Recent Quarkonia results by PHENIX

Disclaimer: this is not a review of all the results

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The historical introduction, Quarkonia as QGP probes

- **Goal:** Study QCD matter under extreme conditions (QGP)
- **1986, Matsui Satz**
  - **Dissociation in a QGP**
  - Example: by color screening, based on IQCD calculations that predict sequential states dissociation

<table>
<thead>
<tr>
<th></th>
<th>$J/\psi(1S)$</th>
<th>$\chi_c(1P)$</th>
<th>$\psi'(2S)$</th>
<th>$\Upsilon(1S)$</th>
<th>$\chi_c(1P)$</th>
<th>$\Upsilon'(2S)$</th>
<th>$\chi_c(2P)$</th>
<th>$\Upsilon''(3S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$ [GeV]</td>
<td>3.10</td>
<td>3.41</td>
<td>3.60</td>
<td>9.46</td>
<td>9.86</td>
<td>10.02</td>
<td>10.23</td>
<td>10.36</td>
</tr>
<tr>
<td>$E_s$ [GeV]</td>
<td>0.84</td>
<td>0.20</td>
<td>0.05</td>
<td>1.10</td>
<td>0.67</td>
<td>0.54</td>
<td>0.31</td>
<td>0.20</td>
</tr>
<tr>
<td>$T_d/T_c$</td>
<td>2.1</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>
</tr>
</tbody>
</table>

**Cartoons just for illustration**

cf Friday talks

[Satz, JPG 32 R25 (2006)]
Quarkonia menu by PHENIX

- Absence of medium effects, p+p coll.
  - Production processes ($J/\psi, \psi', \Upsilon$)
  - Feed-down contributions ($\psi', \chi_c, B$)

- Cold Nuclear environment, d+Au coll. ($J/\psi$)
  - Nuclear PDFs
  - Gluon saturation
  - Nuclear absorption

- Hot Nuclear environment, Au+Au coll. ($J/\psi$)
  - Quarkonia could be suppressed
    - Color screening
    - Gluon Saturation
    - Comovers
    - … or regenerated

Talk outline:

- $J/\psi$ & $\psi'$ in p+p collisions
  - Production processes, polarization, feed-down
- $J/\psi$ ultra-peripheral Au+Au collisions
  - Production processes, shadowing
The PHENIX Experiment

\[ J/\psi \rightarrow e^+ e^- , \psi' \rightarrow e^+ e^- \]
\[ \chi_c \rightarrow \gamma e^+ e^- \]

- Tracking: Drift & Pad Chambers
- Electrons identified by the RICH & EmCal
- \(|\eta| < 0.35\)
- \(p_t^e > 0.2\) GeV/c
- \(\Delta\phi = 2\times90^\circ\)

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

- Front absorber
- Tracking: Cathode Strip Chambers
- Trigger: Iarocci tubes
- \(1.2 < |\eta| < 2.4\)
- \(p_t^\mu > 2\) GeV/c
- \(\Delta\phi = 2\times90^\circ\)
Quarkonia production processes: \(J/\psi\) polarization, \(\psi'\) and feed-downs

p-p collisions at 200 GeV
Understanding the production mechanisms

- At RHIC the predominant process is gluon fusion

- Multiple model descriptions:
  - CEM predicts no polarization
  - COM predicts transverse polarization ($\alpha > 1$) increasing with $p_t$
    - Contradicted by Tevatron data
  - CSM at NNLO* seems to reproduce $\Upsilon$ Tevatron spectra
    - Unclear for $J/\psi$

- Models have difficulties to reproduce quarkonia cross-section, $p_t$ shape, and polarization as a whole.

