Experimental Status of $J/\psi$ measurements in nucleus-nucleus collisions

A. Marín
Index

- Introduction: J/ψ properties, discovery
- Experimental results: SPS, RHIC
- Outlook: $v_2$, LHC
\(J/\psi\) properties (PDG2006)

\(J/\psi\) (1S)

\[
m = 3096.916 \pm 0.011 \text{ MeV}
\]

\[
\Gamma = 93.4 \pm 2.1 \text{ KeV}
\]

decays: \[
BR(e^+e^-) = (5.94 \pm 0.06)\%
\]

\[
BR(\mu^+\mu^-) = (5.93 \pm 0.06)\%
\]

hadrons: 87.7 %
J/ψ discovery (1974)

\[ e^+e^- \rightarrow \text{hadrons} \]

\[ e^+e^- \rightarrow e^+e^- \]

\[ e^+e^- \rightarrow \mu^+\mu^-, \pi^+\pi^-, K^+K^- \]


Quarkonia

  - color screening in deconfined matter $\rightarrow J/\psi$ suppression = “smoking gun”

- experimental & theoretical progress since then
  $\rightarrow$ story is much more complicated
  - cold nuclear matter / initial state effects
    - “normal” absorption in cold matter
    - (anti)shadowing
    - saturation, color glass condensate
  - suppression via comovers
  - feed down from $\chi_c$, $\psi'$
  - sequential screening (first: $\chi_c$, $\psi'$, $J/\psi$ only well above $T_c$)
  - regeneration via statistical hadronization or charm coalescence
    - relevant for “large” charm yield, i.e. RHIC and LHC
Main Experimental results

- **SPS**
  - **NA38, NA50:**
    - Phys. Lett. B 270 (1991) 105 (0+Cu,O+U)
  - **NA60:**
- **RHIC**
  - **PHENIX:**
    - nucl-ex/0801.0220v1 (Cu+Cu) (...

Multistep fit to extract the 4 signal contributions:
J/ψ, ψ', Drell-Yan, Open charm

Departure from normal nuclear absorption curve for central collisions
Results from p-A and Pb-Pb

- Absorption in cold nuclear matter (p-A) can explain S-U data
- Anomalous suppression sets in for semi-peripheral Pb-Pb collisions

But
- p-A data taken in a different energy/kinematic range
- Is there anomalous suppression for systems lighter than Pb-Pb?
Models without regeneration

Models that reproduce NA50 results:

- **Satz** - color screening in QGP (percolation model) with CNM added (EKS shadowing + 1 mb)
- **Capella** - comovers with normal absorption and shadowing
- **Rapp** - direct production with CNM effects (without regeneration)
NA60 experiment

Muon trigger and tracking
NA10/38/50 spectrometer

2.5 T dipole magnet

Matching in coordinate and momentum space

beam tracker

vertex tracker

targets

hadron absorber

ZDC

Iron wall

— Muon
— Other

magnetic field

2.5 T dipole magnet

Muon trigger and tracking
• Obtain ratio of charmonia production to Drell-Yan (à la NA50)

• Kinematic region
  - $0 < y_{CM} < 1$
  - $-0.5 < \cos \theta_{CS} < 0.5$

• Acceptances
  - $J/\psi$: 0.156
  - $\psi'$: 0.173
  - $D\gamma$ ($2.9 < m_{\mu\mu} < 4.5$): 0.150
Results and systematic errors

Small statistical errors

Careful study of systematic errors is needed

- Sources
- Uncertainty on normal nuclear absorption parameters ($\sigma^{\text{abs}}(J/\psi)$ and $\sigma^{\text{pp}}(J/\psi)$)
- Uncertainty on relative normalization between data and absorption curve
- Uncertainty on centrality determination (affects relative position of data and abs. curve)
  - Glauber model parameters
  - $E_{\text{ZDC}}$ to $N_{\text{part}}$

- $\sim 10\%$ error centrality indep. → does not affect shape of the distribution
- Partly common to analyses a and b
- (Most) Central points affected by a considerable error
Comparison with previous results (vs $N_{\text{part}}$)

