Nuclear matter effects on J/ψ production in Cu+Au and U+U collisions in PHENIX
Heavy Ion collisions and QGP

- The hot, dense state of nuclear matter, **Quark Gluon Plasma**
  - deconfined, color charged state of quarks and gluons
  - experimentally achievable with heavy ion collisions
- High temperature and/or baryon density

**Lattice QCD predictions:**
- \( T_c \approx 170 \text{ MeV} \)
- \( \varepsilon_c \approx 1 \text{ GeV/fm}^3 \) (>5x Nuclear hadron matter)
Heavy quarks & Heavy ion collisions

• “If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $cc$ binding in the deconfined interior of the interaction region.”

• The color (Debye) screening modifies the particle potential due to the charge density of the surrounding medium

• Quarkonium potential in the medium becomes shallower
  – With increasing $T$ different $q\bar{q}$ states “sequentially melt”
  – $J/\psi$ becomes unbound $\rightarrow$ suppression in QGP!

\[
V(r) = \sigma r - \frac{\alpha}{r}
\]

\[
V(r, T) = \frac{\sigma}{\mu} \left[ 1 - e^{-\mu r} \right] - \frac{\alpha}{r} e^{-\mu r}
\]
What can modify J/ψ production?

Phenix has good capabilities to measure J/ψ and probe quarkonia deconfinement and other mechanisms which modify its production.

- Two main sources:
  - Cold nuclear matter effects (CNM)
    - due to the nuclear target (no QGP, systems like d+Au)
  - Hot nuclear matter effects (HNM)
    - modification in the created QGP

- Strategy:
  - Measure (then parametrize) CNM effects in p(d)+A
  - A+A collisions will have both CNM+HNM effects
    - “Remove” CNM effects
    - Learn about QGP mechanisms which modify charmonium
J/ψ measurements in Phenix

- Central arms: electrons
  - J/ψ → e+/e-
  - |η|<0.35, Δφ = π
  - p_e>0.2 GeV/c

- Forward rapidity arms: muons
  - J/ψ → μ+/μ-
  - 1.2 <|η|<2.2, Δϕ = 2π
  - p_μ > 1 GeV/c

- Broad contribution to the world's J/ψ measurements
  - Large energy range: $\sqrt{s_{NN}} = 39\text{-}200$ GeV
  - Broad range of collision species p+p, d+Au, Cu+Cu, Cu+Au, Au+Au, U+U
J/ψ in cold nuclear matter

- d+Au “cold” and asymmetric system
  - Rapidity dependent suppression
- Compared to pp

Quantify suppression in A+B collisions as the ratio of yields in that system to the yield expected from binary scaled* pp collisions

\[ R_{AB} = \frac{dN_{AB}/dp_T}{\langle N_{coll} \rangle \times dN_{pp}/dp_T} \]

* Binary scaling means the number of hard collisions each nucleon suffers
**Phenix d+Au**

- d+Au “cold” and asymmetric system
  - Rapidity dependent suppression
    - Compared to pp
- More suppressed at forward (d-going) rapidity
- CNM effects
  - Modification of gluon densities in nucleus → Nuclear modification of pdfs in nuclear target (EPS09)
  - Gluon saturation → Color Glass Condensate

![Graph showing J/ψ in cold nuclear matter](PHENIX, PRL 107,142301 (2011))

\[
R_{AB} = \frac{dN_{AB}/dp_T}{\left\langle N_{\text{coll}} \right\rangle \times dN_{pp}/dp_T}
\]
J/$\psi$ in cold nuclear matter

- CNM effects
  - Complex admixture of different mechanisms
  - Strongly dependent on rapidity

- Open questions:
  - Can we factorize them?
  - Are there HNM effects in p(d)+Au?
    - Collective phenomenon seen
    - Do they affect J/$\psi$ production?

