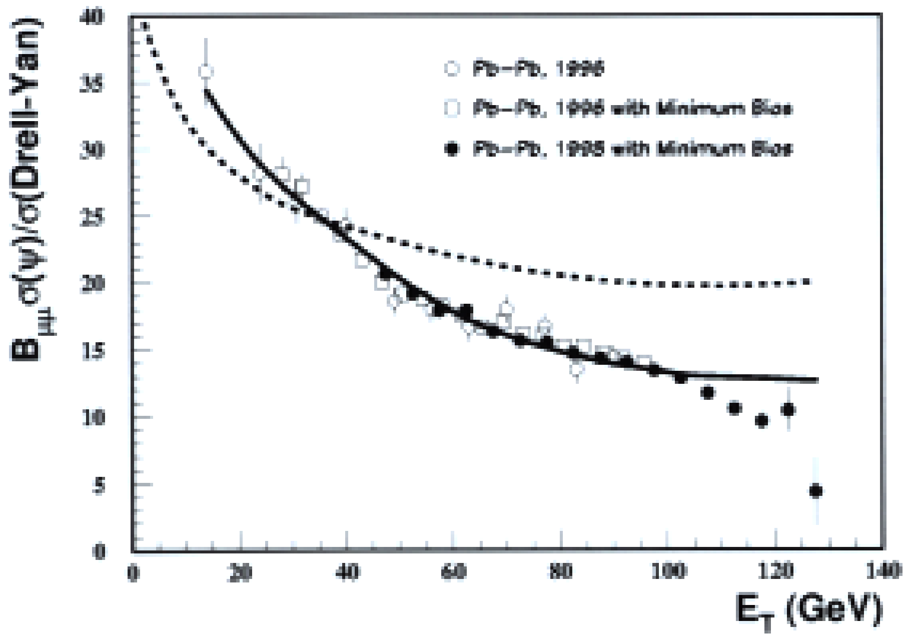
$\Rightarrow$ Suppression!

COMPARISON WITH J/ψ SUPPRESION DATA*

- J/ψ production as a function of effective medium length:



- Ratio of J/ψ over Drell-Yan as a function of E_T:



*Data from Phys. Lett. B410, 337 (1997); B477, 28 (2000)

3. Summary and Outlook

- Color Evaporation Model and NRQCD Model of J/ψ production correspond to two different approximations of the QCD factorized production formula
- Fermilab data on J/ψ polarization could be understood in terms of QCD calculations
- In terms of our new suppression mechanism, all observed data on J/ψ suppression in pA and AA collisions are consistent with our calculations, except the five NA50 data points (the "second drop") at the highest E_T bins
- Suppression in our mechanism is not limited by any "upper" limit on the absorption cross section
- Instead, it depends on the functional form of the transition probability from a pre-J/ψ partonic state to a physical J/ψ meson
- Our suppression mechanism predicts $\sqrt{S}$ dependence on J/ψ suppression from the fixed target energies to collider energies.
- Multiple scattering induce radiations from the pre-J/ψ $c\bar{c}$ states, and lead to stronger suppression at large x_F.