- **NA50**: $N_{\text{part}}$ estimated through $E_T$ (left), or $E_{\text{ZDC}}$ (right, as in NA60)
- Good agreement is observed
$(J/\psi)/DY$ at 158 GeV

$\langle (J/\psi)/DY \rangle = 29.2 \pm 2.3$

$\langle L \rangle = 3.4$ fm

$\exp(-\sigma_{abs} \rho_0 L)$

Preliminary NA60 result shows that the rescaling of the $J/\psi$ production cross section from 450(400) GeV to 158 GeV is correct!
Transverse momentum distributions

Kinematical region
0.1 < y_{CM} < 0.9
-0.4 < \cos \theta_H < 0.4

Transverse momentum distributions fitted with

\[ \frac{1}{p_T} \frac{dN}{dp_T} = e^{-m_T/T} \]

- Study evolution of T and \( \langle p_T^2 \rangle \) with centrality
\( \langle p_T^2 \rangle \) vs centrality

- If \( p_T \) broadening is due to gluon scattering in the initial state
  \[ \langle p_T^2 \rangle = \langle p_T^2 \rangle_{pp} + \alpha_{gN} \cdot L \]

- NA60 In-In points are in fair agreement with Pb-Pb results

- We get
  \[ \alpha_{gN}^{\text{InIn}} = 0.067 \pm 0.011 \text{ (GeV/c)}^2/\text{fm} \]
  \[ \langle p_T^2 \rangle_{pp}^{\text{InIn}} = 1.15 \pm 0.07 \text{ (GeV/c)}^2 \]
  \[ \chi^2/\text{ndf} = 0.62 \]
  
  to be compared with
  \[ \alpha_{gN}^{\text{PbPb}} = 0.073 \pm 0.005 \text{ (GeV/c)}^2/\text{fm} \]
  \[ \langle p_T^2 \rangle_{pp}^{\text{PbPb}} = 1.19 \pm 0.04 \text{ (GeV/c)}^2 \]
  \[ \chi^2/\text{ndf} = 1.22 \]

(NA50 2000 event sample)
Fitting functions

1) \( \frac{dN}{dp_T} = p_T \ m_T \ K1(m_T/T) \)
2) \( \frac{dN}{dp_T} = p_T \ e^{-mT/T} \)

- Used by NA50
- Gives slightly higher \( T \) values (~ 7 MeV)
J/ψ rapidity distributions

- Data are consistent with a gaussian rapidity distribution
- Centrality independent
- Slightly narrower at high $p_T$?
Azimuthal distribution of the J/ψ

More peripheral data → hint for a non isotropic emission pattern?
Only 50% of the statistics analyzed
Comparison with theoretical predictions

- Suppression by hadronic comovers ($\sigma_{co} = 0.65$ mb, tuned for Pb-Pb collisions)
- Dissociation and regeneration in QGP and hadron gas
- Percolation, with onset of suppression at $N_{part} \sim 140$

- Size of the anomalous suppression reasonably reproduced
- Quantitative description not satisfactory
$J/\psi$ Production from the PHENIX Experiment@RHIC
PHENIX Detector

\[ J/\psi \rightarrow e^+ e^- \]
\[ p > 0.2 \text{GeV/c} \]
\[ |\eta| < 0.35 \]
\[ \Delta \phi = \pi \]

\[ J/\psi \rightarrow \mu^+ \mu^- \]
\[ p > 2 \text{GeV/c} \]
\[ 1.2 < |y| < 2.2 \]
\[ \Delta \phi = 2\pi \]
Signal Extraction

Mid-Rapidity: $|y| < 0.35$

Like Sign Subtraction

PHENIX
p+p 200GeV

Forward Rapidity: $1.2 < |y| < 2.2$

Event Mixed Background Subtraction
Mass plots

Run-2 p+p $e^+e^-$
Run-2 p+p $\mu^+\mu^-$
Run-2 Au+Au $e^+e^-$
Run-2 Au+Au $\mu^+\mu^-$
Run-3 d+Au $e^+e^-$
Run-3 d+Au $\mu^+\mu^-$
Run-3 p+p $e^+e^-$
Run-3 p+p $\mu^+\mu^-$
Run-4 Au+Au $e^+e^-$
Run-4 Au+Au $\mu^+\mu^-$
Run-5 p+p $e^+e^-$
Run-5 p+p $\mu^+\mu^-$
Run-5 Cu+Cu $e^+e^-$
Run-5 Cu+Cu $\mu^+\mu^-$

