ϒ production at the STAR experiment

with a focus on new U+U results

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for the STAR collaboration
Outline

- Quarkonia in heavy ion collisions
- $\Upsilon$ measurements with the STAR experiment

**Results** ($\sqrt{s_{NN}} = 193..200$ GeV, mid-rapidity)
- $p+p$ $\rightarrow$ pQCD baseline
- $d+Au$ $\rightarrow$ CNM effects
- $Au+Au$ and $U+U$ $\rightarrow$ sQGP modification

**Outlook**
- New high-statistics measurements, $\sqrt{s}=500$ GeV $p+p$
- Muon Telescope Detector (MTD)
Quarkonia in the sQGP

- Debye screening of heavy quark potential
  → Quarkonium states are expected to dissociate


Charmonia: $J/\Psi$, $\Psi'$, $\chi_c$  
Bottomonia: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\chi_B$
Quarkonia in the sQGP

- Debye screening of heavy quark potential

  Quarkonium states are expected to dissociate


  Charmonia: \( J/\psi, \psi', \chi_c \)

  Bottomonia: \( \Upsilon(1S), \Upsilon(2S), \Upsilon(3S), \chi_b \)

- Sequential melting: Different states are expected to melt at different temperatures


Quarkonia may serve as sQGP thermometer
\( \Upsilon \) measurements at RHIC

- \( J/\psi \) yield is strongly affected by recombination, feed-down, co-mover absorption

\[ \sqrt{s_{NN}} = 200 \text{ GeV} \ Au + Au \rightarrow J/\psi + x \]

Model:

Data:

\( \rightarrow \) P. Chaloupka’s talk
\( \Upsilon \) measurements at RHIC

- \( J/\psi \) yield is strongly affected by recombination, feed-down, co-mover absorption

\[ \rightarrow \text{P. Chaloupka's talk} \]

- \( \Upsilon \) recombination and co-mover absorption are negligible at RHIC energies

\( \Upsilon \) states provide a cleaner probe at RHIC

- However: Low production rate makes it a difficult measurement
  Requires good acceptance and specific triggering
**U+U: Higher energy densities**

**RHIC $\sqrt{s_{NN}}$=193 GeV U+U data (2012)**

- Reach higher $N_{\text{part}}$ than in Au+Au
U+U: Higher energy densities

**Au+Au Collisions**

**Oblate**

**U+U Collisions**

**Prolate**

RHIC $\sqrt{s_{NN}}=193$ GeV U+U data (2012)

- Reach higher $N_{\text{part}}$ than in Au+Au
- Provide higher energy density

Way to test the sequential melting hypothesis
$\gamma$ measurements in RHIC/STAR

$\gamma \rightarrow e^+e^- \ (BR \sim 2\%)$

- Large invariant mass ($m_{ee} \sim 10 \text{ GeV/c}^2$)
- Back-to-back electron-positron pair
- Rather energetic electrons (typically $>3 \text{ GeV}$)
\( \Upsilon \) measurements in RHIC/STAR

\[ \Upsilon \rightarrow e^+e^- \ (\text{BR} \sim 2\%) \]

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a central Au+Au event in STAR
1. Triggering on $\Upsilon$ events

- **L0**: ‘High tower trigger’ saves events with high energy hit in the Barrel Electromagnetic Calorimeter (BEMC) tower
- **L2** in $p+p$ and $d+Au$ only – software trigger: coarse reconstruction of cluster energy, opening angle, invariant mass

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1. Trigger on energetic hits in the BEMC
2. Finding electron tracks

- Find tracks in the Time Expansion Chamber (TPC) based on Fractional energy loss $dE/dx$
  - $-1.2 < n\sigma_e < 3$ (A+A analyses)

1. Trigger on energetic hits in the BEMC

2. Find electron tracks in the TPC
3. Matching

- Clusterize energy in the BEMC
  
  *Cluster: 3 adjacent towers with most of the energy deposit*

- Project TPC tracks onto clusters to match them
  
  \[
  \Delta R_{\text{match}} = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.04
  \]
4. ID in the calorimeter

