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.

- ATLAS data: $\sqrt{s} = 7$ TeV, $|y| < 0.75$
- CDF data: $\sqrt{s} = 1.96$ TeV, $|y| < 0.6$

- BELLE data: $\sqrt{s} = 10.6$ GeV

- $p\bar{p} \rightarrow J/\psi + X$, helicity frame
- CDF data: $\sqrt{s} = 1.96$ TeV, $|y| < 0.6$

- $60$ GeV < $W$ < $240$ GeV
  $0.3 < z < 0.9$
  $Q^2 < 2.5$ GeV$^2$
  $\sqrt{s} = 319$ GeV

- H1 data: HERA1
- H1 data: HERA2

- CS+CO, NLO: Butenschön et al.
NLO theory fits – Gong et al.

ATLAS data: $\sqrt{s} = 7$ TeV, $|y| < 0.75$

CDF data: $\sqrt{s} = 1.96$ TeV, $|y| < 0.6$

$pp \to J/\psi + X$, helicity frame

BELLE data: $\sqrt{s} = 10.6$ GeV

With $60$ GeV < $W < 240$ GeV, $0.3 < z < 0.9$, $Q^2 < 2.5$ GeV$^2$, $\sqrt{s} = 319$ GeV
NLO theory fits – Chao et al.

![Graphs and plots showing NLO theory fits for various experiments and conditions](Image)
**Jet fragmentation function:**

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

Jet cross section with a fully reconstructed \( J/\psi \) within it

Inclusive jet cross section

\[ z_h \equiv p_{J/\psi}^+/p_{\text{jet}}^+ \]

**Production and factorization:**

\[ \frac{d\sigma^{J/\psi}}{dp_T d\eta dz_h} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes G_{c}^{J/\psi} \]

- **Semi-inclusive fragmenting jet function:**

\[ G_i^{J/\psi}(z, z_h, p_{\text{jet}}^+, \mu) = \sum_j \left( \int_{z_h}^1 \frac{dz'_h}{z_h} J_{ij}(z, z_h/z'_h, p_{\text{jet}}^+, \mu) \right) \times D_j^{J/\psi}(z'_h, \mu) + \mathcal{O}(m_{J/\psi}^2/(p_{\text{jet}}^+ R)^2) \]

- **Fragmentation function:**

\[ D_{i\rightarrow J/\psi}(z'_h, \mu_0) = \sum_n \hat{d}_{i\rightarrow [Q\bar{Q}(n)]}(z'_h, \mu_0) \langle \mathcal{O}_{[Q\bar{Q}(n)]}^{J/\psi} \rangle \]
J/Ψ -production and polarization within a jet

- **Jet fragmentation function:**

$$F^{J/Ψ}(z_h, p_T) = \frac{dσ^{J/Ψ}}{dpTdηdz_h} / \frac{dσ}{dpTdη}$$

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

Inclusive jet cross section

- **Polarization:**

$$z_h \equiv \frac{p_{J/Ψ}^+}{p_{jet}^+}$$

- **Physical constraint:**

$$\left| \lambda_F(z_h, p_T) \right| \leq 1$$

Since \( F_{T,L}^{J/Ψ} \) are positive

- **Expansion in terms of NRQCD LDMEs:**

$$F_{T,L}^{J/Ψ}(z_h, p_T) \sum_{[Q̄Q(n)\rangle} \hat{F}_{T,L}^{[Q̄Q(n)\rangle}(z_h, p_T, Λ)\langle 0|O_{[Q̄Q(n)\rangle}^{J/Ψ}(Λ)|0\rangle$$

Linear combination of LDMEs, like \( p_Τ \) spectrum in NRQCD
### J/ψ-production and polarization within a jet

