Heavy Quarkonia Measurements with STAR

Thomas Ullrich for the STAR Collaboration
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International Workshop on Heavy Quark Production in Heavy-ion Collisions
Purdue University
STAR Detector & Analysis Techniques
STAR’s Quarkonium Program (for now):

- **Golden channel for Quarkonia is** $\bar{Q}Q \rightarrow e^+e^-$
- **Strength:**
  - $\Upsilon$ measurements over all $p_T$
  - $J/\psi$ measurements at high-$p_T$
  - Sampling of full luminosity (trigger)
- **Current weaknesses:**
  - Low S/B ratio for $J/\psi$ at low-$p_T$
  - Moderate mass resolution for $\Upsilon$ 1,2,3 S states
    - possible but requires large statistics
  - Feed-down from B can be measured only indirectly
- **Future improvements:**
  - Time-of-flight provides improved e ID at low-$p_T$
  - Vertex detectors (direct measure of B feed-down)
  - $\mu^+\mu^-$ at mid-rapidity (MTD)
STAR detectors for onium physics …
STAR detectors for onium physics ...

TPC: $|\eta| \leq 1$ ($|\eta| \leq 1.3$ possible), $0 < \phi \leq 2\pi$
Tracking $\Rightarrow p_T, \eta, \phi$
dE/dx $\Rightarrow$ PID (incl. electron ID)
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BEMC:

- $|\eta| \leq 1$, $0 < \phi \leq 2\pi$
- $E/p \Rightarrow$ electron ID
- Tower: $\Delta \phi \times \Delta \eta = 0.05 \times 0.05$
- $E_{\text{tower}} \Rightarrow$ fast trigger
STAR detectors for onium physics ...

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BSMD:
double layer wire PC
\(\Delta \phi \times \Delta \eta = 0.0064 \times 0.1\) rad
(0.1 \times 0.0064) for \(\eta(\phi)\) strips
\(\Rightarrow\) spatial resolution
\(\Rightarrow e/h\) separation
STAR detectors for onium physics ...

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dE/dx \[ \Rightarrow \text{PID (incl. electron ID)} \]

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\[ (0.1 \times 0.0064) \text{ for } \eta(\phi) \text{ strips} \]
\[ \Rightarrow \text{spatial resolution} \]
\[ \Rightarrow \text{e/h separation} \]

Note EEMC is a detector whose potential is not fully exploited so far:
\[ 1 < \eta \leq 2, \ 0 < \phi \leq 2\pi \]
... and how they are used (trigger)

**γ Trigger**

- **L0:** high-tower $E_T > 3.5$ GeV (p+p) or 4.0 GeV (d+Au, Au+Au)
  - alternatively: trigger patch 4×4 towers (p+p only)
- **L2:** software algorithm building pairs from EMC towers
  - $E_1, E_2, \cos(\theta) \Rightarrow M_{inv}$
  - Rejection $\sim 10^5$ in p+p
... and how they are used (trigger)

**High-\(p_T\) J/\(\psi\) Trigger**

- **L0**: *single* high-tower \(E_T > 3-4\) GeV
  - alternatively: topology trigger (2 high towers separated \(\geq 60^\circ\))

**Low-\(p_T\) J/\(\psi\) Trigger**

- not implemented - L0/L2 provide too little rejection
- use minimum bias data sets instead (\(\Rightarrow\) low \(\int Ldt\))

**New: Higher Level Trigger**

- Computer farm with fast algorithm using tracking (TPC) & calorimeter data
- Still in R&D phase but used in parallel during energy scan
- Promising results (see later)
Example: Υ reconstruction

- TPC: track reconstruction
  - $M_{\text{inv}}$ peaks at $\sim 2 \times$ trigger $E_T$ threshold
  - dominated by $h^+h^-$ pairs
Example: $\Upsilon$ reconstruction

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- **TPC tracks extrapolate to EMC**
  - track-cluster match if distance $R < 0.04$ in $\eta-\phi$
... and how they are used (reconstruction)

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- **Electron ID cuts**
  - $E/p$ - EMC energy vs TPC momentum
  - $dE/dx$ in TPC: $n\sigma_e$ of matched tracks
... and how they are used (reconstruction)