- Cluster energy matches track momentum
  \[0.75 < \frac{E}{p} < 1.4\] \((U+U\) analysis\)

- Energy deposit is compact, mostly in a single tower
  triggered \(e^\pm: \frac{E_{\text{tower}}}{E} > 0.7\), associated \(e^\pm: \frac{E_{\text{tower}}}{E} > 0.5\) \((U+U\) analysis\)
Peak extraction (U+U example)

- Combinatorial background is fitted with exponential, then subtracted
Peak extraction (U+U example)

- Combinatorial background is fitted with exponential, then subtracted
- Shape of Drell-Yan is from pQCD calculations; open b\(\bar{b}\) contribution is from PYTHIA
- \(\Upsilon\) peak shape is from embedded MC simulation
- Normalization of \(\Upsilon\) peak and Drell-Yan+\(b\bar{b}\) is fitted simultaneously

Note: log-likelihood method applied in the fits
\( \gamma \) x-section and \( p_T \)-spectrum in U+U

\[
B_{ee} \frac{d\sigma_{\gamma}}{dy} \mid_{|y|<1} = (4.37 \pm 1.09 \pm 0.65 \pm 1.01) \mu b
\]

\( f(p_T) = \frac{p_T}{\exp(p_T / T + 1)} \)

Expected T is extrapolated from ISR, CDF and CMS pp (p\bar{p}) results

PLB91, 481 (1980).
PRL88, 161802 (2002).
PRD83, 112004 (2011)
**ϒ in p+p and d+Au**


**ϒ in p+p 200 GeV, |y|<0.5, L0 & L2**

\[ \int L \ dt = 20.0 \ \text{pb}^{-1} \]

\[ N_\gamma(\text{total}) = 152 \pm 23 \ (\text{stat.} + \text{fit}) \]

\[
\sum_{n=1}^{3} B(nS) \times \frac{d\sigma(nS)}{dy} = 64 \pm 10^{+14}_{-12} \ \text{pb}
\]

**ϒ in d+Au 200 GeV, |y|<0.5, L0 & L2**

\[ \int L \ dt = 28.1 \ \text{nb}^{-1} \]

\[ N_\gamma(\text{total}) = 46 \pm 13 \ (\text{stat.} + \text{fit}) \]

\[
\sum_{n=1}^{3} B(nS) \times \frac{d\sigma(nS)}{dy} = 12.2 \pm 3.4^{+2.1}_{-1.9} \ \text{nb}
\]
R. Vértesi for STAR – $\Upsilon$ production in U+U collisions

$\Upsilon$ in Au+Au


$\Upsilon$ in Au+Au 200 GeV, $|y|<1$

$\int L \, dt = 1075 \, \mu b^{-1}$

$N_{\Upsilon} = 254 \pm 29$

0-60% centrality

mid-peripheral (30-60%)

mid-central (10-30%)

central (0-10%)

centrality bins
\( \Upsilon \) in p+p – QCD baseline

- p+p \( \Upsilon \) cross section vs. \( y \), compared to pQCD predictions

\( \Upsilon \) in p+p – QCD baseline

- p+p \( \Upsilon \) cross section vs. \( y \), compared to pQCD predictions


\( \Upsilon(1S+2S+3S) \)

- p+p \( \Upsilon \) cross section, compared to world data trend

**Y R_{dAu} – CNM effects**

- **Models include**
  - Gluon nPDF (Anti)shadowing
  - Initial parton energy loss
- **Indication of suppression at mid-rapidity beyond models**

\[ R_{dAu} = 0.48 \pm 0.14 \text{ (stat)} \pm 0.07 \text{ (syst)} \pm 0.02 \text{ (pp stat)} \pm 0.06 \text{ (pp syst)} \]

\[ |y| < 0.5 \]
\( \Upsilon R_{dAu} \) – CNM effects

- Models include
  - Gluon nPDF (Anti)shadowing
  - Initial parton energy loss
  - Indication of suppression at mid-rapidity beyond models