- **Fitting values of LDMEs:**

<table>
<thead>
<tr>
<th></th>
<th>$\langle O(3S^1_1) \rangle$ GeV$^3$</th>
<th>$\langle O(1S^8_0) \rangle$ 10$^{-2}$ GeV$^3$</th>
<th>$\langle O(3S^8_1) \rangle$ 10$^{-2}$ GeV$^3$</th>
<th>$\langle O(3P^8_0) \rangle$ 10$^{-2}$ GeV$^5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bodwin</td>
<td>0 $^a$</td>
<td>9.9</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Butenschoen</td>
<td>1.32</td>
<td>3.04</td>
<td>0.16</td>
<td>−0.91</td>
</tr>
<tr>
<td>Chao</td>
<td>1.16</td>
<td>8.9</td>
<td>0.30</td>
<td>1.26</td>
</tr>
<tr>
<td>Gong</td>
<td>1.16</td>
<td>9.7</td>
<td>−0.46</td>
<td>−2.14</td>
</tr>
</tbody>
</table>

**TABLE I.** $J/\psi$ NRQCD LDMEs from four different groups.

All fit the $J/\psi$'s $p_T$ distribution

*Kang et al. 1702.03287*
Predictions:

Factor of 10 difference in the predicted rate?!
J/Ψ -production and polarization within a jet

Predictions:

Bad LDMEs values: Negative “cross section”?! LHCb has been measuring the J/Ψ fragmenting function
Exclusive production of heavy quarkonium

Exclusive DIS:

A folden process for imagining gluon

Figure 1.1: Proton parton distribution functions plotted as functions of Bjorken $x$. Note that the gluon and sea quark distributions are scaled down by a factor of 20. Clearly gluons dominate at small-$x$.
Double $c\bar{c}$ production in $e^+e^-$

- **Inclusive production:**
  \[
  \sigma(e^+e^- \to J/\psi c\bar{c})
  \]
  - **Belle:** $(0.87^{+0.21}_{-0.19} \pm 0.17) \text{ pb}$
  - **NRQCD:** $0.07 \text{ pb}$

- **Ratio to light flavors:**
  \[
  \frac{\sigma(e^+e^- \to J/\psi c\bar{c})}{\sigma(e^+e^- \to J/\psi X)}
  \]
  - **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: $e^+e^- \to J/\psi gg$, $e^+e^- \to J/\psi q\bar{q}$, ... combined?
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:
  \[ \text{Active pair: } P_1, P_2; \text{ spectators: } P_3, P_4 \]

- 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:
  \[ -i g^2 \int \frac{d^Dk}{(2\pi)^D} \frac{4P_i \cdot P_j}{[2P_i \cdot k + k^2 + i\epsilon][-2P_j \cdot k + k^2 + i\epsilon][k^2 + i\epsilon]} \]
  \[ = \frac{\alpha_s}{2\pi} \left[ -\frac{1}{2\epsilon} \left( \frac{1}{\beta_{ij}} + \beta_{ij} \right) (2\beta_{ij} - i\pi) + \ldots \right] \]
  \[ \approx i \frac{\alpha_s}{\epsilon \beta_{ij}} \]
Associated production is enhanced

- **NLO correction to the amplitude:**

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

Does not contribute to NLO production rate in NRQCD  
Zhang, Chao, PRL 2007

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

  - **Velocity expansion:**

\[
\frac{1}{\beta_{13}} - \frac{1}{\beta_{23}} \sim - \frac{4}{\beta_S^3} \frac{q_S \cdot q}{m^2} \sim \frac{4}{\beta_S^2} \nu \cos \phi_S
\]

  - **Velocity-ordered region:**

\[
\beta_S < 1, \quad \frac{\nu}{\beta_S} < 1
\]

  - **Enhancement factor:**

\[
\left| A_{\text{Singlet}}^{\text{NNLO}} \right|^2 : \left( C_{8 \rightarrow 1} \frac{\alpha_s^2 \nu^2}{\varepsilon^2} \right) \left( \frac{\pi^2}{\beta_S^4} \right) \left| A_{\text{Octet}}^{\text{LO}} \right|^2
\]

- **All other two-loop diagrams give a single pole!**

  Nayak, Qiu, Sterman, 2007
LO hard parts with color factor:

\( (P + p_3)^2 \quad (P + p_4)^2 \)

Matrix elements:

\[ \frac{\pi^2 \alpha_s^2 v^2}{\epsilon^2} \Rightarrow \langle O_8 \rangle \]

\[
\frac{d\sigma_{e^+e^- \rightarrow H+X}^{\text{tot}}(p_H)}{d\sigma_{e^+e^- \rightarrow Q\bar{Q}[S_1]+Q'(\beta_S)(p_H)}^{3S_1^H}} \]

Two terms are equally important if \( \beta_s : 0.3 \)

Same feature for heavy quark fragmentation

Nayak, Qiu, Sterman, 2007

Kang, et al. 2007
Heavy quarkonium – puzzles

Regeneration?

Energy loss?
Heavy quarkonium – puzzles

**Regeneration?**

\[ R_{AA} \]

- **Inclusive \( J/\psi \to \mu^+\mu^- \), Pb-Pb \( |s_{NN}| = 2.76 \text{ TeV} \) and Au-Au \( |s_{NN}| = 0.2 \text{ TeV} \)
  - ALICE (arXiv:1311.0214), 2.5<y<4, 0<p_T<8 \text{ GeV/c}
  - PHENIX (PRC 84(2011) 054912), 1.2<y<2.2, p_T>0 \text{ GeV/c}
  - global syst. ± 15%

**Energy loss?**

\[ R_{p-Pb} \]

- **p-Pb \( |s_{NN}| = 5.02 \text{ TeV} \)**
  - ALICE (JHEP 02 (2014) 073): inclusive \( J/\psi \to \mu^+\mu^- \), 0<p_T<15 \text{ GeV/c}
    - L_{\text{rec}} (-4.46<y_{c.m.}<2.96) = 5.8 \text{ nb}^{-1}
    - L_{\text{rec}} (2.03<y_{c.m.<3.53}) = 5.0 \text{ nb}^{-1}
  - ALICE Preliminary: inclusive \( J/\psi \to e^+e^- \), p_T>0
    - L_{\text{rec}} (-1.37<y_{c.m.<0.43}) = 52 \mu \text{b}^{-1}
  - global uncertainty = 3.4%

**J/\psi vs \( \psi' \)?**

\[ \frac{[\sigma_{J/\psi}]/[\sigma_{\psi'}]}{[\sigma_{J/\psi_{p-Pb}}]/[\sigma_{\psi'_{p-Pb}}]} \]

- **ALICE, p-Pb, \( |s_{NN}| = 5.02 \text{ TeV} \)
- **PHENIX, d-Au, \( |s_{NN}| = 0.2 \text{ TeV} \)

**X_2 scaling?**

\[ X_2, y_{c.m.} \]

- **NA3 (19 GeV)**
- **E666 (30 GeV)**
- **PHENIX (200 GeV)**
Melting a quarkonium in QGP – deconfinement

Matsui & Satz (1986)

QGP Thermometer

See suppression at SPS, RHIC, and the LHC

But, Time dependent quarkonia formation!
Production in A+A collisions

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

Many model approaches are available, …,
But, not to be discussed here!
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:**
  - Perturbative
    - \[ \Delta r \leq \frac{1}{2m_Q} \]
  - Non-perturbative

- **Coherent soft interaction**
- **Same wave function**
- **Almost Not affected**
- **Quarkonium**
- **Nuclear PDFs**
Production in p(d)+A collisions

- Multiple scattering:
  - Perturbative: $\Delta r \leq \frac{1}{2m_Q}$
  - Non-perturbative: Almost Not affected
  - Coherent soft interaction: Quarkonium
  - Same wave function

- Nuclear PDFs

- Multiple scattering could change spectrum & rate!!

