J/ψ PRODUCTION AND SUPPRESSION
IN NUCLEAR COLLISIONS

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1. Hadronic Production of J/ψ Mesons

- Process: \( A(P) + B(P') \rightarrow J/\psi(q) + X \)

- Parton model picture:

  ![Diagram](image)

- Energy exchange: \( > 2M_c \sim 3 \text{ GeV} \)

- \( c\bar{c} \) produced at a short-distance: \( r_H \leq \frac{1}{2M_c} \sim \frac{1}{15} \text{ fm} \)
  \( \Rightarrow J/\psi \) is unlikely to be formed at \( \frac{1}{15} \text{ fm} \)

- 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:

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

- 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-\(J/\psi\) partonic states can become color-singlet \(J/\psi\) mesons
  - Transition probabilities are proportional to non-perturbative local matrix elements
  - Factorized cross section:
    \[
    \hat{\sigma}_{ab \rightarrow J/\psi} \approx \sum_{[O]} \hat{\sigma}_{ab \rightarrow [O]}(m_{c\bar{c}}, k_i = 0) \langle O_{J/\psi}(0) \rangle
    \]
  - 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 \(J/\psi\) meson is independent of the pair's color and its invariant mass
  - Factorized cross section:
    \[
    \hat{\sigma}_{ab \rightarrow J/\psi} \approx F_{c\bar{c} \rightarrow J/\psi} \int_{4M_c^2}^{4M_D^2} dm_{c\bar{c}}^2 \frac{d\hat{\sigma}_{ab \rightarrow c\bar{c}}(m_{c\bar{c}})}{dm_{c\bar{c}}^2}
    \]
  - Approximation: \(F_{c\bar{c} \rightarrow J/\psi}\) is a constant
NRQCD Model vs. CDF Data

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

![Graph](image1.png)

Figure 1

- Prompt $\psi'$ as a function of $p_T$:

![Graph](image2.png)

Figure 3

COLOR EVAPORATION MODEL VS. DATA

- Charm hadroproduction as a function of collision energy.

- Charmonia production as a function of $p_T$:

**CAN POLARIZATION DISTINGUISHES TWO MODELS?**

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

![Diagram](image)

- 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*

- $J/\psi$ polarization as a function of $p_T$:

- $\psi'$ polarization as a function of $p_T$:

QCD FACTORIZATION FOR HADRONIC J/ψ PRODUCTION *

- Total hadronic J/ψ cross section:

\[
\sigma_{AB \rightarrow J/\psi} \approx \sum_{[c\bar{c}]} \int dm_{c\bar{c}}^2 \left[ \frac{d\sigma_{AB \rightarrow [c\bar{c}]} }{dm_{c\bar{c}}^2} + O \left( \frac{1}{R^2} \right) \right] \\
\times F_{[c\bar{c}] \rightarrow J/\psi} (m_{c\bar{c}}^2)
\]

- Hadronic J/ψ production at large q_T:

\[
\frac{d\hat{\sigma}_{ab \rightarrow J/\psi} }{dq_T^2 dy} = \frac{d\hat{\sigma}^{(R)}_{ab \rightarrow J/\psi} }{dq_T^2 dy} + \frac{d\hat{\sigma}^{(Y)}_{ab \rightarrow J/\psi} }{dq_T^2 dy}
\]

- \( \hat{\sigma}^{(R)} \) resums large \( \ln(q_T^2/m_{c\bar{c}}^2) \) to all orders in \( \alpha_s \)

- \( \hat{\sigma}^{(Y)} = J/\psi \) produced at a distance scale \( \sim 1/q_T \)

*J.-W. Qiu and G. Sterman, in preparation
**Transition Probability:** \( F_{c\bar{c} \to J/\psi}(m_{c\bar{c}}^2) \)

\[
F_{c\bar{c} \to J/\psi}(m_{c\bar{c}}^2) \propto \int \tilde{m}_{c\bar{c}}^2 K_{[c\bar{c}]}(m_{c\bar{c}}^2, \tilde{m}_{c\bar{c}}^2) |\bar{\psi}(k)|^2 \\
\text{with } \tilde{m}_{c\bar{c}}^2 = 4M_c^2 + k^2
\]

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

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

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

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

\[ F_{[c\bar{c}]} \rightarrow J/\psi (m_{c\bar{c}}^2) \propto \frac{1}{z} \]

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

- Without radiation:
  \[ \tilde{\psi}(k) \]
  - Very small \( F_{[c\bar{c}]} \rightarrow J/\psi \)
  \[ k = m_{c\bar{c}} - 2M_c \]

- With radiation:
  - Heavy quark mass suppresses radiation
  - Radiation reduces invariant mass
    \[ \overline{m}_{c\bar{c}}^2 < m_{c\bar{c}}^2 \]
    \[ \Rightarrow \text{Smaller invariant mass enhances} \]
    the \( F_{[c\bar{c}]} \rightarrow J/\psi (m_{c\bar{c}}^2) \) due to \( |\tilde{\psi}|^2 \).