- STAR data consistent with E772

Au+Au data

- Peripheral data and d+Au (|y|<1) is consistent with no suppression
- Significant suppression in central data
Au+Au and U+U data

- Peripheral data and d+Au ($|y|<1$) is consistent with no suppression
- Significant suppression in central data

Trend in U+U follows and extends trend in Au+Au
Model calculations:

- Strong binding scenario, CNM effects included

- Potential model based on heavy quark internal energy ‘B’
  assumes $428 < T < 443$ MeV

- Potential model based on heavy quark free energy ‘A’ disfavored

$\Upsilon$ suppression indicates color deconfinement

However: CNM effects need further study

→ Planned p+Au run at RHIC for 2015
R. Vértesi for STAR – $\Upsilon$ production in U+U collisions

**$\Upsilon R_{AA}$ – RHIC comparison**


- **STAR vs. PHENIX:** data are consistent

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**Au+U, d+Au**

- $\Upsilon(1S+2S+3S)$, $|y|<1$
- $\sqrt{s_{NN}} = 193$ GeV
- $\sqrt{s_{NN}} = 200$ GeV

**d+Au**

- $\sqrt{s_{NN}} = 200$ GeV
- PHENIX

- $|y|<0.35$

- p+p stat. uncertainty
- common normalization syst.

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PHENIX Collaboration, arXiv:1404.2246
STAR vs. PHENIX: data are consistent

RHIC vs. LHC:
- High-$N_{\text{part}}$ suppression comparable at LHC and RHIC
- Suppression of $\Upsilon$ appears to be $\sim$flat at LHC

→ is suppression driven by the energy density?

Note the uncertainties, however
\[ \gamma(1S) R_{AA} \text{ in } \text{Au+Au} \]

Model calculations

- Strickland-Bazov model B: Hot and cold effects
  

- Liu-Chen model: Dissociation of Quarkonium
  No CNM effects
  

\[ \gamma(1S) R_{AA} \] is consistent with unity in d+Au and peripheral and mid-central Au+Au

Indication of suppression consistent with model calculation in central Au+Au
Excited $\Upsilon$ states in Au+Au

Central Au+Au:

- Excited states $\Upsilon(2S)$ and $\Upsilon(3S)$ consistent with complete melting
- $\Upsilon(1S)$ suppression is similar to high-$p_T$ J/$\psi$
**Excited **$\Upsilon$** states in Au+Au**

**Central Au+Au:**
- Excited states $\Upsilon(2S)$ and $\Upsilon(3S)$ consistent with complete melting
- $\Upsilon(1S)$ suppression is similar to high-$p_T$ $J/\psi$

Y suppression pattern supports sequential melting
Excited $\Upsilon$ states – LHC comparison

- RHIC $\sqrt{s_{NN}}=200$ GeV Au+Au and LHC $\sqrt{s_{NN}}=2.76$ TeV Pb+Pb collisions: Similar suppression of central $\Upsilon(1S)$


**STAR Inclusive Quarkonium Measurements**
- Au+Au, $\sqrt{s_{NN}}=200$ GeV, $|y|<1$

- $J/\psi$, $p_T > 5$ GeV/$c$, 0-10% Centrality
- $\Upsilon(1S)$, 0-10% Centrality
- $\Upsilon(2S+3S)$, 95% limit, 0-60% Centrality

**CMS Preliminary**
- PbPb $\sqrt{s_{NN}}=2.76$ TeV

- Prompt $\psi(2S)$ ($6.5 < p_T < 30$ GeV/$c$, $|y| < 1.6$)
- $\Upsilon(3S)$ ($|y| < 2.4$), 95% upper limit
- $\Upsilon(2S)$ ($|y| < 2.4$)
- Prompt $J/\psi$ ($6.5 < p_T < 30$ GeV/$c$, $|y| < 2.4$)
- $\Upsilon(1S)$ ($|y| < 2.4$)

