Quarkonia Results from PHENIX
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- Quarkonia & Deconfinement
- PHENIX A+A Results
- Cold Nuclear Matter (CNM)
- Production Issues
- Sequential Screening
- Regeneration
- Flow, \( <p_T^2> \) & high-\( p_T \)
- Heavier Quarkonia

PHENIX - Approx. #’s J/\( \psi \) vs Year

1/23/2009
Quarkonia & Deconfinement

For the hot-dense medium (QGP) created in A+A collisions at RHIC:
• Large quark energy loss in the medium implies high densities
• Flow scales with number of quarks
• Is there deconfinement? → look for Quarkonia screening

Debye screening predicted to destroy J/ψ’s in a QGP with other states “melting” at different temperatures due to different sizes or binding energies.

RHIC: T/T_c ~ 1.9 or higher

Different lattice calculations do not agree on whether the J/ψ is screened or not - measurements will have to tell!

Satz, hep-ph/0512217

<table>
<thead>
<tr>
<th>state</th>
<th>J/ψ(1S)</th>
<th>χ_c(1P)</th>
<th>ψ′(2S)</th>
<th>Y(1S)</th>
<th>χ_b(1P)</th>
<th>Y(2S)</th>
<th>χ_b(2P)</th>
<th>Y(3S)</th>
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<tbody>
<tr>
<td>T_d/T_c</td>
<td>2.10</td>
<td>1.16</td>
<td>1.12</td>
<td>&gt; 4.0</td>
<td>1.76</td>
<td>1.60</td>
<td>1.19</td>
<td>1.17</td>
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</table>
PHENIX Au+Au data shows suppression at mid-rapidity about the same as seen at the SPS at lower energy
• but stronger suppression at forward rapidity.
• Forward/Mid $R_{AA}$ ratio looks flat above a centrality with $N_{\text{part}} = 100$

Several scenarios may contribute:
• Cold nuclear matter (CNM) effects  
  • in any case are always present
• Sequential suppression  
  • QGP screening only of $\chi_c$ & $\psi'$-removing their feed-down contribution to $J/\psi$ at both SPS & RHIC
• Regeneration models  
  • give enhancement that compensates for screening
What CNM effects are important?  
(CNM = Cold Nuclear Matter)

Traditional shadowing from fits to DIS or from coherence models

Absorption (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers

Gluon saturation from non-linear gluon interactions for the high density at small $x$; amplified in a nucleus.

Energy loss of incident gluon shifts effective $x_F$ and produces nuclear suppression which increases with $x_F$
New Analysis of Run3 d+Au with new 2005 p+p baseline

PRC 77, 024912 (2008)

Compared to E866/NuSea p+A results & lower-energy NA3 at CERN

Not universal vs $x_2$ as expected for shadowing, but closer to scaling with $x_F$, why?
- initial-state gluon energy loss?
- gluon saturation?
Present CNM Constraints on A+A data

CNM effects (EKS shadowing + dissociation from fits to d+Au data, with R. Vogt calculations) give large fraction of observed Au+Au suppression, especially at mid-rapidity.

more accurate d+Au constraint badly needed
Mistake in extracting $\sigma_{\text{breakup}}$ vs. rapidity

- The data points, statistical and systematic uncertainties in the figure are correct.
- The one standard deviation uncertainty band for the breakup cross section contains a mistake.
- The band does not account for all the systematic uncertainties, as intended in the paper.
- Correctly including the systematic uncertainties will make the band larger.
- We expect to release corrected values soon.

\[
\tilde{\chi}^2(\epsilon_b, \epsilon_c, p) = \left[ \sum_{i=1}^{n} \frac{(y_i + \epsilon_b \sigma_y + \epsilon_c y_i \sigma_y - \mu_i(p))^2}{\bar{\sigma}_i^2} \right] + \epsilon_b^2 + \epsilon_c^2
\]
Run-6 & run-8 p+p 200 GeV data.