[CDF, PRL 99: 132001 (2007)]
**J/ψ production at 200 GeV**

- PHENIX measures the \( p_t \) & rapidity dependence
- PHENIX & STAR cross-sections agree and are compatible with CEM, COM

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### POLARIZATION IN THE HELICITY FRAME

\[
dN / d \cos \theta = A ( 1 + \lambda \cos^2 \theta )
\]

### RESULTS, INTEGRATED OVER PT:

- **Forward rapidity:** \( \lambda = 0.05^{+0.160}_{-0.186} \)
- **Mid-rapidity:** \( \lambda = -9.6 \pm 7.2 \pm 3.9 \%

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J/ψ data-theory confrontation

- CSM model including a s-channel cut fits PHENIX J/ψ p_t dependence
  - CSM at LO plus s-channel cut fits to reproduce J/ψ Tevatron
- Mid-rapidity polarization measurements seem in agreement with this model
- But it underestimates forward-rapidity polarization
- What is up?
  - Is it a matter of \( χ_\text{c} \) & \( ψ' \) feed-down contributions?
  - Are higher order contributions needed?
- \( ψ' \) polarization measurement is challenging

[ PHENIX Coll. Preliminary 2008]
ψ' measurement at PHENIX

- ψ' → e⁺ e⁻ at mid-rapidity

\[ B_{\psi'\rightarrow e^+e^-} = 0.88^{+0.30}_{-0.20} \, \text{(stat)} \pm 0.12 \, \text{(sys)} \, \text{nb} \]

- ψ' over J/ψ ratio
  \[ \left( \frac{BR\sigma(\psi')} {BR\sigma(J/\psi)} \right) = 1.9 \pm 0.5 \pm 0.2 \% \]
  - Compatible with HERA-B and E789 measurements

[PHENIX Coll. Preliminary 2008]
Measurement of feed-down contributions

- **J/ψ from ψ’**: 8.6 ± 2.5 % via ψ’ → e e

- **J/ψ from χ_c** < 42 % with 90% C.L. via χ_c → ψ + γ

- **J/ψ from B = 4 +3_-2 %**

[PHENIX preliminary, Quark Matter 2008]
Studying $J/\psi$ & $e^+e^-$ photo-production

Ultra-peripheral Au-Au collisions at 200 GeV

\[ b > 2R \]
Ultra-Peripheral Collisions

- Ultra-Peripheral Collisions (UPC), $b > 2R$:
  - Electromagnetic field of UR particle $\approx$ photon flux with continuous energy
  - Possibility to study $\gamma\gamma$ & $\gamma A$ interactions
  - How? Via dilepton & vector meson production

- Why?
  - Test QED on a strongly interacting regime
  - Low-$x$ $(10^{-2})$ gluon PDFs, QQbar propagation in Cold Nuclear Matter


\[ \text{(Balz et al, P.R.L.89 012301 (2002) + private comm.)} \]
\[ \text{[J.Nystrand, NPA752 (2005) 470]} \]
\[ \text{[Baur et al, N.P.A729 787 (2003)]} \]
Paper released last week!

- Observed 28 $e^+e^-$ and no like-sign pairs in $m_{ee}>2.0$ GeV/c$^2$
- Continuum subtracted by theoretical basis (MC+detector response)
  
  $9.9 \pm 4.1$ (stat) $\pm 1.0$ (syst) $J/\psi$
  
  $13.7 \pm 3.7$ (stat) $\pm 1.0$ (syst) $e^+e^-$ in $m_{ee}[2.0,2.8]$ GeV/c$^2$

| $m_{e^+e^-}$ [GeV/c$^2$] | $d^2\sigma/dm_{e^+e^-}dy|_{y=0}$ [\mu b/(GeV/c$^2$)] | $d\sigma/dy|_{y=0}$ [\mu b] |
|--------------------------|-------------------------------------------------|--------------------------|
| $e^+e^-$ continuum [2.0,2.8] | $86 \pm 23$ (stat) $\pm 16$ (syst) | $76 \pm 31$ (stat) $\pm 15$ (syst) |
| $e^+e^-$ continuum [2.0,2.3] | $129 \pm 47$ (stat) $\pm 28$ (syst) | $13.7 \pm 3.7$ (stat) $\pm 1.0$ (syst) |
| $e^+e^-$ continuum [2.3,2.8] | $60 \pm 24$ (stat) $\pm 14$ (syst) | $9.9 \pm 4.1$ (stat) $\pm 1.0$ (syst) |

Compatible with QED calculations & consistent with e-p and p-p results.