- Signal extraction

\[ S = N_{+-} - 2\sqrt{N_{++}N_{--}} \frac{A_{+-}}{\sqrt{A_{++}A_{--}}} \]

- Describing the line shape
  - Crystal ball function accommodates detector resolution and bremsstrahlung: \( f(m; \alpha, n, \langle m \rangle, \sigma) \)

\[ \begin{align*}
\text{const} &\quad 8.865 \pm 0.01395 \\
\text{mean} &\quad 3.081 \pm 8.432e-05 \\
\text{sigma} &\quad 0.04122 \pm 0.000108 \\
n &\quad 1.044 \pm 0.01239 \\
a &\quad 1.155 \pm 0.007413 \\
\end{align*} \]

\( J/\psi \)
\( m=3.097 \text{ GeV} \)

\[ \begin{align*}
\text{const} &\quad 5.307 \pm 0.007208 \\
\text{mean} &\quad 3.066 \pm 0.0001347 \\
\text{sigma} &\quad 0.04542 \pm 0.0001429 \\
n &\quad 0.8456 \pm 0.00631 \\
a &\quad 0.7551 \pm 0.005171 \\
\end{align*} \]

\( J/\psi \)
(with SVT/SSD)
STAR’s new detector ...

ToF: $|\eta| \leq 0.9$, $0 < \phi \leq 2\pi$, MRPC technology
Timing resolution $< 100$ ps
Improve electron ID at low-$p_T$

Run 10 data taken with full ToF
Analysis in progress
... and how they are used (ToF)

- TOF: $e$ PID for $p_T < 3 \text{ GeV/c}$
- High electron purity: 99%
- Efficiency: greater than 60% using standard cuts
... and how they are used (ToF)

Time-of-Flight Detector is an enormous asset for STAR’s dilepton physics program

Expect great things soon!

- TOF: e PID for $p_T < 3$ GeV/c
- High electron purity: 99%
- Efficiency: greater than 60% using standard cuts
STAR detectors in the near future ...

- **Heavy Flavor Tracker (HFT)**
  - $|\eta|\leq1$, $0 < \phi \leq 2\pi$
  - PXL: 2 layers of thinned (50 µm) CMOS pixel detectors (2.5, 8 cm)
  - IST: layer of low mass silicon strip-pad sensors (17 cm)
  - SSD: layer of double-sided silicon strip sensors at a radius of 23 cm
  - Distinguish prompt quarkonia from B feed-down ($B \rightarrow J/\psi + X$)

- **Muon Telescope Detector (MTD)**
  - Acceptance: 45% at $|\eta|<0.5$
  - MRPCs covers magnet iron bars
  - 6 interaction length (yoke)
  - 117 modules, 1404 readout strips, 2808 readout channels
  - Optimal mass resolution for $\Upsilon$ 1,2,3 S despite increased material (HFT)

See X. Dong’s talk tomorrow
Results

\(J/\psi\)
High-$p_T$ $J/\psi$ production

**STAR, PRC80, 041902(R), 2009**

- **Steady improvements due to higher $L$ & improved trigger**
- **SVT/SSD detectors taken out before run 2008**
  - 7-10 times less $X/X_0$
- **Spectra for 2009 data soon**

2009 data
here: tight cuts for correlation study

- **(a) 200 GeV $p+p$**
  - $5 < p_T < 14$ GeV/c
  - $J/\psi \rightarrow e^+ e^-$
  - unlike-sign
  - like-sign
  - simulation

- **(b) 200 GeV $Cu+Cu$**
  - $5 < p_T < 8$ GeV/c
  - 2005

Counts / (30 MeV/c^2)

- **p+p 200GeV**
  - $p_T > 4.0$ GeV/c
  - #J/\psi = 376
  - S/B = 22

(counts / (40 MeV/c^2))

(counts / (50 MeV/c^2))