- Factor of **three** more data in run-6 compared to the previous run-5 p+p baseline

Run-8 d+Au 200 GeV data

- Factor of **thirty** more data in run-8 compared to the previous run-3 d+Au
- Constrain the CNM effects present in HI collisions to make un-ambiguous statements about anomalous suppression.
- The statistics are there! **Main Focus** is on reducing systematics.

\[ J/\psi \rightarrow \mu^+\mu^- \]

\[ J/\psi \rightarrow e^+e^- \]
Quarkonia Production is Also an Issue
Let's look at p+p Collisions
Quarkonia Production is Also an Issue

- gluon fusion dominates
- but is $c\bar{c}$ produced in a color-singlet or -octet state?
  - important for CNM effects
- difficult to get both absolute cross section & polarization correct
  - singlet models under-predict cross sections
  - octet models get cross section but predict transverse polarization at large $p_T$
    - but small longitudinal polarization was seen ($E866$, CDF)
  - recently a new singlet model seems to get both correct ($Haberzettl, Lansberg, PRL 100, 032006 (2008)$)
- Latest PHENIX data starting to define rapidity dependence
\[ \lambda = +1 \text{ (transverse)} \]
\[ = -1 \text{ (longitudinal)} \]

- Octet models get correct cross section size (unlike singlet), but...
- CDF and Fermilab E866 J/\( \psi \) data show little polarization & disagree with NRQCD predictions

And \( \Upsilon \) maximally polarized for (2S+3S), but NOT (1S)
* Is feed-down washing out polarization? (~40% of 1S from feed-down)
(\( \psi' \) polarization measurement would be helpful here but is very experimentally challenging)
$J/\psi$ polarization at mid-rapidity in PHENIX vs $p_T$

Probably most interesting at the highest $p_T$ (2-5 GeV/c) since this is where theoretical models predict non-zero polarization.
J/ψ Polarization at forward rapidity in PHENIX

Forward rapidity measurement with dimuons gives zero polarization with large uncertainties, and presently is unable to study vs $p_T$.

$\begin{align*}
\lambda &= -1 \text{ longitudinal} \\
\lambda &= +1 \text{ transverse}
\end{align*}$
J/ψ polarization at in PHENIX vs $p_T$

- Small polarization at mid-rapidity seems consistent with s-channel cut theory
- but at forward rapidity data smaller than prediction

(Singlet model with s-channel cut; does not include effect of feeddown from $\chi_c$ & $\psi'$)
Complications due to substantial feed-down from higher mass resonances ($\psi', \chi_c$)

J/$\psi$ from $\psi'$

$8.6 \pm 2.5\%$

Also measured $B \rightarrow J/\psi - 4^{+} \pm 3^{-}_{2}\%$

Nuclear dependence of (parent) resonance, e.g. $\chi_c$ is probably different than that of the J/$\psi$

Also measured $B \rightarrow J/\psi - 4^{+} \pm 3^{-}_{2}\%$

(but will be strongest at high-$p_T$)
New invariant yield measurement from larger luminosity Run-6 agrees with published results!

\[ \frac{d\sigma_{J/\psi}}{dy} \bigg|_{|y|<0.35} = 45.3 \pm 1.0 (\text{stat}) \pm 5.4 (\text{sys}) \pm 4.5 (\text{global}) \text{ nb} \]

\[ B_{J/\psi \to e^+ e^-} \sigma_{J/\psi} \bigg|_{|y|<0.35} (p_T < 7 \text{ GeV/c}) = 41.0 \pm 0.9 (\text{stat}) \pm 4.9 (\text{sys}) \text{ nb} \]
$\psi'$ vs $p_T$ in $p+p$ collisions at mid-rapidity

Within uncertainties $\psi'/(J/\psi)$ agrees with HERA-B & E789 measurements
- with $(BR^*\psi')/(BR^*J/\psi) = 1.9\%$

$BR^*\sigma_{\psi'}(p_T < 7\text{ GeV/c, } |y|<0.35) = 0.88 \pm 0.30/-0.20 \pm 0.12 \text{ nb}$

$<0.38 \text{ 90\% CL}$
And Now back to A+A and the QGP - consider two scenarios

\[ \chi_0 (0.56 \text{ fm}) \]
\[ \psi (0.56 \text{ fm}) \]
\[ \lambda_0 \text{ Debye length from lattice QCD} \]
\[ J/\psi (0.29 \text{ fm}) \]
\[ \rho (0.13 \text{ fm}) \]

\[ 0 \]
\[ 0.1 \]
\[ 0.2 \]
\[ 0.3 \]
\[ 0.4 \]
\[ 0.5 \]
\[ 0.6 \]

\[ 1 \]
\[ 1.5 \]
\[ 2 \]
\[ 2.5 \]
\[ 3 \]
\[ 3.5 \]
\[ 4 \]
\[ 4.5 \]