$J/\psi$ mass: $3.097 \text{ GeV}/c^2$
$J/\psi \to e^+e^-: BR 5.94 \pm 0.06\%$
$J/\psi \to \mu^+\mu^-: BR 5.93 \pm 0.06\%$

Measured $\sim 30k J/\psi$ by Run-5.
Production in p+p Collisions

\[ f(p_T) = p_0 \left[ 1 + \left( \frac{p_T}{p_1} \right)^2 \right]^{-6} \]

or from data

- \( p_T \) spectrum mapped from 0-9 GeV/c
- Ratio of \( p_T \) distributions shows a softening at forward rapidity

PRL 98 (2007) 232002
Cross Section Model Comparisons

Comparison with theory allows differentiation among the available $J/\psi$ production mechanisms.

Many calculations are inconsistent with the steepness of the slope at forward rapidity and the slight flattening observed at mid-rapidity.

PHENIX acceptance covers 92% of integrated cross section

$$B_{ll}^* \sigma_{pp}(J/\psi) = 178 \pm 3 \pm 53 \pm 18 \text{ nb}$$
J/ψ Production in Au+Au Collisions

- Shape of rapidity dependence of J/ψ yield narrows slightly as a function of centrality
- No difference observed between peripheral Au+Au and p+p distributions
- Sharp rapidity narrowing predicted by recombination models not present
J/ψ Production in Au+Au Collisions

\[ R_{AB} = \frac{N_{\psi}^{AB}}{N_{\psi}^{PP} \times \langle N_{\text{coll}} \rangle} \]

Flat \(R_{AA}\) for \(N_{\text{part}} < 100\)

\(R_{AA}-p_T\) of model predictions?
**$R_{AA}$-rapidity**  
**Au+Au data**

- Flat $R_{AA}$ for $N_{\text{part}} < 100$.
- Rapidity narrowing in central Au+Au collisions
  - (Modest) Recombination?
    - $N_{\text{rec}}^{J/\psi} \propto N_{c}^{2}$
    - Color Glass Condensate?
  - Measurement of $J/\psi$ elliptic flow can make clear the origin of rapidity narrowing.

---

SCM : A.Andronic et al., nucl-th/0701079.
\(J/\psi\) at RHIC: \(R_{AA}\) vs \(N_{\text{PART}}\) \(y\)-dependence

- \(p+p\) ref. and \(Au+Au\) data
  - rapidity and \(p_T\) spectra challenge for production models
- **more suppression at forward rapidity!**
  - opposite to trend from co-mover or CNM absorption
    - more co-movers at \(y\approx0\)
  - suppression not only driven by local particle density
  - more regeneration at \(y\approx0\)?
  - gluon saturation at forward \(y\)?

- models
  - no clear picture yet, but important new constraints
  - two (or more) ingredients needed to describe suppression pattern
    - suppression + regeneration
    - sequential dissociation + saturation
Direct comparison to SPS

- J/ψ were also measured in HICs at SPS
  - S+U (NA38), Pb+Pb (NA50) and In+In (NA60), fixed target (√s_{NN} \sim 20\text{GeV})

- Comparing RHIC and SPS is delicate
  - Factoring out CNM effects (not same at SPS/RHIC)
  - \( R_{AA} \) (y~0) \sim R_{AA} \) (SPS)
    - Not what’s expected from √s_{NN,SPS} < √s_{NN,RHIC}
    - Rapidity ranges not same
      - 0 < y_{sps} < 1
    - Big error bars on RHIC data points
    - ~10% normalization error at SPS

Err. Glo = 7%
Err. Glo = 12%

Scomparin (proc. QM06) : nucl-ex/0703030
\( N_{\text{part}} \)
Models that reproduce NA50 results at lower energies (above):