- Initial parton energy loss

- Gluon shadowing / antishadowing

- Nuclear transverse momentum broadening

- cc-bar breakup in the target nucleus

- Gluon saturation
Heavy ion collisions & Hot Nuclear Matter

• HI collision
  – How to control the properties of the created state

Spectators $\rightarrow$ nucleons outside overlap volume
characteristic nuclear size

Participants $(N_{\text{part}})$ $\rightarrow$ nucleons inside overlap volume
Hot, dense region
Heavy ion collisions & Hot Nuclear Matter

- HI collision
  - How to control the properties of the created state
    - Collision centrality
    - System size
      - e.g. Cu+Cu vs Au+Au
    - Center of mass energy
Heavy ion collisions & Hot Nuclear Matter

- HI collision
  - How to control the properties of the created state
    - Collision centrality
    - System size
      - e.g. Cu+Cu vs Au+Au
    - Center of mass energy
  - e.g. Cu (63 nucleons) vs Au (197 nucleons)
Global particle production & Hot Nuclear Matter

- Charged particle density – measure of the initial energy density of the created state
  - Increases with increasing collision energy.
  - There is an increase for more central collisions at all collision energies.
  - Decreases at higher rapidity.
J/ψ production & Hot Nuclear Matter

• Au+Au measurements in Phenix
  − Energy dependence
  − Rapidity dependence
J/ψ energy dependence

Phenix Au+Au

● Forward rapidity
  - Suppression with respect to pp collisions
  - Suppression increases slightly with increasing energy density ($N_{\text{part}}$)
  - Very little, if any, energy dependence

HNM effect

Competing effects of dissociation and regeneration (corrected for CNM)
J/ψ energy dependence

- Forward rapidity
  - Suppression with respect to pp collisions
  - Suppression increases slightly with increasing energy density ($N_{\text{part}}$)
  - Very little, if any, energy dependence

- HNM effect
  - Competing effects of dissociation and regeneration (corrected for CNM)

Model: Zhao and Rapp, PRC 82,064905 (2010)
J/ψ energy dependence

- At LHC
  - Suppression is much reduced

ALICE. PRL 109.072301 (2012)
J/ψ energy dependence

- At LHC
  - Suppression is much reduced

- Recombination (coalescence) important at LHC
  - Smaller $R_{AA}$ at low $p_T$ at RHIC energy
  - Larger $v_2$ at LHC

Zhao and Rapp, Nucl.Phys.A859 (2011)

ALICE, PRL 109,072301 (2012)

ALICE, arXiv:1311.0214
J/ψ rapidity dependence

- Stronger suppression at forward/backward rapidity
  - Does not increase with increasing energy density as seen in charge particle multiplicity

- HNM effects
  - Coalescence
  - CNM effects?
J/ψ in hot nuclear matter

- HNM effects
  - complex admixture of different mechanisms
  - strongly depend on rapidity

- Open questions:
  - Can we factorize CNM effects?

- Study new systems
  - Cu+Au at 200 GeV
  - U+U at 193 GeV
Cu+Au: asymmetric system

- Forward/Backward asymmetry
  - Along the beam axes
- Adds more variation to the initial state
  - Initial asymmetry → translates into asymmetric distribution of final particle density

- $J/\psi$ expectations in Cu+Au
  - Similar to d+Au
    - CNM effects asymmetric
  - Similar to A+A → added HNM effects
    - But possibly asymmetric
J/ψ in Au+Au vs Cu+Au

- Au+Au collisions
  - Strong suppression
    (with respect to binary scaled pp collisions)
J/ψ in Au+Au vs Cu+Au

- Cu+Au: Au-going direction
  - Same suppression as in Au+Au at same $N_{\text{part}}$

arXiv:1404.1873
**J/ψ in Au+Au vs Cu+Au**

Phenix Cu+Au

Forward rapidity

- Cu+Au: **Cu-going direction**
  - Less suppression than in Au+Au at same $N_{\text{part}}$

arXiv:1404.1873
Cu+Au CNM effects

go to asymmetric in rapidity

Forward CNM effects (Cu-going)
- gluon modification
  - \( J/\psi \) probes gluons at high-\( x \) in Cu, low -\( x \) in Au
- dynamical processes
  - \( E_{\text{loss}} \), \( J/\psi \) short crossing proper time in Au
  - c\( \bar{c} \) breakup by nucleon collisions, long crossing proper time in Cu

Backward (Au-going)
- Reversed CNM effects

Ratio ~ 20% for non-peripheral data
Cu+Au CNM effects

- CNM calculation
  - only includes shadowing
  - Uses EPS09 nPDF and 4 mb effective cross section at all rapidities
  - Shadowing effect comparable with data
  - Has same sign as data

- Not considering other mechanisms, e.g. color screening, which will increase the ratio