\( T/T_c \)
QGP Effects on Quarkonia
Sequential Screening and Gluon Saturation

Some recent lattice calculations suggest $J/\psi$ not screened at all

- suppression then comes only via feed-down from screened $\chi_c$ & $\psi'$

- then the situation would be the same at lower energies (NA38/50/60) as for RHIC mid-rapidity

- and the stronger suppression at forward rapidity at RHIC could come from, e.g., gluon saturation

- But can this picture explain flat forward/mid-rapidity $R_{AA}$ super-ratio?
QGP effects on Quarkonia
Regeneration - Compensating for Screening

- larger gluon density at RHIC expected to give stronger suppression than SPS
- but larger charm production at RHIC gives larger regeneration
- forward rapidity lower than mid due to smaller open-charm density there
- very sensitive to poorly known open-charm cross sections
  - Vertex upgrades will help here

- expect inherited flow from open charm
- regeneration would be HUGE at the LHC!
- can the two compensating components (screening & regeneration) which may have diff. centrality dependences, give a flat forward/mid-rapidity $R_{AA}$?
QGP effects on Quarkonia - $p_T$ Broadening

- AA data same as pp & relatively flat with centrality
- CNM effects broaden $p_T$
  - initial-state mult. scatt. for both gluons
- but regeneration should narrow $p_T$ (compensates for above?)
  - square of small-$p_T$ peaked open-charm cross section
How does the QGP affect Quarkonia? $J/\psi$ flow

$J/\psi$'s from regeneration should inherit the large charm-quark elliptic flow

- also need to measure open-charm flow at forward rapidity

This is a first measurement, at both mid and forward rapidity.

Very limited statistics so that no strong conclusion can be drawn.

Need more data, and detector upgrades.
Reaching Higher $p_T$ for $J/\psi$ - probing for the “hot wind”?

New PHENIX $R_{CuCu}$ out to $p_T = 9$ GeV/c !
• shows large suppression that looks roughly constant up to high $p_T$
• STAR points with their huge uncertainties were misleading

AdS/CFT (“hot wind”) - more suppression at high $p_T$:
  Liu, Rajagopal, Wiedemann
  PRL 98, 182301(2007)

Regeneration (2-component):
  Zhao, Rapp
  hep-ph/07122407
  & private communication

Equilibrating Parton Plasma:
  Xu, Kharzeev, Satz, Wang,
  hep-ph/9511331

Gluonic dissoc. & flow:
  Patra, Menon, nucl-th/0503034

Cronin - less suppression at higher $p_T$:
  use d+Au data as a guide
**PHENIX & STAR Preliminary \( \Upsilon \) p+p Cross Sections**

**Graphs:**
- **PHENIX Preliminary p+p QM05 \( \Upsilon \rightarrow \mu\mu \)**
- **STAR Preliminary d+Au \( \mu^+\mu^- \)**
- **PHENIX Preliminary \( \Upsilon \rightarrow \mu\mu \)**

**Images:**
- **1st Upsilons at RHIC**
- **Upsilons from Run8 d+Au? (online spectrum)**

**Text:**
- **PHENIX & STAR Preliminary \( \Upsilon \) p+p Cross Sections**
- **1st Upsilons at RHIC**
- **Upsilons from Run8 d+Au? (online spectrum)**

**Date:**
1/23/2009
Pushing J/ψ to higher-p_T:

- PHENIX Preliminary
- Centrality 0-94%
- 200 GeV Cu+Cu J/ψ
- Run 5+6 pp ref
- STAR Cu+Cu(90-60)%pp

Better CNM baseline coming from Run8!

Sequential screening & gluon saturation:

flow from regeneration is difficult to see:
Backup Slides
How does the QGP affect Quarkonia?

**CNM Effects**

CNM effects (EKS shadowing + dissociation) give large fraction of observed AuAu suppression, especially at mid-rapidity.