- Satz – color screening in QGP (percolation model) with CNM added (EKS shadowing + 1 mb)
- Capella – comovers with normal absorption and shadowing
- Rapp – direct production with CNM effects (without regeneration)

But predict too much suppression for RHIC mid-rapidity (at right)!
Clear signal for generation of charmonia due to statistical hadronization at the phase boundary
**J/ψ** Production in d+Au Collisions

1.4 nb⁻¹, 1.7 nb⁻¹

-2.2 < y < -1.2

±4% Global Scale Uncertainty

<table>
<thead>
<tr>
<th>y</th>
<th>0.35</th>
</tr>
</thead>
<tbody>
<tr>
<td>J/ψ Invariant Yield</td>
<td></td>
</tr>
</tbody>
</table>

1.2 < y < 2.2

±4% Global Scale Uncertainty

<table>
<thead>
<tr>
<th>p_T (GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>y</th>
<th>0.35</th>
</tr>
</thead>
<tbody>
<tr>
<td>J/ψ Invariant Yield</td>
<td></td>
</tr>
</tbody>
</table>

New and old analysis are compatible
$J/\psi$ in d+Au: Cold Nuclear matter effects

Statistically significant suppression
$\sigma_{\text{breakup}}$ consistent with values at SPS
CNM effects: extrapolation to Cu+Cu, Au+Au

Non suppression beyond CNM effects

d+Au data set with much improved statistical precision is needed!
Data driven Extrapolation of CNM effects to Au+Au

A d+Au data set with much improved statistical precision is needed!

Larger range of CNM effects than previous model
J/ψ in Cu+Cu (nucl-ex / 0801.0220v1)

$\langle p_T^2 \rangle$ Independent of $N_{\text{part}}$ for Cu+Cu

Agree with Au+Au
**J/ψ in Cu+Cu** (nucl-ex/ 0801.0220v1)

No-pt dependence
Similar behaviour forward-midrapidity

Same behaviour Cu+Cu/Au+Au@ ~$N_{\text{part}}$
Prospects

- J/ψ flow: promising test of regeneration
  - Elliptic flow: collective phenomenon, transforms initial spatial anisotropy of collision region into momentum anisotropy
  - Electrons from c and b quark meson decays have been observed with nonzero elliptic flow
  - If regeneration takes place, J/ψ elliptic flow should show similar trend

Expected resolution of J/ψ $v_2$ with 2007 data: QM2008 !?
BACKUP
Au+Au mid rapidity data

- None reproduce RHIC data both at mid and forward rapidity well.
- Relatively large errors in data at RHIC.
- Relatively large variations in model predictions for RHIC.

Data and models at SPS

- **Orange solid**: HSD,
  E.L. Bratkovskaya et al.,
  PRC 71, 044901 (2005).
- **Blue**: co-mover,
  A. Capella and E.G. Ferreiro
- **Orange dashed**: SCM,
  A. Andronic et al., nucl-th/0701079.
- **Magenta**: recombination,
J/ψ Production

**p+p Collisions**
- **Production Mechanism:**
  - cc pairs predominantly generated in hadronic collisions via gluonic diagrams
  - Details of hadronization process remain unclear

---

Color Singlet Model

Color Octet Model

pQCD with 3-gluons

PHENIX $J/\psi$ Nuclear Dependence

- Data favors weak shadowing & absorption
  - With limited statistics difficult to disentangle nuclear effects
  - Need another dAu run!

- Not universal vs $x_2$ as expected for shadowing, but does scale with $x_F$, why?
  - initial-state gluon energy loss?
  - Sudakov suppression (energy conservation)?
Cold Nuclear Matter
Transverse Momentum Broadening

\[ \sigma_A = \sigma_N A^\alpha \]

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

PHENIX 200 GeV results show \( p_T \) broadening comparable to that at lower energy (\( \sqrt{s}=39 \) GeV in E866/NuSea)

High \( x_2 \) ~ 0.09

Low \( x_2 \) ~ 0.003
**J/ψ** kinematical distributions

- Study of differential distributions important in order to assess
  - Role of initial state effects $\rightarrow p_T$ distributions
  - Production mechanisms and/or deconfinement $\rightarrow$ polarization