**$M_{inv}(ee)$ (GeV/c^2)**

2005 & 2006

**$M_{inv}^{ee}$ (GeV/c^2)**

STAR Preliminary

(c) 200 GeV $p+p$

$J/\psi \rightarrow e^+ e^-$

5 < $p_T$ < 14 GeV/c

5 < $p_T$ < 8 GeV/c

$M_{inv}(ee)$ (GeV/c^2)

Counts / (30 MeV/c^2)

$M_{inv}^{ee}$ (GeV/c^2)

2009 data
here: tight cuts for correlation study

- **Direct $J/\psi$ (p+p):**
  - LO CS+CO
  - NNLO* CS

$$B \cdot \frac{1}{2 \pi p_T} \cdot \frac{d^2 \sigma}{dp_T dy} (\text{GeV/c})$$

$$B \cdot \frac{1}{2 \pi p_T} \cdot \frac{d^2 \sigma}{dp_T dy} (\text{nb/GeV/c})$$

$M_{inv}(ee)$ (GeV/c^2)

$M_{inv}^{ee}$ (GeV/c^2)
High-$p_T$ J/$\psi$: $p+p$ spectra

CEM:


- MRST
- Curve includes feed-down from $\chi_c + \psi'$
- Leaves no (little) room for B feed-down
- Varying $m_R$, $m_\mu$, $k_T$ can heal this
High-$p_T$ J/$\psi$: p+p spectra

NNLO* CS:
P. Artoisenet et al., PRL 101, 152001, J.P. Lansberg private communications.

- Only CS contributions, but go to higher orders, partially with loops, partially with just tree-level higher order diagrams.
- Curve does not include feed-down from $\chi_c + \psi'$ ($\psi'$ available)
- $\chi_c$ might be large because of high $x_T$ range of STAR data
- Leaves room for substantial feed-down
- Still too low at $p_T > 10$ GeV/c
  - CO needed?
High-\( p_T \) J/\( \psi \): p+p spectra

CO+CS in NRQCD:
G. Nayak, et al., PRD68, 034003 and private communications

- LO calculations
- direct J/\( \psi \) (singlet and octet)
- CO dominating
- color octet matrix elements from P. Cho, A. Leibovich, PRD 53:6203,1996
- Curve does not include feed-down from \( \chi_c + \psi' \) (\( \chi_c \) available)
- Leaves little to no room for feed-down
J/ψ in p+p: x_T Dependence

\[ E \frac{d^3\sigma}{dp^3} = g(x_T)/s^{n/2} \]

In parton model:
n is related to number of point-like constituents taking active role in interaction

n=8: diquark scattering
n=4: QED-like scattering

\[ x_q \approx x_g \approx x_T \]

- \( \pi \) and \( p \) at \( p_T > 2 \) GeV/c: \( n=6.6\pm0.1 \) (PLB 637, 161(2006))
- J/ψ at high \( p_T \): \( n=5.6\pm0.2 \) (the power parameter close to CS+CO prediction)
- low & high-\( p_T \) J/ψ production dominated by different processes?

\( \pi \times 10^4 \) (n=6.6)
\( p \) (n=6.6)
\( \Delta \) CDF
\( \blacklozenge \) UA1
\( \bigtriangleup \) FNAL
\( \blacklozenge \) PHENIX
\( \blacklozenge \) STAR
\( \blacklozenge \) ISR

\( x_T = 2p_T/\sqrt{s} \)

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\( x_T = 2p_T/\sqrt{s} \) (n=5.6)
Assessing feed-down from B mesons

So far at RHIC no Si-Det. to tag B decays. Need alternative!

Method 1
- Comparing measured J/ψ spectra with NLO b calculations + b FF + B → J/ψ + X decay kinematic
- Considerable uncertainties in absolute normalization from NLO calculations (m_µ, m_R, M_b, PDF) and ψ’,χ_c feeddown

Method 2
- Use J/ψ–h correlations (dφ)
  - Interpretation is model dependent (here PYTHIA)
    - B fragmentation is hard and rather well known
  - Good S/B with STAR at high-p_T makes this possible
High-$p_T$ J/$\psi$-h Correlations: PYTHIA/LO

- PYTHIA 8 with STAR HF-tune v1.1
- J/$\psi$ tuned to describe measured RHIC spectra with emphasis on low-$p_T$ (PHENIX) where B feed-down is smallest
- B tuned with parameters $m_\mu$, $m_R$, $M_b$, ..., from latest calculations (M. Cacciari et al.)