**Talks by Moon & Abdulsalam**
PRL109 (2012) 2220301, PAS-HIN-12-014, PAS-HIN-12-007
Outlook: analyses underway

\[ p+p \sqrt{s}=500 \text{ GeV}, 2011 \]
\[ \sim 22 \text{ pb}^{-1} \]
- Double x-section, L0-only
- \( p_T \) spectrum
- Excited-to-ground ratio

\[ Au+Au \sqrt{s}_{NN}=200 \text{ GeV}, 2011 \]
\[ \sim 2800 \text{ ub}^{-1} \]
- same setup as in 2010
Outlook: Muon Telescope Detector

- Outermost, gas detector
- Physics goal: **Precision measurement of heavy quarkonia through the muon channel**
- Acceptance: 45% in azimuth, $|y|<0.5$

![Muon Telescope Detector diagram](image)

**Y projection**

<table>
<thead>
<tr>
<th>STAR Muon Telescope Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au+Au</td>
</tr>
<tr>
<td>p+p, 20 nb^{-1}</td>
</tr>
<tr>
<td>60 pb^{-1}</td>
</tr>
</tbody>
</table>

\[ R_{AA} \]

\[ N_{part} \]

- $\Upsilon(1S)\rightarrow\mu^+\mu^-$
- $\Upsilon(2S)\rightarrow\mu^+\mu^-$
- $\Upsilon(3S)\rightarrow\mu^+\mu^-$
- $\Upsilon(1S+2S+3S)\rightarrow e^+e^-, |y|<0.5$
Outlook: Muon Telescope Detector

- Outermost, gas detector
- Physics goal: Precision measurement of heavy quarkonia through the muon channel
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Complete in 2014, sampled ~13.8 nb\(^{-1}\) in Au+Au data
Summary

- Strong $\Upsilon$ suppression in $\sqrt{s_{NN}}=200$ GeV central Au+Au data
- New $\sqrt{s_{NN}}=193$ GeV U+U measurement confirms Au+Au trend and extends it to higher $N_{\text{part}}$
- Similar $R_{AA}$ at RHIC and LHC in most central collisions
- Sequential melting: ground state is suppressed, no evidence for surviving excited states in central Au+Au collisions
- Unexpected suppression in mid-rapidity $d+Au$
  
  CNM effects need further studies $\Rightarrow$ upcoming $p+A$ run
Summary

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  CNM effects need further studies $\rightarrow$ upcoming p+A run

Stay tuned for new $\Upsilon \rightarrow \mu^+\mu^-$ results with MTD
Thank You!

AGH University of Science and Technology
Alikhanov Institute for Theoretical and Experimental Physics
Argonne National Laboratory
Brookhaven National Laboratory
Central China Normal University
Cracow University of Technology
Creighton University
Czech Technical University in Prague
Frankfurt Institute for Advanced Studies (FIAS)
Indian Institute of Technology. Mumbai
Indiana University, CEEM
Institute of High Energy Physics - Beijing
Institute of High Energy Physics - Protvino
Institute of Modern Physics, Lanzhou
Institute of Nuclear Physics PAS
Institute of Physics. Bhubaneswar
Instituto de Fisica da Universidade de Sao Paulo
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University of Zagreb
Valparaiso University
Variable Energy Cyclotron Centre. Kolkata
Warsaw University of Technology
Wayne State University
World Laboratory for Cosmology and Particle Physics (WLCAPP)
Yale University

STAR Collaboration
High-\(p_T\) \(J/\psi\) – motivation

\[ R_{dAu} \sim 1 \text{ at high } p_T \]
\[ \rightarrow \text{CNM effects do not play a strong role} \]

Outlook: Heavy Flavor Tracker

- Innermost, silicon detectors (3 subsystems)
- Resolves secondary vertex
- Physics goal: Precision measurement of heavy quark production

Complete and taking data in Run14

IST at 14 cm

PXL at 2.9 and 8.2 cm

SSD at 22 cm

\( \sigma_r^\phi: 170 \mu m \)

\( \sigma_z: 1800 \mu m \)

\( r: 14 \text{ cm} \)

\( X/X_0 < 1.5 \% \)

\( \text{See details at poster M-30 by Yaping Wang} \)

The task of SSD and IST is to guide the track from TPC to the innermost PXL detector with high hit density.