- Technique
  - 3-D acceptance correction ($p_T$, $y$, $\cos \theta$)
  - Fine binning (0.1 GeV/c $p_T$, 0.05 $y$-units, 0.1 $\cos \theta$-units)
  - Define fiducial region (zone with local acceptance >1%)

---

![Graph showing kinematical distributions](image_url)

Viewed from **J/ψ** rest frame

- Collins Soper Frames for polarization studies
- Helicity
**J/ψ polarization**

- Quarkonium polarization → test of production models
  - CSM: transverse polarization
  - CEM: no polarization
  - NRQCD: transverse polarization at high $p_T$

- Deconfinement should lead to a higher degree of polarization (Ioffe,Kharzeev PRC 68(2003) 094013)

$$\alpha_{CS} = -0.03 \pm 0.17$$
$$\chi^2/\text{ndf} = 1.42$$

$$\alpha_H = 0.03 \pm 0.06$$
$$\chi^2/\text{ndf} = 1.01$$
Polarization vs $p_T$, $y$, centrality

- Helicity reference system (good coverage in NA60, $-0.8 < \cos \theta_H < 0.8$)
- No significant polarization effects as a function of
  - Centrality
  - Kinematical region
- Similar results in the Collins-Soper reference frame, albeit with much narrower coverage ($-0.4 < \cos \theta_{CS} < 0.4$)
Comparison with recent results (HERA-B, E866)

- HERA-B, in p-A collisions at 920 GeV, sees (mostly in the Collins-Soper reference system) a significant longitudinal polarization at low $p_T$ (P. Faccioli et al., Hard Probes 2006)

- No polarization in NA60, which covers a higher $x_F$ region

- E866, at still larger $x_F$, sees a (slight) transverse polarization (T.H. Chang et al., PRL 91(2003), 211801)
Summary

- **p+p data:**
  - Provide a challenge for production models
  - $p_T$ spectrum mapped from 0-9 GeV/c
  - Ratio of forward and mid-rapidity $p_T$ distributions show a softening at forward rapidity
  - Rapidity distribution slightly flatter than most models and falls off more rapidly at forward rapidity

- **Au+Au data:**
  - Significant $J/\Psi$ suppression in central collisions $R_{AA} \sim 0.3$
  - Similarity between suppression observed at the SPS and RHIC is striking
  - Suppression weaker than pure color screening predictions
    - Recombination of uncorrelated quarks?
    - Sequential dissociation of charmonium states?
    - Other explanations??
**NA60-Conclusions and perspectives**

- NA60 has performed a high-quality study of $J/\psi$ production in Indium-Indium collisions at the SPS
- Confirms, for a much lighter system, the anomalous suppression seen in Pb-Pb collisions by NA50
- Onset of anomalous suppression at $\varepsilon_{\text{Bj}} \sim 1.5 \text{ GeV/fm}^3$
- Preliminary results from p-A collisions at 158 GeV show that the normalization of the absorption curve is correct
- Peripheral In-In and Pb-Pb results are compatible with p-A
- Absence of $J/\psi$ polarization in the kinematical window probed by NA60
- $p_T$ distributions sensitive to initial state effects
- Study of $J/\psi$ suppression for other collision systems, with the accuracy allowed by a vertex spectrometer, would be very interesting
Comparison with extrapolations from d+Au

- Two calculations shown
  - CNM effects model based on 1-3mb absorption and shadowing. (*)
  - Glauber model + rapidity symmetrization of d+Au points (**)  
    - $R_{AA}(\pm y) = R_{dA}(-y)xR_{dA}(+y)$
- Suppression much higher than accountable by CNM effects
- Not possible with Cu+Cu
  - No d+Cu/p+Cu run

(**) R. Granier de Cassagnac, hep-ph/0701222
Testing sequential melting

- Latest L-QCD results suggest:
  - No $J/\psi$ suppression for $T < 1.5T_c$ ($\gtrsim 10\text{GeV/fm}^3$) complete only $T > 2.5T_c$
  - $\psi'$ and $\chi_c$ start melting at $1.1T_c$ (possibly at RHIC)
  - Is suppression seen at RHIC & SPS only on feed down part?