$p_T(J/\psi) > 5$ GeV/c, $p_T(h) > 0.5$ GeV/c
- soft processes added to mock up underlying event (minor effect)
- little difference between CO/S: confirm studies at LHC by Bargiotti & Vagnoni (LHCb-2007-042) and Kraan (arXiv:0807.3123)
- Pronounced near-side for B feed-down (moderate recoil in away-side)
Constraining bottom contribution

Previous result:
- No significant near side \(J/\psi\)-hadron azimuthal angle correlation
- Correlation show low B contribution \((13 \pm 5)\%\)

STAR, PRC80, 041902(R), 2009

Run 9:
- Higher statistics
- Divide into 3 \(p_T\) bins
**Latest results on B feed-down**

- New results consistent with previous results
- No significant beam energy dependence! Why?
- Away side: Consistent with h-h correlation ( gluon/light quark fragmentation?)
Latest results on B feed-down

J/ψ-h correlations are a powerful tool to study B feed-down.

There’s one assumption:
NLO effects are negligible

This has not been demonstrated yet.
- No NLO calculations for J/ψ-h exist
- Neither CDF nor CMS have conducted a study comparing B-tagged J/ψ and J/ψ-h (they could)
- Needs to be done to ultimately establish the validity of this approach
High-\(p_T\) J/\(\psi\): \(R_{AA}\)

**STAR Cu+Cu 0-20%**: \(R_{AA}(p_T>5) = 1.4\pm0.4\pm0.2\)

- The only hadron measured to be not suppressed?
- Contrast to open charm. CS vs. CO? Formation Time?
- 2-component models describes the overall “trend”
A look into the (near) future

![Graph showing data distribution](image)

- **Beam energy scan: 39 GeV Au+Au**
  - Expect ~1000 (13σ) J/ψ from full MB data
  - Able to cover p_T range 0-5 GeV/c
  - Reference data available from Fermi Lab Experiments and ISR

- **200 GeV p+p**
  - J/ψ polarization study in progress

- **200 GeV Au+Au**
  - J/ψ v_2 in progress
Results
Some thoughts …

Reality check: What have we learnt about medium from J/ψ?

• IMHO: not much when compared to flow, spectra & high-p_T
• Studies need to go on (augmented by LHC results)
• Interpretation difficult
  ‣ production mechanism?
  ‣ feed-down from B and \( \chi_c \) states?
  ‣ recombination?
  ‣ energy loss (see open heavy flavor)?
  ‣ life and formation time effects?
  ‣ co-mover absorption?

Study of \( \Upsilon \) states avoid many of these difficulties

• Ratios: \( \Upsilon(2S)/\Upsilon(1S) \) and \( \Upsilon(3S)/\Upsilon(1S) \) are powerful tools
• No recombination (dN/dy too small), no co-mover-absorption (\( \sigma \) too small), less E-loss (\( m_b \gg m_c \)), feed-down only from \( \chi_b \) states
• Caveat: Experimentally difficult but possible given enough L
\[ \gamma \text{ in } p+p \ 200 \text{ GeV} \]

\[ L = 7.9 \pm 0.6 \ \text{pb}^{-1} \]

\[ N_{\gamma}(8 < m < 11) = S - \text{DY-bb} = 61 \pm 20 \text{(stat.)} \]

\[ N_{\gamma}(\text{total}) = 67 \pm 22 \text{(stat.)} \]

\[ \sum_{n=1}^{3} B(nS) \times \sigma(nS) = 114 \pm 38^{+23}_{-24} \ \text{pb} \]

\[ \left( \sigma_{\text{DY}} + \sigma_{\text{bb}} \right)_{|y|<0.5, 8<m_{ee}<11 \text{ GeV/c}^2} = 38 \pm 24 \ \text{pb} \]
STAR Y vs. theory and world data

\[ \sum_{n=1}^{3} \mathcal{B}(nS) \times \sigma(nS) = 114 \pm 38 \pm 23 \text{ pb} \]

\[ \sqrt{s}=200 \text{ GeV} \\ p+p \ \ \gamma + \gamma' + \gamma'' \rightarrow e^+e^- \text{ cross section} \text{ consistent with pQCD and world data trend} \]
$\Upsilon$ in d+Au 200 GeV

$\Upsilon(1S+2S+3S) + DY + \bar{b}b$: raw yield (7<m<11) = 172 ± 2(stat.)