[PHENIX, arXiv: 0903.2041, submitted to PLB]
[D.d’Enterria et al, nucl-ex/0601001 (2005)]
Comparison to theoretical predictions $J/\psi$ UPC

- Measured $p_t$ spectra suggests both of coherent ($\gamma A$) and incoherent ($\gamma N$) $J/\psi$ production
- Cross-section is consistent with different model predictions
- ... though current precision precludes any detailed conclusion on the basic ingredients: shadowing and nuclear absorption
- Rough comparison is consistent with HERA data $\sigma_{\gamma p} = A^\alpha \sigma_{\gamma A} \rightarrow \alpha \sim 1$
Summary

- **J/ψ production** has been studied (among others) in p-p collisions
  - $p_t$ and rapidity dependence start to be defined
  - Polarization rapidity and $p_t$ dependence are calculated
  - Results are compatible (within uncertainties) with predictions

- **ψ’ & χc** have been detected at mid-rapidity in p-p collisions
  - ψ’ $p_t$ spectra is drawn
  - Feed-down contribution to J/ψ are computed
  - Results are in agreement with world data and theoretical calculations

- **J/ψ & e⁺e⁻** have been observed in ultra-peripheral Au-Au collisions
  - Dielectron production cross-sections is consistent with QED calculations
  - J/ψ production cross-section is compatible with different model predictions but precludes yet detailed conclusions on CNM effects

- Those measurements are crucial as a baseline, to understand the cold nuclear matter effects present in the most central heavy-ion collisions, and so to study the QGP.
Backup slides
The PHENIX Central Arm
Rencontres de Moriond, March 2009

**J/ψ production at 200 GeV**

- PHENIX measures the $p_t$ & rapidity dependence
- PHENIX & STAR cross-sections agree and are compatible with CEM, COM

![Graph showing $p+p \rightarrow J/\psi$ with $|y|<0.35$, $\sqrt{s} = 200$ GeV](image)

![Graph showing $dN/d(\cos(\theta))$ for $0 < p_t < 6$ GeV](image)

**What about polarization?**

\[ \frac{dN}{d\cos(\theta)} = A (1 + \lambda \cos^2(\theta)) \]

- Measurement in the helicity frame
- Forward rapidity results:
  - Gives zero polarization
    \[ \lambda = 0.05^{+0.160}_{-0.186} \]
  - Integrated over $pt$

\[ B_{ll} \cdot \sigma_{pp}^{J/\psi} = 178 \pm 3^{\text{stat}} \pm 53^{\text{sys}} \pm 18^{\text{norm}} \text{nb} \]


- **Note that $\lambda = \alpha$ !**
**J/ψ polarization at mid-rapidity**

- At mid-rapidity there is a $p_t$ dependent polarization measurement!
- Though with big uncertainties
- More interesting at high $p_t$, where the theoretical predictions differ

$\lambda < 0$ longitudinal

$\lambda > 0$ transverse  

[M. Donadelli @ PANIC 2008]

\[ p_t \in (0,5)\text{GeV/c} \rightarrow \lambda = -9.6 \pm 7.2 \text{ (stat)} \pm 3.9 \text{ (syst)} \% \]
J/ψ polarization at mid-rapidity

- Pt dependent measurement
- Big uncertainties
- More interesting at high pt
S-channel cut model

- Adding s-channel cut contributions to the typical CSM models
- Adapt model parameters to fit J/ψ Tevatron data
- Extrapolation to PHENIX measurements is in good agreement.
- Advice: J/ψ polarisation is affected by feed-down contributions

Some plots

Transverse momentum $p_T$ (GeV/c)

$J/\psi$ $p+p$ Cross Section vs Energy

Some plots

CDF Coll. PRL 99, 132001 (2007)
J/ψ photo-production at CDF