- Survival probability
  - $R_{AA}/CNM$
    - RHIC: $\sigma_{\text{CNMabs}} = 1\text{mb}$
    - SPS: $\sigma_{\text{CNMabs}} = 4.18\text{mb}$
  - $\epsilon_{Bj} = \frac{dE_T}{dy} \frac{1}{\tau_0\pi R^2}$

- Cautions
  - $\tau_0 = 1\text{fm/c}$ too much for RHIC?
  - CNM contribution at RHIC energy badly constrained!

(*) Karsch, Kharzeev, Satz, PLB 637 (2006) 75
Model results

- Reproduce experimental $S_{J/\psi}^{tot} = R_{AA}/CNM$.
  - Min. $\chi^2$ at $(T_{J/\psi}, T_\chi, f_{FD}) = (2.02T_c, 1.22T_c, 30\%)$
  
$$
\chi^2 = \sum_{N_{part}} \left( \frac{S_{data}(N_{part}) - S_{theory}(N_{part})}{\sigma_{stat\_data}(N_{part})} \right)^2
$$

Onset of $J/\psi$ suppression at $N_{part} \sim 160$.
($\rightarrow$ Highest $T$ at $N_{part} \sim 160$ reaches to $2.02T_c$.)

Gradual decrease of $S_{J/\psi}^{tot}$ above $N_{part} \sim 160$ reflects that the transverse area with $T > T_{J/\psi}$ increases.
Sensitivity for $T_{J/\psi}$

- $T_{J/\psi}/T_c = 1.9, 1.96, 2.02, 2.08, 2.14$
- $T_\chi = 1.22T_c$ and $f_{FD}=30\%$

Theoretical $S_{J/\psi}^{\text{tot}}$ is very sensitive to $T_{J/\psi}$.
J/ψ Production

Au+Au Collisions
- J/ψ Suppression Models:
  - Assume quarkonia are formed only during the initial hard collisions
  - Subsequent interactions only result in additional loss of yield
  - Suppression of J/ψ yield with increasing collision centrality
J/ψ Production

Au+Au Collisions

- J/ψ Suppression Models:
- J/ψ Recombination Models:
  - In central heavy ion collisions more than one c-cbar pair is formed
  - Regeneration of J/ψ pairs from independently produced c and cbars
  - Increased J/ψ yield with increasing collision centrality
  - Narrowed J/ψ rapidity and $p_T$ distributions with increasing centrality
**J/ψ Production**

**Au+Au Collisions**
- J/ψ Suppression Models:
- J/ψ Recombination Models:
- Sequential Melting:
  - J/ψ yield is populated from both direct production and feeddown from the higher resonance states
  - Relative yield from each source experimentally found:
    - 60% direct production, 30% \( \chi_c \) feeddown, 10% \( \psi' \) feeddown
  - Medium conditions determine whether each state is bound
  - Recent lattice results => J/ψ suppression turns on at \( T > 2 T_c \)

![Graphs showing J/ψ, \( \chi_c \), \( \psi' \) yields](image)
### Screening in deconfined medium

- **Debye screening**
  - QCD screening length $\lambda_D$ in deconfined medium decreases with temperature
  - Quarkonia “melt” when their binding distance becomes bigger than screening length

  ![Graph showing Debye length from lattice QCD](image)

  - Binding distance depends on quarkonium state
  - “Melting” in QGP occurs at different temperatures

<table>
<thead>
<tr>
<th>state</th>
<th>$J/\psi(1S)$</th>
<th>$\chi_c(1P)$</th>
<th>$\psi'(2S)$</th>
<th>$\Upsilon(1S)$</th>
<th>$\chi_b(1P)$</th>
<th>$\Upsilon(2S)$</th>
<th>$\chi_b(2P)$</th>
<th>$\Upsilon(3S)$</th>
</tr>
</thead>
<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>
</tr>
</tbody>
</table>

F. Karsch et al. (Nucl. Phys. A698(2002) 199c; hep-lat/0106019)
J/ψ yield vs nuclear absorption (analysis b)

- Compare data to the expected J/ψ centrality distribution, calculated assuming nuclear absorption (with $\sigma_{\text{abs}} = 4.18$ mb) as the only suppression source.

require the ratio measured/expected, integrated over centrality, to be equal to the same quantity from the (J/ψ)/DY analysis ($0.87 \pm 0.05$)
Smoothing effect or sharp drop?