Strong signal (8$\sigma$)

$R_{dA} = 0.78 \pm 0.28$ (stat) $\pm 0.20$ (sys)

Consistent with $N_{\text{bin}}$ scaling
Year 2007
8<m<11 GeV/c^2
Includes: \( \Upsilon \), Drell-Yan, \( \bar{b}b \)

0-60%
4.6\( \sigma \) significance
95 Signal counts
1.11\( \times 10^9 \) events

0-10%
3.5\( \sigma \) significance
47 Signal counts
1.78\( \times 10^8 \) events
Y Yield Extraction 0-60% Centrality

How solid is the signal in $\gamma(1S+2S+3S)$ in 0-60% centrality?

Force $\gamma$ yield to zero

Raw yield of 0 is many sigma away from minimum $\chi^2$
Yield Extraction 0-60% Centrality

Scaling p+p results for $\Upsilon$ and $DY + \bar{b}b$ gives us colored rectangles $R_{AA} \Upsilon(1S+2S+3S) + DY + \bar{b}b$ of 1 would be at the center of the intersection between the two rectangles.

$\Upsilon$ yield determined by:

$$\Upsilon(8.5 < m < 11 \text{ GeV}/c^2) = N_{+-} - 2\sqrt{N_{++}N_{--}} - \int\text{DY} + \bar{b}b = 64 \pm 16(\text{stat}) \pm 25(\text{sys})$$
**$Y R_{AA}$ and comparison with predictions**

- $0-60\% = 0.78 \pm 0.32\,(\text{stat}) \pm 0.22\,(\text{sys, Au+Au}) \pm 0.09\,(\text{sys, p+p})$
- $0-10\% = 0.63 \pm 0.44\,(\text{stat}) \pm 0.29\,(\text{sys, Au+Au}) \pm 0.07\,(\text{sys, p+p})$

<table>
<thead>
<tr>
<th>$q\bar{q}$</th>
<th>$T/T_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y (1S)$</td>
<td>2.31</td>
</tr>
<tr>
<td>$\chi_b (1P)$</td>
<td>1.13</td>
</tr>
<tr>
<td>$Y (2S)$</td>
<td>1.10</td>
</tr>
<tr>
<td>$\chi_b (2P)$</td>
<td>0.83</td>
</tr>
<tr>
<td>$Y (3S)$</td>
<td>0.75</td>
</tr>
</tbody>
</table>

S. Digal, P. Petreczky, and H. Satz, PRD 64, 094015 (2001)

No constraints from data yet: need considerably more statistics
Summary

STAR’s quarkonium program is in full swing

- **J/ψ**
  - focus on high-$p_T$
  - spectra in 200 GeV $p+p$ measured
  - $R_{AA}$ (Cu+Cu) at high-$p_T$ consistent with unity
  - B feed-down in $p+p$ through $J/ψ$-h correlations
  - RHIC energy scan: due to good S/B solid signal at 39 GeV

- **ϒ**
  - first cross-section measured in $p+p$
    - consistent with pQCD calculations
  - $d+Au$: $R_{dAu} = 0.78 \pm 28({\text{stat}}) \pm 20({\text{sys}})$
  - $Au+Au$:
    - 0-60%: $0.78\pm0.32({\text{stat}}) \pm 0.22({\text{sys,Au+Au}}) \pm 0.09({\text{sys,p+p}})$
    - 0-10%: $0.63\pm0.44({\text{stat}}) \pm 0.29({\text{sys,Au+Au}}) \pm 0.07({\text{sys,p+p}})$
  - More statistics needed but we are well on our way