- Multiple scattering:
Production in p(d)+A collisions

- Multiple scattering:
  - Perturbative
    - $\Delta r \leq \frac{1}{2m_Q}$
  - Non-perturbative
  - Almost Not affected
  - Coherent soft interaction
  - Quarkonium
  - Nuclear PDFs
    - Almost Not affected
  - Same wave function
  - Multiple scattering

*Can multiple scattering interfere with nonperturbative formation of quarkonia?*
Breaking of factorization in hadronic collisions

- A-enhanced power corrections, $A^{1/3}/Q^2$, may be factorizable:

\[ \approx \left[ \begin{array}{c} p_1 \\ l_1 \\ l_1 \\ l_1 \\ l_1 \\ l_1 \end{array} \right] \quad \otimes \quad \left[ \begin{array}{c} x_j p_1 \\ x_j p_1 \\ x_j p_1 \\ x_j p_1 \\ x_j p_1 \end{array} \right] \]

\[ + \quad \ldots \]

- No $A^{1/3}$-enhancement

- 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

\[
\frac{d\sigma_{pA \to J/\psi X}}{d^2bdr} = x_1 G(x_1, m_c^2) \frac{d\sigma_{gA \to J/\psi X}}{d^2br}
\]

PHENIX: \(y=0, \sqrt{s}=200\) GeV

PHENIX: \(y=1.7, \sqrt{s}=200\) GeV

ALICE: \(y=3.25, \sqrt{s}=2.76\) TeV

bCGC Model for dipole scattering

OK for \(pA\), but, far off for \(AA\) – \(J/\psi\) melting in QGP (MS 1986)?
Production with multiple scattering

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

  $J/\Psi$ could be formed inside nucleus

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

- Production at low $P_T \rightarrow 0$ in p(d)+A collisions:

  Co-mover interaction

  to interfere with quarkonium formation - Break of factorization!!
Production with multiple scattering

- **Forward** production in p(d)+A collisions:
  - Multiple scattering with incoming parton & heavy quarks, not J/Ψ
  - Time dilation

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

---

Brodsky and Mueller, PLB 1988
Production with multiple scattering

- **Forward** production in \( p(d)+A \) collisions:
  - Time dilation
  - Non-perturbative formation of \( J/\Psi \) is far outside of nucleus

- Multiple scattering with incoming parton & heavy quarks, not \( J/\Psi \)
  - Induced gluon radiation – energy loss – suppression at large \( y \)
  - Modified \( P_T \) spectrum – transverse momentum broadening
  - De-coherence of the pair – different \( QQ \) state to hadronize – lower rate

\( Q \) \( Q \) – Soft multiple scattering – “random walk”

\( Q \) \( Q \) – Momentum imbalance – larger invariant mass

Match to the tail of wave function - “suppression”
Suppression in total production rate

Glauber model

\[ \frac{1}{AB} \frac{\sigma_{AB}}{\sigma_{NN}} \approx e^{-\rho_0 \sigma_{\text{abs}} L_{AB}} \]

Multiple scattering of the pair

\[ \overline{Q}^2 = Q^2 + \varepsilon L_{AB} \]

\[ \varepsilon \sim \hat{q} \sim \langle \Delta q^2_T \rangle \]

Suppression of \( J/\psi \)

Threshold effect leads to different effective \( \sigma_{\text{abs}} \)

\[ \sigma_{\text{abs}} = 4.18 \pm 0.35 \text{ mb} \]
A-dependence in rapidity \( y (x_F) \) in \( p+A \)

- **Picture + assumptions:**
  - Color neutralization happens on long time scales: \( t_{\text{octet}} \gg t_{\text{hard}} \)
  - 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:**

\[
\frac{1}{A} \frac{d\sigma_{pA}}{dE} (E, \sqrt{s}) = \int_{0}^{\varepsilon_{\text{max}}} d\varepsilon \, \mathcal{P}(\varepsilon, E) \frac{d\sigma_{pp}}{dE} (E + \varepsilon, \sqrt{s})
\]

\[
\hat{q}(x) \sim \hat{q}_0 \left( \frac{10^{-2}}{x} \right)^{0.3}
\]