Silicon Trip Detector:
- Existing detector with new faster electronics
- Double sided silicon strip modules with 95 \( \mu m \)
- \( \sigma_r^\phi: 20 \mu m \)
- \( \sigma_z: 740 \mu m \)
- \( r: 22 \text{ cm} \)
- \( X/X_0: 1 \% \)

Intermediate Silicon Tracker:
- Single-sided double-metal silicon pad sensors with 600 \( \mu m \times 6 \text{ mm} \)
- \( \sigma_r^\phi: 170 \mu m \)
- \( \sigma_z: 1800 \mu m \)
- \( r: 14 \text{ cm} \)
- \( X/X_0 < 1.5 \% \)

HFT Design

Qiu Hao

Newly commissioned STAR HFT detector
- 2 layers of thin Silicon pixel (MAPS)
- 0.4% \( X_0 \) /layer, 12x12\( \mu m \), 360M pixels
- 2 layers of Silicon pad/strip detectors
- Fast readout, bridging TPC and PXL
- Stay tuned for greatly improved \( R_{AA} \) and \( v_2 \) HF measurements from STAR soon!

Talk: Qiu-557; Posters: Lomnitz-M13 and Wang-M30

Outlook:

- 200 GeV Au+Au Collisions
  - \( D^0 \): 1B min bias events; \( |y|<0.5 \)
- Anisotropy Parameter \( v_2 \) (%)
- Hydro
- Charged hadrons
- \( v_2(c) = v_2(q) \)
- \( v_2(c) = 0 \)

\( D^0 v_2 \) projection
Rapp WBS & SBS

FIG. 2: Bottomonium lifetimes in the QGP for the two binding scenarios defined in the text; left panel: WBS with quasifree dissociation; right: SBS with gluo-dissociation; solid lines: $\Upsilon$, dashed lines: $\Upsilon'$, dotted lines: $\chi_b$.

CMS Collaboration, PRL 109 (2012) 222301

CMS Collaboration, PRL 109 (2012) 222301

- CMS

2.76 TeV

Pb+Pb
Peak extraction

- For 0-10% pT<2GeV:
  - Pair invariant mass: N_{comb} bg fit, BB+DY, # under peak 7.1, bg+Y CrystalBall
  - Raw net pair yield: N_{comb} bg fit, BB+DY, # under peak 1.4, bg+Y CrystalBall

- For 10-30% 2<pT<4GeV:
  - Pair invariant mass: N_{comb} bg fit, BB+DY, # under peak 4.8, bg+Y CrystalBall
  - Raw net pair yield: N_{comb} bg fit, BB+DY, Y peak 28:3.6, bg+Y CrystalBall

- For 30-60% pT>4GeV:
  - Pair invariant mass: N_{comb} bg fit, BB+DY, # under peak 12, bg+Y CrystalBall
  - Raw net pair yield: N_{comb} bg fit, BB+DY, Y peak 38:0.8, bg+Y CrystalBall
U+U acceptance and efficiency

- 15M high-tower-triggered U+U 193 GeV events (263 µb⁻¹)

- Divided into 3 centrality bins:
  - 0 – 10%
  - 10 – 30%
  - 30 – 60%

- or... 3 bins in $p_T^γ$:
  - 0 – 2 GeV/c
  - 2 – 4 GeV/c
  - 4< GeV/c

- Total acceptance & efficiency for $γ \rightarrow e^+e^-$ reconstruction:
  ~ 2-3%
Nuclear modification

- p+p: pQCD baseline
- Nuclear modification factor \( R_{dA,AA} \)

\[
R_{dA,AA}^\gamma = \frac{1}{\langle N_{coll} \rangle} \frac{N_{dA,AA}^\gamma \epsilon_{dA,AA}^{-1}}{N_{pp}^\gamma \epsilon_{pp}^{-1}}
\]

- d+Au: generally considered as proxy for CNM
- A+A: hot nuclear matter effects – sQGP

\( R_{AA} = 1 \) if no modification by the medium