U+U: larger system

- New RHIC energy density record in U+U collisions
  \[ e_B = 6.15 \text{ GeV/fm}^2/\text{c}. \]

- Moderate increase from central Au+Au to very central U+U (20%)
  - Some expected up to 55% for tip-tip orientation

- PRL 94, 132301 (2005)
J/$\psi$ in U+U predictions

- The higher energy density (15-20% expected in this model)
  - should lead to stronger suppression due to color screening
- Larger $N_{\text{coll}}$ (than in Au)
  - Should lead to increased charm by statistical coalescence
- Both effects in opposite direction

- CNM: gluon shadowing is expected to be similar for U+U and Au+Au

$$N_{\text{coll}}^{\text{stat}} \propto N_c^2$$

$N_{\text{coll}}$ – number of binary nucleon-nucleon collisions
Weaker suppression in central collisions in U+U?
Higher coalescence?
Conclusions

- Phenix has measured the $J/\psi$ production in two new collision systems
  - Cu+Au
    - adds variation in the studied initial geometry.
    - shows significantly stronger $J/\psi$ suppression in the Cu-going direction, consistent with the direction and magnitude expected from differences in EPS09 shadowing between Cu and Au.
  - U+U
    - a larger system than Au+Au.
    - $J/\psi$ suppression seems to be slightly less than Au+Au at the same rapidity for central data.
Backup
There is now a long history of studying charmonium in A+A collisions.

<table>
<thead>
<tr>
<th>$\sqrt{s_{\text{NN}}}$ (GeV)</th>
<th>Species</th>
<th>Rapidity</th>
<th>Experiment</th>
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<td>17.3</td>
<td>Pb+Pb, In+In</td>
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<td>Au+Au</td>
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<td>y</td>
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<tr>
<td>2760</td>
<td>Pb+Pb</td>
<td></td>
<td>ALICE</td>
</tr>
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</table>
Heavy quarks & Heavy ion collisions

• Heavy quarks are produced during the collision of two nuclei – important probe

• Any modification in their production with respect to pp
  – Signal a deconfined state, QGP
    (Matsui & Satz PLB 178, 416(1986))
      Different charmonium states have different binding energy
        Suppression of given state – QGP
          “thermometer”

• In this talk
  – Look at how J/ψ production is modified in heavy ion collisions in Phenix
Quarkonium binding and dissociation

review by L. Kluberg and H. Satz, arXiv:0901.3831

- Cornell confining potential for qq-bar at separation distance \( r \)
  - \( \sigma=0.2 \text{ GeV}^2 \) (string tension), \( \alpha \sim \pi/12 \)

- In vacuum (\( T=0 \)), the free energy of the cc-bar is \( F_0 \) and the distance for string breaking is \( r_0 \)

- With increasing \( T \)
  - Early string break up, until reaching \( T_c \)

- In the QGP, the Debye screening radius \( r_D(T) \) decreases with increasing \( T \).
  - for \( r_D(T) < r(\text{cc-bar}) \) the system becomes unbound → suppression compared to charmonium production without QGP.

\[
V(r) = \sigma r - \frac{\alpha}{r}
\]

\[
F(r) \sim \sigma r
\]

\[
F_0 = 2(M_D - m_c) \sim 1.2 \text{ GeV};
\]

\[
r_0 \sim 1.2 \text{ GeV}/\sigma \sim 1.5 \text{ fm},
\]

\[
V(r, T) = \frac{\sigma}{\mu} \left[ 1 - e^{-\mu r} \right] - \frac{\alpha}{r} e^{-\mu r}
\]

\( r_D \sim 1/\mu \)

<table>
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<tr>
<th>state</th>
<th>( J/\psi )</th>
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</thead>
<tbody>
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<td>mass [GeV]</td>
<td>3.10</td>
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<tr>
<td>( \Delta E ) [GeV]</td>
<td>0.64</td>
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<tr>
<td>( \Delta M ) [GeV]</td>
<td>0.02</td>
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<tr>
<td>( r_0 ) [fm]</td>
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Color screening
Screening-like dissociation
Vacuum string breaking
Free energy of qq-bar pair

The screening radius can be computed using potential models or solving QCD on the lattice.

Color screening free energy
\[ F_1(T) = U(T) - T S(T) \]

\( J/\psi \) is bound by 640 MeV.

\( J/\psi \) disappears for \( T > 1.6 T_c \).