\[ \Rightarrow \text{Transition probability is between the approximations of NRQCD and Color Evaporation Model.} \]
Transition probability:

\[ F_{[c \bar{c}] \rightarrow \pi^0 (m_{c\bar{c}})} \propto \int d\bar{m}_{c\bar{c}}^{\pm} K_{[c \bar{c}]} (m_{c\bar{c}}, \bar{m}_{c\bar{c}}^{\pm}) |\tilde{\psi}(k)|^2 \]

Narrow width

⇒ Velocity expansion

⇒ NRQCD Model

\[ \langle k \rangle \sim \left( \frac{M_c}{3} \right)^2 \]

QCD Factorization

Color evaporation

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

\[ \sqrt{s} \gg Q_T \]

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

for \( m_{c\bar{c}}^2 \in [4M_c^2, 4M_b^2] \).

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

\[ \text{insensitive to the shape of } F_{c\bar{c} \to J/\psi}(m_{c\bar{c}}^2) \sim \text{Constant} \]

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

- When \( q_T^2 \gg M_{J/ψ}^2 \), reliable QCD calculations require to resum the large logarithms, \( \ln^n(q_T^2/M_{J/ψ}^2) \)

- Logarithms are resummed into fragmentation functions

\[
\frac{d\sigma^{(R)}_{ab \to J/ψ}}{dq_T^2 \, dy} = \frac{d\sigma_{ab \to d}}{dp_T^2 \, dy} (\vec{p}_d = \frac{\vec{q}}{z}) \otimes D_{d \to J/ψ}(z)
\]

- Due to heavy quark mass, we can approximate

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

- 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

\[
\alpha = \frac{d\sigma_{AB \to γ^*_T}}{dq_T^2 \, dy} - \frac{d\sigma_{AB \to γ^*_L}}{dq_T^2 \, dy} + \frac{d\sigma_{AB \to γ^*_T}}{dq_T^2 \, dy} + \frac{d\sigma_{AB \to γ^*_L}}{dq_T^2 \, dy}
\]

\[
\sigma_{AB \to γ^*_\lambda} = \sigma^{(R)}_{AB \to γ^*_\lambda} + \sigma^{(Y)}_{AB \to γ^*_\lambda}
\]

*Jianwei Qiu and Xiaofei Zhang, hep-ph/0101004
DRELL-YAN POLARIZATION $\alpha_{DY}$

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

- CDF data on $\alpha_{J/\psi}$ along with Drell-Yan $\alpha_{DY}$ at $Q = 3.1$ GeV and $\sqrt{S} = 1.8$ TeV.
2. J/$\psi$ Suppression without QGP

- Multiple scattering in nuclear medium breaks J/$\psi$
  $\Rightarrow$ J/$\psi$ suppression

- The ordinary nuclear absorption
  - J/$\psi$ color singlet
  - J/$\psi$-Nucleon absorption
    $\sigma_{\text{abs}}^{J/\psi-N} \sim 3 \text{ mb}$
  - Same $\sigma_{\text{abs}}$ along the path

$\Rightarrow$ Glauber Model:

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

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

- Need $\sigma_{\text{abs}} \sim 7 \text{ mb}$ to fit most data, but Pb-Pb data.
NEW SUPPRESSION MECHANISM

- $J/\psi$ 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 $J/\psi$ (see figure)

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

- Expect a non-linear behavior on the semi-log plot
\( \bar{m}_{c\bar{c}}^2 = m_{c\bar{c}}^2 + \epsilon^2 L > 4M_D^2 \)  
\( \Rightarrow J/\psi \) Suppression

\( \bar{m}_{c\bar{c}}^2 < 4M_D^2 \)  
More radiation

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

Without multiple scattering

\[ \int_{4M_c^2}^{4M_D^2} d\bar{m}_{c\bar{c}}^2 \longrightarrow \int_{4M_c^2}^{4M_D^2 - \epsilon^2 L} d\bar{m}_{c\bar{c}}^2 \] Smaller
\[ \text{phase space} \]

\( \Rightarrow \) Suppression!
**COMPARISON WITH J/ψ SUPPRESSION DATA**

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

![Graph showing J/ψ production versus effective medium length](image)

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

![Graph showing ratio of J/ψ to Drell-Yan versus $E_T$](image)

3. Summary and Outlook

- Color Evaporation Model and NRQCD Model of $J/\psi$ production correspond to two different approximations of the QCD factorized production formula.

- Fermilab data on $J/\psi$ polarization could be understood in terms of QCD calculations.

- In terms of our new suppression mechanism, all observed data on $J/\psi$ 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-$J/\psi$ partonic state to a physical $J/\psi$ meson.

- Our suppression mechanism predicts $\sqrt{S}$ dependence on $J/\psi$ suppression from the fixed target energies to collider energies.

- Multiple scattering induce radiations from the pre-$J/\psi$ $c\bar{c}$ states, and lead to stronger suppression at large $x_F$. 