J/ψ production measurements by PHENIX at RHIC

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Probing QGP with J/ψ

• The start:
  – J/ψ anomalously suppressed in heavy ion collisions due to color screening if Quark Gluon Plasma is formed (Matsui & Satz PL B178 (1986) 416)
  – The NA38, NA50 and NA60 experiments at CERN SPS measured J/ψ suppression in a variety of systems

• Anomalous suppression
  – ‘measured/expected’ J/ψ yield for light-light and heavy-light type collisions follow a universal scaling as a function of L
  – Trend is broken by central heavy-heavy type collisions
  – Models with no QGP have reproduced this behavior, so further investigation is needed
• Heavy ion and polarized proton colliding machine
  - 200GeV, 500GeV in p+p
  - 22.5GeV, 63GeV, 200GeV in Cu+Cu
  - 62.5GeV, 200GeV in Au+Au
  - 200GeV in d+Au
Central Arms:
Hadrons, photons, electrons

- \( J/\psi \rightarrow e^+e^- \)
- \(|\eta| < 0.35\)
- \(p_e > 0.2 \text{ GeV/c}\)
- \(\Delta \phi = \pi \) (2 arms x \(\pi/2\))

Forward rapidity Arms:
Muons

- \( J/\psi \rightarrow \mu^+\mu^- \)
- \(1.2 < |\eta| < 2.2\)
- \(p_\mu > 1 \text{ GeV/c}\)
- \(\Delta \phi = 2\pi\)

Global detectors
Beam-Beam Counter (BBC)
Zero Degree Calorimeter (ZDC)
Reaction Plane Detector (RxNP)
Contributions to $J/\psi$ yield in HICs

• Production (RHIC energies)
  - Mainly by gluon fusion ($gg \rightarrow J/\psi$)
    • Very early in nucleon-nucleon hard scatterings
  - Feed down from excited states of charmonia, multiple measurements
    • HERA-B: ($\chi_c \rightarrow J/\psi X$) $\sim 21\pm5\%$ and ($\psi' \rightarrow J/\psi X$) $\sim 7\pm0.4\%$ (*)
    • PHENIX preliminary: ($\psi' \rightarrow J/\psi X$) $\sim 8.6 \pm 2.5\%$
      • …

• Gluon shadowing: modification of PDFs in nuclei

• Suppression
  - Breakup by scattering on fragments from initial heavy ions ($J/\psi + N \rightarrow X$)
  - Dissociation by comovers
  - Melting in QGP

• Enhancement
  - Possible recombination from uncorrelated $c$ and $\bar{c}$ quarks
J/ψ measurements in p+p collisions

• Why J/ψ in p+p?
  - Constrain J/ψ production models
  - Baseline to heavy ion yields
    • Compared to a superposition of independent pp collisions

\[
R_{AB}(y, p_t) = \frac{d^2 N_{AB}/dydp_t}{<N_{coll}> \times d^2 N_{pp}/dydp_t}
\]

Nuclear modification factor

Total cross section:

\[
BR_{ll} \cdot \sigma_{tot} = 178 \pm 3^{\text{stat}} \pm 53^{\text{sys}} \pm 18^{\text{norm}} \text{ nb}
\]

\(B_{ll}\) is the J/ψ dilepton branching ratio (≈12%)
Cold nuclear matter (CNM) effects

- **J/ψ** suppression in d+Au:
  - Study CNM effects
    - Shadowing, absorption/breakup

\[ R_{dAu}(y) = \frac{dN_{dAu}/dy}{<N_{coll}> \times dN_{pp}/dy} \]

\[ N_{coll}(dAu) = 7.6 \pm 0.3 \]

Example of prediction: gluons in Pb / gluons in p

- \(<x_2> \sim 0.01-0.05\)
- \(<x_2> \sim 0.002-0.01\)
- \(<x_2> \sim 0.05-0.2\)

\[ x_2 : \text{Momentum fraction in nucleus} \]
Breakup cross-section

• Extraction method
  
  - Rapidity dependence of $R_{dAu}$ calculated (*) assuming a shadowing model EKS (**) or NDSG (#)
  
  - Any additional suppression is accounted for by a single free parameter : breakup cross-section ($\sigma_{\text{breakup}}$)
    
    * EKS => $\sigma_{\text{breakup}} = 2.8^{-1.4}_{+1.7}$ mb
    
    * NDSG => $\sigma_{\text{breakup}} = 2.2^{-1.5}_{+1.6}$ mb
  
  - Compatible with SPS (##):
    