Normal CNM descriptions give similar AuAu suppression at mid vs forward rapidity:
- but if peaking in “anti-shadowing” region were flat instead then one would get larger suppression for forward rapidity as has been observed in AuAu data.
- could come from gluon saturation or from a shadowing prescription that has no anti-shadowing.

*In any case more accurate dAu data is sorely needed.*
Nuclear Dependence Nomenclature – Ratio \( R_{dAu}, R_{AA} \) and Alpha (\( \alpha \))

\[ R_{dAu} = \alpha = 1 \] if every N-N collision in a Nucleus contributes as if it were in a free nucleon

\[
R_{dAu} = \frac{d\sigma^{dAu}/dy}{2 \times 197 \cdot (d\sigma^{pp}/dy)}
\]

\[
= \frac{dN^{dAu}/dy}{\langle n_{\text{coll}}^{dAu} \rangle dN^{pp}/dy}
\]

\( <n_{\text{coll}}^{dAu}> \) from Glauber model calc. – can also be used for centrality bins

Where \( dN^{dAu}/dy \) is an invariant yield w/o absolute normalization factors that would be needed for a cross section (lower systematical uncertainties)

Alternatively, a power law with \( \alpha \) - especially useful when comparing expts that used different nuclear targets

\[
\sigma_{pA} = \sigma_{pp} A^{\alpha}
\]

\[
\alpha = 1 + \ln\left( R_{pA} \right)/\ln(A)
\]
Transverse Momentum Broadening
Another Cold Nuclear Matter Effect

Initial-state gluon multiple scattering causes $p_T$ broadening (or Cronin effect)

$$\sigma_A = \sigma_N A^\alpha$$

PHENIX 200 GeV dAu shows some $p_T$ broadening, but may be flatter than at lower energy ($\sqrt{s}=39$ GeV in E866/NuSea)
# Recent Quarkonia Yields in PHENIX & STAR

<table>
<thead>
<tr>
<th>Run</th>
<th>species</th>
<th>Expt.</th>
<th>Lumi</th>
<th>$p_T$</th>
<th>J/ψ ee</th>
<th>J/ψ μμ</th>
<th>Ψ ee</th>
<th>Ψ μμ</th>
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<tr>
<td>2005</td>
<td>pp</td>
<td>PHENIX</td>
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<td>400</td>
<td>1250</td>
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<td></td>
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<tr>
<td></td>
<td>CuCu</td>
<td>PHENIX</td>
<td>3 nb⁻¹</td>
<td></td>
<td>2k</td>
<td>9k</td>
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<tr>
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<td></td>
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<td>STAR</td>
<td>0.4 pb⁻¹</td>
<td>~150</td>
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<td></td>
<td>11 pb⁻¹</td>
<td>&gt; 4</td>
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<td>9 pb⁻¹</td>
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<td>0.3 nb⁻¹</td>
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Reaching Higher $p_T$ for $J/\psi$ - probing for the “hot wind?”

Approximate ratios by combining PHENIX & STAR data reach higher $p_T$ & appear to be consistent with $R_{AA}=0.9\pm0.2$ at high $p_T$
• but also consistent with lower $p_T$ data at $R_{AA} = 0.52$
• & regeneration models
• & rough projection from d+Au
• but not with gluon dissociation + flow (Patra, nucl-th/0503034 2005)

Most models expect a decrease in $R_{AA}$ at high $p_T$:
AdS/CFT (“hot wind”):
H. Liu, K. Rajagopal and U.A. Wiedemann, PRL 98, 182301(2007) and hep-ph/0607062
Regeneration (2-component):
X. Zhao and R. Rapp, hep-ph/07122407
Private communication
EPS08 (Strong) Shadowing
Eskola, Paukkunen, Salgado, hep-ph 0802.0139v1

Fit includes RHIC (Brahms) forward hadron data (as well as the usual DIS and DY data)
$R_{AuAu}$ vs $R_{CuCu}$

$CuCu$ provides more accurate $R_{AA}$ at smaller $N_{part}$, but within errors confirms the trends seen in $AuAu$ in that region.

$R_{AA}(y\sim1.7)/R_{AA}(y\sim0)$
New results from Run7 AuAu data

Preliminary analysis of new Run7 AuAu forward rapidity (dimuon) J/ψ data (black points) is consistent with published results (blue points) from Run4
Ratios vs $p_T$ for d+Au and Au+Au