Quarkonia at High-Luminosity LHC:
Can we determine the in-medium QCD force?

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1.) Introduction: A “Calibrated” QCD Force

- Vacuum quarkonium spectroscopy well described
- Confinement ↔ linear part of potential

Opportunity: Utilize quarkonia to probe in-medium QCD force
↔ infer consequences for transport coeffs. + spectral functs.
↔ probe QGP properties at varying resolution

[Bazavov et al ’13]
1.2 Quarkonia in Medium

- In-medium spectral functions:
  - Mass / binding energy $E_B(p,T)$
  - Inelastic reaction rate $\Gamma_{in}(p,T,E_B)$
- Remnant of confining force above $T_{pc}$
- $\Upsilon(1S)$: color-Coulomb ($E_B=1.1\text{GeV}$)
- $J/\psi$, $\Upsilon(2S,3S)$: confining force (0.6-0.2)
- $\psi(2S)$: barely bound (<0.1)

**Objective:**
Utilize production systematics of the different states to probe the in-medium QCD force (not a good thermometer …)

**Tool:**
Observables sensitive to production “time”
1.3 Excitation Functions in AuAu / PbPb

Charmonium
- Gradual increase of total $J/\psi$ $R_{AA}$
- Regeneration and suppression increase
- Regeneration concentrated at low $p_T$

Bottomonium
- Gradual suppression
- Regeneration ($N_{Y^{eq}}$) small
- Qualitative difference from $J/\psi$

[data: NA50, PHENIX, STAR, ALICE, CMS]
1.4 Current Quarkonium Phenomenology

Use temperature estimates from hydro/photons/dileptons to infer:

\[ T_{\text{melt}}(\psi') < T_{\text{SPS}}^{\text{melt}} (~240) < T_{\text{melt}}(J/\psi, \Upsilon') \leq T_{\text{RHIC}}^{\text{melt}} (~350) < T_{\text{melt}}(\Upsilon) \leq T_{\text{LHC}}^{\text{melt}} (~550) \]

- Remnants of confining force survive at SPS [melt \( \psi' \), \( J/\psi \) intact]
- Confining force screened at RHIC+LHC [melt \( J/\psi + \Upsilon' \)]
- Color-Coulomb screening at LHC [\( \Upsilon(1S) \) suppression]
- Thermalizing charm quarks recombine at LHC [large \( J/\psi \) yield]
2.1 Sensitivity of $R_{AA}$ to Binding Energies

- $\Upsilon$(1S) suppression can discriminate melting scenarios, need good control over auxiliary model components (bulk, CNM, ...)
- $\Upsilon$(2S,3S): smaller systems, p+Pb, Ar+Ar? or ...
2.2 Υ Elliptic Flow

• Directly reflects production/suppression time!

Υ(1S): early, Υ(2S): late(r)
2.3 Charmonia: Production Time + “Flow Bump”

- Need low-$p_T$ $R_{AA}$ data to discriminate
- Sequential regeneration?!
- Recall double ratio of CMS…
- Similarly for $v_2$ ($pPb$ puzzle?)
2.4 NRQCD-based quarkonium dissociation theory

- NRQCD input cross sections
- Importance of $p_T$-differential feed-down
- Different states modified differently in the QGP

- Simultaneous description of ground and excited $J/\psi$ and $\Upsilon$ states;
- Importance of high-$p_T$ measurements
- Also constrain energy loss mechanisms

S. Aronson, I. Vitev et al. (2017)
3.) **Summary**

- Heavy quarkonia: hard production but **soft medium probe**
- Unique opportunity to unravel **in-medium QCD** force via in-medium “spectroscopy” (i.e. production/suppression of different states)
- $p_T$ spectra + $v_2$ provide sensitive tests of **temperature profile** of both regeneration ($\Psi$) and dissociation ($\Upsilon$)
- Dissociation/regeneration rates closely related to individual **heavy-quark** reaction rates (↔ open-HF phenomenology; charm Xsec!)
- Systematic studies of model dependences
3.1 Binding Energies + Reaction Rates: Y States