    $\sigma_{\text{abs}} = 4.2 \pm 0.5$ mb
    
    (Anti shadowing neglected)


Au+Au and Cu+Cu collisions

- $R_{AA}$ summary plot:
  - $J/\psi$ suppression measurements in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}}=200$GeV
  - Suppression in most central Au+Au goes as far as by a factor of 5

$N_{\text{part}}$: number of nucleons that undergo inelastic collisions
Two surprises

- **Comparison to SPS**
  - $R_{AA} (\text{RHIC}, |y|<.35) \approx R_{AA} (\text{SPS})$
  - Not what’s expected from $\varepsilon_{\text{SPS}} < \varepsilon_{\text{RHIC}}$
  - Caution:
    - Rapidity ranges not same
      - $0 < y_{\text{sps}} < 1$
    - Different CNM effects

- **Rapidity trend**
  - $R_{AA} (|y|<.35) > R_{AA} (1.2<|y|<2.2)$
  - Challenge to most “local density” based suppression models
    - More (hot/cold) matter at mid rapidity, should lead to more suppression there

Scomparin (proc. QM06) : nucl-ex/0703030

PRL 98, 232301 (2007)
Data driven extrapolation from d+Au

- **Minimal model dependence**
  - Modification depends only on local impact parameter
  - Glauber model + rapidity symmetrization of d+Au points (*)
    \[ R_{AA}(\pm y,b) = \frac{1}{N_{coll}} \sum_i R_{dA}(-y,b_1,i) \times R_{dA}(+y,b_2,i) \]
  - Suppression slightly higher than accountable by CNM effects at least at y=0

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If we want minimal model dependence, \( R_{AA}/CNM \) doesn’t exclude the same anomalous suppression at forward and mid rapidities.

Regeneration

- Why regeneration explains rapidity trend?
  - Uncorrelated $c$ and $\bar{c}$ quarks join at hadronization
  - At mid rapidity, more charm quarks $\Rightarrow$ enhance the direct $J/\psi$ yield
  - Just an example below (*), a number of other models do as good a job (**)

(*) O. Linnyk et. al. arXiv:0801.4282
(**) Without being exhaustive some of these models are listed below:
Testing regeneration with J/ψ flow

• Elliptic flow
  - In non central collisions, almond shaped interaction region results in a pressure gradient
  - More particles are emitted ‘in plane’ than ‘out of plane’
  - Magnitude measured by \( v_2 \)

• J/ψ flow : promising test of regeneration
  - Electrons from open c and b semileptonic decays show large nonzero elliptic flow
  - J/ψ regenerated from c quarks should inherit their flow

\[
\frac{dN}{dp_t dy d\phi} \approx \frac{dN}{dp_t dy} \left[ 1 + 2v_2 \cos(2(\phi - \Psi_{RP})) \right]
\]

where \( v_2 = \langle \cos(2(\phi - \Psi_{RP})) \rangle \)
J/ψ flow result at mid rapidity

• Preliminary result
  - Current precision doesn’t allow to draw any conclusions
  - Data points are compatible with zero to maximum flow predictions within errors
  - This is just a proof of principle that the measurement is feasible
  - Slight improvement to expect from full data sample and forward rapidity measurements
  - Will probably still not permit to discriminate. Much larger data sample is needed.
Summary

• Reviewed $J/\psi$ results from PHENIX
  - In $p+p$ collisions, production baseline is measured
  - In $d+Au$ collisions, despite lack of statistics, data is used to extract
    • $J/\psi$ CNM $\sigma_{\text{breakup}}$, compatible within errors to SPS measurement
    • Extrapolation to $Au+Au$ and $Cu+Cu$ collisions
  - In $Au+Au$ and $Cu+Cu$ measurements:
    • Very similar suppression to SPS at mid rapidity
    • Higher suppression at forward rapidity than at mid rapidity
    • $R_{AA}/CNM$ (abnormal suppression) difference b/n mid and forward not very clear
  - Regeneration is a possible scenario to explain rapidity trend
    • Many models describe data satisfactorily when regeneration is allowed
    • A promising experimental test : $J/\psi$ $v_2$, so far limited by statistics

• Outlook
  - New $d+Au$ data set (30x more statistics), better constraint on CNM effect
  - Better precision on $J/\psi$ $v_2$
Backup
Measuring J/ψ flow

• Estimate reaction plane
  - New detector for event by event reaction plane determination

