STAR quarkonium measurements in heavy ion collisions

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Quarkonium in nuclear matter

- In heavy ion collisions at RHIC hot and dense quark gluon plasma is created.
- Heavy-flavor quarks are good probes for studying QGP.
  - $m_{c,b} \gg T_C, \Lambda_{QCD}$, $m_{u,d,s}$ produced dominantly by high-$Q^2$ scatterings in the early stage.
- Due to color screening of quark-antiquark potential in QGP quarkonium dissociation is expected.

Diagram:
- $J/\psi$ at $T=0$.
- $T_C>T>0$.
- $T>T_C$.

A. Rothkopf HP12
Quarkonium in nuclear matter

- **Sequential melting:** suppression of different states is determined by medium temperature and their binding energies - QGP thermometer

  \[ T < T_c \quad \psi \; \chi_c \psi' \quad Y \; \chi_b Y' \chi_b' \]

  \[ T \approx 1.2 \; T_c \quad \psi \quad Y \; \chi_b Y' \]

  \[ T \approx 3 \; T_c \quad Y \]

- **Hot nuclear matter effects**
  - Dissociation
  - Regeneration from deconfined quarks
  - Medium-induced energy loss
  - Formation time effect

- **Cold nuclear matter effects (CNM)**
  - Nuclear absorption, gluon shadowing, initial state energy loss, Cronin effect and gluon saturation.
  - Feed-down from excited states and B-hadrons


https://indico.cern.ch/event/443462/images/6069-hf_cartoon1.png
STAR experiment

TPC/TOF/BEMC: $|\eta|<1$
HFT: $|\eta|<1$ (2014-2016)
MTD: $|\eta|<0.5$
J/ψ and ψ(2s) production in 200 GeV p+Au collisions

• Models with only nPDF effects can reach upper uncertainty limit of the data at low and high p_T, but underpredicts the suppression at p_T of 3-6 GeV/c
  • Additional nuclear absorption is favored by data

• First ψ(2S) to J/ψ double ratio measurement from STAR between p+Au and p+p at midrapidity at RHIC: 1.37 ±0.42(stat.) ±0.19(syst.)
J/ψ production in 200 GeV Au+Au collisions

- $R_{AA}$ increases from ~0.5 to 1.0 at high-$p_T$ in 20-40% and 40-60% centrality, most likely due to CNM, formation time effects and B-hadron feed-down
- No obvious $p_T$ dependence for 0-20% and 0-60% centrality
  - Suppression at low $p_T$ is interplay of dissociation, Cold Nuclear Matter effects and regeneration
  - Suppression at high $p_T$ is mainly due to dissociation, other effects are small
J/ψ production in 200 GeV Au+Au collisions

Suppression in central collisions at low $p_T$:
- dissociation, Cold Nuclear Matter effects, regeneration

Suppression in central collisions at high $p_T$: due to dissociation

LHC vs RHIC:
- More regeneration at the LHC leads to less suppression at low $p_T$
- Higher temperature at the LHC, higher dissociation leads to more suppression at high $p_T$

ALICE, PLB 734 (2014) 314
PHENIX, PRL 98 (2007) 232301

CMS, JHEP 05 (2012) 063
J/ψ production in 200 GeV Au+Au collisions

Models (dissociation + regeneration effects) can describe centrality dependence at RHIC, but overestimate suppression at the LHC at low $p_T$

At high $p_T$ both models can qualitatively describe data at RHIC and the LHC
J/ψ production at very low $p_T$

- Large enhancement at low $p_T$ in peripheral collisions
  - Cannot be explained by hadronic production (color screening, CNM, regeneration)

- Coherent photoproduction of J/ψ can qualitatively explain the observation
  - In semicentral collisions data favor model configuration Nucleus+Spectator and Spectator+Nucleus as photon and Pomeron emitters

Bottomonia $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$

- Recombination effects
  - $J/\psi$: Evidence for large effects at the LHC.
  - $\Upsilon$: Expecting negligible contribution.
    \[
    \sigma_{cc^-} @ RHIC: 797 \pm 210 ^{+208}_{-295} \text{ mb. (PRD 86, 072013(2012))}
    \]
    \[
    \sigma_{bb^-} @ RHIC: \sim 1.34 - 1.84 \text{ mb (PRD 83 (2011) 052006)}
    \]

- Co-mover absorption effects
  - $\Upsilon (1S)$: tightly bound, larger kinematic threshold.
    - Expect $\sigma \sim 0.2 \text{ mb}$, 5-10 times smaller than for $J/\psi$
      - Lin & Ko, PLB 503 (2001) 104
$\Upsilon(1S,2S,3S)$ in 200 GeV p+Au collisions

- Indication of $\Upsilon(1S,2S,3S)$ suppression in p+Au collisions
- $R_{pAu}|_{y<0.5} = 0.82 \pm 0.10$ (stat.) $+0.08$ (syst.) $-0.07$ (glob.)
- Suppression due to CNM effects - beyond expectation from nPDFs only
\( \Upsilon(1S,2S,3S) \) in 200 GeV Au+Au collisions

- Dielectron and dimuon results consistent with each other
- Stronger suppression of \( \Upsilon(2S + 3S) \) than \( \Upsilon(1S) \) in central coll.
  - Consistent with sequential melting expectations
Similar suppression for $\Upsilon(1S)$, despite higher medium temperature at the LHC.

- Regeneration? Larger at the LHC than at RHIC
- CNM effects

Indication of smaller suppression for $\Upsilon(2S+3S)$ at RHIC than at the LHC.
\( \Upsilon(1S), \Upsilon(2S,3S) \) \( R_{AA} \) vs \( p_T \)

- Consistent with no \( p_T \) dependence
- Similar suppression for \( \Upsilon(1S) \) at RHIC and the LHC
- Indication of smaller suppression for \( \Upsilon(2S+3S) \) at RHIC than at the LHC
Data to model comparison

- Krouppa, Rothkopf, Strickland
  Phys. Rev. D 97, 016017
- Lattice QCD-vetted potential for heavy quarks in hydrodynamic-modeled medium
- No regeneration, no CNM effects

- De, He, Rapp
  Phys. Rev. C 96, 054901
- Quarkonium in-medium binding energy described by thermodynamic T-matrix calculations with internal energy potential (strongly bound scenario)
- Includes both regeneration and CNM effects
  - $\Upsilon(1S)$ well described;
  - $\Upsilon(2S+3S)$ underestimates data in 30-60% centrality by Rothkopf model
Summary

• **J/ψ in p+Au at 200GeV**
  • $R_{pAu}$ favors additional nuclear absorption on top of nPDF

• **J/ψ in Au+Au at 200GeV**
  • $R_{AA}$ described qualitatively by models including dissociation and regeneration
  • Suppression observed at $p_T>$5 GeV/c due to dissociation
  • Low $p_T$ (<100MeV) enhancement consistent with coherent photoproduction

• **ϒ production in p+Au at 200 GeV**
  • Indication of $ϒ(1S,2S,3S)$ suppression

• **ϒ production in Au+Au at 200GeV**
  • Stronger suppression of $ϒ(2S + 3S)$ than $ϒ(1S)$
  • Consistent with sequential melting
  • No $p_T$ dependence of suppression observed
Nuclear modification of non-prompt J/ψ

- Non-prompt J/ψ fraction in Au+Au 200GeV of about 0.03-0.06 extracted
- Strong suppression of $B \rightarrow J/ψ$ at high $p_T (> 5 \text{ GeV/c})$ observed