- Reduced binding “accelerates” dissociation \((\Gamma_Y(E_B=0) = 2\Gamma_b)\)
- Localizes dissociation temperatures (centrality dependence!)
- Same rate for regeneration – experimental signatures of production time?
4.5 $\gamma_p t$ Spectra in Pb-Pb(5.02 TeV)
4.1 Divide out Cold-Nuclear-Matter Effects

\[ R_{AA}^{hot} \equiv R_{AA}^{tot} / S_{CNM} \]

- \( J/\psi \) suppression at SPS mostly from feeddown (\( \sigma_{\psi N} \sim 7.5\text{mb} \)), melts in the RHIC → LHC regime (not unlike \( \Upsilon(2S) \))
1.2 Heavy Quark/onia on the Lattice

**Q\bar{Q}** Free Energy

Onium Correlators

Quark Suscept./Diffusion

**Heavy-quark potential**

Energy + 3-mom. dep. of $\Psi + \Upsilon$ spectral fcts.

Individual heavy quarks in QGP

Ample source of information $\iff$ Compelling Case for Experiment!
3.5 $\psi(2S)$ in p/dA: A Sensitive Medium Probe

- noticeable $\psi'$ but little $J/\psi$ suppression, consistent with “comovers”
- supports fireball formation with:
  $\tau_{FB} \Gamma(\psi') \sim 1 \Rightarrow \Gamma_{avg}(\psi') \sim 50$-100 MeV
  $\tau_{FB} \Gamma(J/\psi) << 1 \Rightarrow \Gamma_{avg}(J/\psi) < 20$ MeV

similar to thermal widths at $T \approx 200$ MeV

[Du et al ‘15] [Ferreiro ‘15] [PHENIX] [ALICE] [EPS09]
4.2 Heavy-Quark Potential and $\Upsilon(1S)$ Suppression

**Input “Potential”**

- **$U_{QQ}$**
  - $r$ [fm]
  - $U_{QQ}$ values:
    - $1.09T_c$
    - $1.13T_c$
    - $1.19T_c$
    - $1.29T_c$
    - $1.57T_c$
    - $1.89T_c$

- **$F_{QQ}$**
  - $r$ [fm]
  - $F_{QQ}$ values:
    - $0.76T_c$
    - $0.81T_c$
    - $0.90T_c$
    - $0.96T_c$
    - $1.00T_c$
    - $1.07T_c$
    - $1.23T_c$
    - $1.50T_c$
    - $1.98T_c$
    - $4.01T_c$

**Graphs and Data**

- $\sqrt{s_{NN}} = 2.76$ TeV
- $|y| < 2.4$
- $0 < p_T < 40$ GeV
- $\Upsilon(1S)$, CMS Preliminary
- $\Upsilon(2S)$

- **Regeneration for $\Upsilon(1S), \Upsilon(2S)$?**

- **$\Upsilon(1S)$ suppression prefers “strong” ($U$) over “weak” ($F$) in-med. potential**

- **Role of regeneration for $\Upsilon(1S), \Upsilon(2S)$?**
4.2 $\Upsilon(1S)$: Rapidity Puzzle

- problem of large(r) suppression in 2.76 TeV ALICE data
- beware of cold nuclear matter effects
- Regeneration: $N_{bb} \sim 1$ for central PbPb
  \[ \Rightarrow \text{canonical limit } N_Y \sim (N_{bb})^1 \]
2.2 Quarkonium Width Comparisons

- Fair agreement for $J/\psi$
- Larger spread for $\Upsilon$ states
- Binding energies differ
2.) Theoretical Tools

- **Statistical Hadronization model:** chem. equil. of charm hadrons

\[ N_{\psi}^{eq}(T_{ch}) = V_{FB} d_{\psi} \gamma_c^2 \int \frac{d^3 p}{(2\pi)^3} f_{\psi}(m_{\psi}, T_{ch}) \]

- **Transport Approaches**

**Boltzmann** equat.

\[ p^\mu \partial_\mu f_{\psi} = -E_p \Gamma_{\psi} f_{\psi} + E_p \beta \]