• Measure $v_2$
  - $N_{\text{sig}} \times v_{2, J/\psi} = N_{fg} \times v_{2,fg} - N_{bg} \times v_{2,bg} (M_{J/\psi})$
  - $v_{2,fg} = \langle \cos(2*(\phi - \Psi_{RP})) \rangle$ of unlike sign pairs in J/ψ mass window
  - $v_{2,bg}$ at $M_{J/\psi}$ is interpolated from a polynomial fit outside of J/ψ mass window of like sign $v_2(m)$

• Correct for finite resolution
  - $v_2 = v_{2,\text{meas}} / \sigma_{RP}$, where

$$\sigma_{RP} = 2 \times \sqrt{\langle \cos(2 \times (\Psi_{RP,1A} - \Psi_{RP,1B})) \rangle}$$

24 segment plastic scintillator
1 < $\eta$ < 2.8
Centrality classes

- Dividing total cross section according to centrality
  - Use BBC charge vs. ZDC energy
  - $N_{\text{coll}}$ : number of binary inelastic N–N collisions
  - $N_{\text{part}}$ : number of nucleons that undergo inelastic collisions
  - Glauber model + detector response simulation $\Rightarrow \langle N_{\text{part}} \rangle$ & $\langle N_{\text{coll}} \rangle$

Most peripheral
80 - 92.2%
$\langle N_{\text{part}} \rangle = 6.3 \pm 1.2$
$\langle N_{\text{coll}} \rangle = 4.9 \pm 1.2$

Most central
0 - 5%
$\langle N_{\text{part}} \rangle = 351.4 \pm 2.9$
$\langle N_{\text{coll}} \rangle = 1065 \pm 105$
Indirect comparisons to SPS

- Test with RHIC data models that worked at SPS
  - Most models are strongly challenged by the rapidity trend, and less suppression at mid rapidity

All calculations shown here give predictions at mid rapidity

- Digal, Fortunato, Satz
  - hep-ph/0310354
- Capella, Ferreiro
  - hep-ph/0505032
- Grandchamp, Rapp, Brown
  - hep-ph/0306077
Model dependent extrapolation from d+Au

- Shadowing + $\sigma_{\text{breakup}}$ from $R_{dAu}$ fit used to get $R_{AA}$
  - Same theoretical framework as one used for $R_{dAu}$

- Observations
  - Statistically significant suppression observed at forward rapidity in AuAu
  - Less clear in other cases
  - Forward and mid extrapolation uncertainties correlated
  - According to these models, anomalous suppression is higher at forward rapidity in Au+Au
Signal extraction

• Invariant mass spectra of $\mu^+\mu^-$ and $e^+e^-$ ($J/\psi$ branching ratio $\sim 6\%$ each)

• Combinatorial background subtracted by event mixing

• Fitted with:
  - Gaussians for the mass peak
  - Exponentials for physical background (heavy flavor decay and/or Drell–Yan)
  - Average value of various fits used as $J/\psi$ count
  - Dispersion is included in systematic errors.
| Run | Species | $\sqrt{s_{NN}}$ [GeV] | $|Ldt|$ | $J/\psi$ counts ($|y|<0.35$) | $J/\psi$ counts (1.2<|y|<2.2) | Reference |
|-----|---------|-----------------|-------|-----------------|-----------------|------------|
| 1   | Au+Au  | 130             | 1µb-1 |                  |                  |            |
| 2   | Au+Au  | 200             | 24µb-1| ~13             |                  |            |
|     | p+p     | 200             | 0.15pb-1| 46       | 66              | PRC69, 014901(2004) |
| 3   | d+Au   | 200             | 0.35pb-1| 130       | 450             | PRL96, 012304 (2006) |
| 4   | Au+Au  | 200             | 241µb-1| 1000      | 4500            | PRL 98, 232301(2007) |
|     | Au+Au  | 63              | 9µb-1 |                  |                  |            |
|     | p+p     | 200             | 350nb-1|          |                  |            |
| 5   | Cu+Cu  | 200             | 3nb-1 | 2000        | 9000            | arXiv:0801.0220 |
|     | Cu+Cu  | 62              | 0.19µb-1|          | ~146             |            |
|     | Cu+Cu  | 22.5            | 2.7µb-1| 1500      | 8000            | PRL98,232002(2007) |
|     | p+p     | 200             | 3.8pb-1|          |                  |            |
| 6   | p+p     | 200             | 10.7pb-1| ~2300    | ~27000           |            |
|     | p+p     | 62              | 0.1pb-1|          |                  |            |
| 7   | Au+Au  | 200             | 800µb-1|          |                  |            |
| 8   | d+Au   | 200             | 80nb-1| ~4400    | ~57000           |            |
|     | p+p     | 200             |       |          |                  |            |