Data are compatible with a sharp drop.

An onset smoother than our resolution on $N_{\text{part}}$ ($\sim 20$) is disfavored.

Work in progress to extend our $N_{\text{part}}$ range towards more peripheral events.
Models of $J/\psi$ production

- **$J/\psi$ transport** (Zhu et al, PLB 607 (2005) 107)
  - start with primordial charmonium from cold nuclear matter effect. Embedded in a relativistic hydrodynamics fireball
  - Charmonium suppressed by thermal gluon dissociation in the QGP.

- **Statistical hadronization** (Andronic et al, PLB 571 (2003) 306)
  - Charm from primary collisions only. All charmonium destroyed in the QGP. Open and closed charm hadrons form statistically at the chemical freeze-out.
Models of J/ψ production

- **2 component model** (Grandchamp et al, NPA 709 (2002) 415)
  - Uses in-medium binding energies of charm states inferred from lattice. Primordial charmonium suppressed by partonic dissociation in QGP. Charm quark thermal relaxation time fitted to data. Additional charmonium from statistical hadronization of QGP. Suppression of all charmonium by hadron collisions in HG phase. (continuous formation in QGP and HG)

- **Keneitic formation** (Thews, hep-ph/0605322)
Models of J/ψ production

- **Kinetic theory** (Grandchamp et al, PRL 92 (2004) 212301)
  - (Evolved from 2 component model)
  - Uses in-medium binding energies of charm states inferred from lattice. Primordial charmonium suppressed by partonic dissociation in QGP. Charm quark thermal relaxation time fitted to data. Charmonium created/destroyed in QGP(HG) by $\psi + X_1 \leftrightarrow X_2 + c + c$

- **Sequential melting** (Karsch et al, PLB 637 (2006) 75)
  - Start with primordial charm distributions from cold nuclear matter effects. J/ψ bound at RHIC. $\psi'$ and cc do not form in QGP. No destruction or formation of J/ψ after primordial formation. No interaction of J/ψ with the medium at all.
### PHENIX J/ψ measurements summary

| Run | Species | $\sqrt{s_{NN}}$ [GeV] | $\int L dt$ | J/ψ counts ($|y|<0.35$) | J/ψ counts (1.2<|y|<2.5) | Reference |
|-----|---------|----------------------|-------------|--------------------------|--------------------------|-----------|
| 1   | Au+Au   | 130                  | 1µb⁻¹       |                          |                          | PRC69, 014901(2004) |
|     | p+p     | 200                  | 0.15pb⁻¹    | 46                       | 65                       | PRL96, 012304 (2006) |
| 3   | d+Au    | 200                  | 2.74nb⁻¹    | 364                      | 1186                     |           |
|     | p+p     | 200                  | 0.35pb⁻¹    | 130                      | 448                      |           |
| 4   | Au+Au   | 200                  | 241µb⁻¹     | 1000                     | 4449                     | nucl-ex/0611020 |
|     | p+p     | 200                  | 350nb⁻¹     |                          |                          |           |
| 5   | Cu+Cu   | 200                  | 3nb⁻¹       | 2300                     | 9000                     | (prel.)nucl-ex/0510051 |
|     | Cu+Cu   | 62                   | 0.19µb⁻¹    | 146                      |                          |           |
|     | Cu+Cu   | 22.5                 | 2.7µb⁻¹     |                          |                          |           |
|     | p+p     | 200                  | 3.8pb⁻¹     | 1500                     | 8005                     | hep-ex/0611020 |
| 6   | p+p     | 200                  | 10.7pb⁻¹    |                          |                          |           |
|     | p+p     | 62                   | 0.1pb⁻¹     |                          |                          |           |
| 7   | Au+Au   | 200                  | 4x run 4?   |                          |                          |           |

**Running**