→ **Rate** equation

\[ \frac{dN_{\psi}}{d\tau} = -\Gamma_{\psi} \left[ N_{\psi} - N_{\psi}^{eq} \right] \]

- **Reaction Rate** $\Gamma_{\psi}$
  - “Strong” binding $E_B \geq T$
  - “Weak” binding $E_B < m_D$

- gluo-dissociation (“singlet-to-octet”)
  - [Bhanot+Peskin ‘85, Brambilla et al ‘08, Liu et al ‘13…]

- “quasi-free”/ Landau damping
  - [Grandchamp+RR ‘02, Songet al ’07, Laine et al ‘07,…]
1.4 Systematic Approach to Heavy Flavor in Matter

Theory

latQCD HQ free energy

Heavy-quark potential

Quarkonium binding $E_B$

Transport

HQ interactions in QGP ($D_s$)

Quarkonium reaction rate $\Gamma_\Psi$

Experiment

Open HF observables

Quarkonium observables
3.3 Properties of Charmonium Excess

- excess concentrated at low $p_T$
- systematic softening of $J/\psi$ $p_T$-spectra with increasing $\sqrt{s}$
  → nature of source changes
4.1 Charm Thermalization + J/ψ Regeneration

→ Softening of charm-quark spectra facilitates regeneration

**J/ψ Equilibrium Fraction**

![Graph showing J/ψ equilibrium fraction versus T/\(T_c\)]

- **Charm-Quark Diffusion Coeff.**

![Graph showing charm-quark diffusion coefficient versus T/\(T_c\)]

- **Charmonium phenomenology** favors \(\tau_c^{\text{eq}} \leq 5 \text{ fm/c}\) ("strong" coupling)

\[
D_s = \tau_c^{\text{eq}} \frac{T}{m_Q} \leq \frac{(4-8)}{(2\pi T)}
\]
1.3 Quarkonium Transport in URHICs

Production + evolution of cc̄ wave pack.

- Production time: τ \approx 1 \text{fm/c}
- QGP diffusion time in QGP: τ \approx 5 \text{fm/c}
- Hadronization time: τ_\psi \approx 1/Γ_\psi

cc̄ wave pack evolves in the fireball time, T_\text{melt}, where the \psi meson can form.

The cc̄ wave pack hadronizes at T_\text{p_c}.

4.2 $\Upsilon(1S)$ and $\Upsilon(2S)$ Transport cont’d

... as implemented in current transport approaches

- $\Upsilon(2S)$ more sensitive to in-medium potential
4.5 In-Medium Quarkonium Binding Energies
2.1 Potential Extraction from Lattice Data

- **Free Energy**
  \[ F_{Q\bar{Q}}(r_1 - r_2) = -\frac{1}{\beta} \ln (G^\gamma(-i\beta, r_1 - r_2)) = -\frac{1}{\beta} \ln \left( \int_{-\infty}^{\infty} d\omega \sigma(\omega, r_1 - r_2) e^{-\beta \omega} \right) \]

- **\( Q\bar{Q} \) Spectral Function**
  \[ \sigma(\omega, r) = \frac{1}{\pi} \frac{(V + \Sigma)_I(\omega)}{(\omega - (V + \Sigma)_R)^2 + (V + \Sigma)_I^2(\omega)} \]

**Bayesian Approach**

- Potential close to free energy

  [Burnier et al ’14]

**T-Matrix Approach**

- Account for large imaginary parts
- Remnant of confining force!

[S.Liu+RR ’15]
3.3 Heavy-Flavor Transport at RHIC + LHC

- flow bump in $R_{AA}$ + large $v_2$ $\leftrightarrow$ strong coupling near $T_{pc}$ (recombination)
- high-precision $v_2$: transition from elastic to radiative regime?
Outline

1.) Introduction

2.) Current Status

3.) In-Medium Binding and Dissociation
   • Melting vs. Regeneration

4.) Cold-Nuclear-Matter Effects
   • Baseline vs. in-Medium Probe

5.) Conclusions