\( \mathcal{P}(\varepsilon, E) \): Quenching weight \sim 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:**

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

**Nuclear A-dependence:**

$$R_{pA}^\psi(y, p_\perp) \simeq R_{pA}^{\text{loss}}(y, p_\perp) \cdot R_{pA}^{\text{broad}}(p_\perp)$$

---

**Figure:**

$R_{FB}$ for p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV, inclusive $J/\psi \rightarrow \mu^+\mu^-$, $2.96 < |y_{\text{cms}}| < 3.53$.
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
  - Final-state interactions suppress the formation of J/$\psi$:
    - Also modify the $p_T$ spectrum – move low $p_T$ to high $p_T$ – broadening
    - Final-state effect

- Broadening:
  - Sensitive to the medium properties
  - Perturbatively calculable

- $R_{pA}$ at low $q_T$:

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

Qiu, Zhang, PRL, 2001

Guo, Qiu, Zhang, PRL, PRD 2002
Broadening:

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

$$\lambda^2 = \kappa \ln(Q) x^{-\delta} \propto \hat{q}, \quad \kappa = 3.51 \times 10^{-3} \text{ 1/GeV}^2, \quad \delta = 1.71 \times 10^{-1}$$

Calculated in both NRQCD and CEM

ALiCE: I. Lakomov, QWG2014
Final-state multiple scattering - CEM

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

$$
\Delta \langle q_T^2 \rangle_{\text{HQ}}^{\text{CEM}} \approx \int dq_T^2 dq_T' \int_{4m_Q^2}^{4M_Q^2} dQ^2 \frac{d\sigma_{hA\to QQ}}{dQ^2 dq_T^2} / \int_{4m_Q^2}^{4M_Q^2} dQ^2 \frac{d\sigma_{hA\to QQ}}{dQ^2}
$$

- Multiparton correlation:

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

- Broadening – twice of initial-state effect:

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

$$
\approx 2C_A \left( \frac{8\pi^2 \alpha_s}{N_c^2 - 1} \lambda^2 A^{1/3} \right)
$$

if gluon-gluon dominates, and if $r_F > R_A$
Cross section:

\[
\sigma_{hA\rightarrow H}^{\text{NRQCD}} = A \sum_{a,b} \int dx' \phi_{a/h}(x') \int dx \phi_{b/A}(x) \left[ \sum_n H_{ab\rightarrow Q\bar{q}[n]} \langle \mathcal{O}^H(n) \rangle \right]
\]

Broadening:

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

Hard parts:

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

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

\[
\hat{\sigma}_{g\bar{g}}^{(0)} = \frac{\pi^3 \alpha_s^2}{M^3} \frac{5}{12} \delta(\hat{s} - M^2) \left[ \langle \mathcal{O}^H(1S_0^{(8)}) \rangle + \frac{7}{m_Q^2} \langle \mathcal{O}^H(3P_0^{(8)}) \rangle \right]
\]

Leading features:

\[
\Delta \langle q_T^2 \rangle_{\text{NRQCD}}^{\text{HQ}} \approx \Delta \langle q_T^2 \rangle_{\text{HQ}}^{\text{CEM}} \approx (2C_A/C_F) \Delta \langle q_T^2 \rangle_{\text{DY}}
\]
Nuclear modification – low pT region:

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

- SXF
- IXF
- LXF

E772 data

ALICE data
Forward quarkonium production in p(d)+A

- Calculation of multiple scattering:
  - Kang, Ma, Venugopolan, JHEP (2014)
  - Qiu, Sun, Xiao, Yuan PRD89 (2014)

Coherent multiple scattering suppression at large y

Ma et al 1503.07772
It has been over 40 years since the discovery of $J/\Psi$

When $p_T >> m_Q$ at collider energies, earlier model calculations for the production of heavy quarkonia are not perturbatively stable. LO in $\alpha_s$-expansion may not be the LP term in $1/p_T$-expansion.

QCD factorization works for both LP and NLP ($\alpha_s$ 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