Quarkonium tomography of heavy ion collisions at the LHC
• Heavy flavor, both open and quarkonia, is an important probe of all forms of nuclear matter QGP, strong gluon fields, etc

• NRQD and quarkonium production in p+p
• Quarkonia in the medium – thermal and collisional dissociation
• Different systems and rapidities
• Heavy flavor in jets
Quarkonium properties and the QGP

- Quarkonia (e.g. J/ψ, Υ), bound states of the heaviest elementary particles, long considered standard candle to characterize QGP properties. Most sensitive to the space-time temperature profile.

\[
\psi(r) = Y_l^m(\hat{r}) R_{nl}(r)
\]

\[
\left[ -\frac{1}{2\mu_{\text{red}}} \frac{\partial^2}{\partial r^2} + \frac{l(l+1)}{2\mu_{\text{red}}r^2} + V(r) \right] r R_{nl}(r) = (E_{nl} - 2m_Q) r R_{nl}(r)
\]

Mocsy et al. (2007)
Bazavov et al. (2013)

<table>
<thead>
<tr>
<th>l</th>
<th>n</th>
<th>$E_{nl}$ (GeV)</th>
<th>$\sqrt{\langle r^2 \rangle}$ (GeV$^{-1}$)</th>
<th>$k^2$ (GeV$^2$)</th>
<th>Meson</th>
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Matsui et al. (1986)
Quarkonium production at intermediate and high $p_T$

- Use NRQCD, expansion in the small velocity between the heavy quarks

$$d\sigma(J/\psi) = d\sigma(Q\bar{Q}([^3S_1]_1))\langle O(Q\bar{Q}([^3S_1]_1) \rightarrow J/\psi) \rangle + d\sigma(Q\bar{Q}([^1S_0]_8))\langle O(Q\bar{Q}([^1S_0]_8) \rightarrow J/\psi) \rangle + d\sigma(Q\bar{Q}([^3S_1]_8))\langle O(Q\bar{Q}([^3S_1]_8) \rightarrow J/\psi) \rangle + d\sigma(Q\bar{Q}([^3P_0]_8))\langle O(Q\bar{Q}([^3P_0]_8) \rightarrow J/\psi) \rangle + d\sigma(Q\bar{Q}([^3P_1]_8))\langle O(Q\bar{Q}([^3P_1]_8) \rightarrow J/\psi) \rangle + d\sigma(Q\bar{Q}([^3P_2]_8))\langle O(Q\bar{Q}([^3P_2]_8) \rightarrow J/\psi) \rangle + \cdots$$

Example for $J/\psi$

- LO fit, improved $\chi_c$ and $\psi(2s)$ softer at high $p_T$

J. Bodwin et al. (1995)

R. Sharma et al. (2011)
Proto-quarkonia distributed according to the binary collisions density
- QGP modelled by relativistic fluid dynamics

Compare to solutions at $T = 190$ MeV

<table>
<thead>
<tr>
<th>$l$</th>
<th>$n$</th>
<th>$E_{nl}$ (GeV)</th>
<th>$\sqrt{\langle r^2 \rangle}$ (GeV$^{-1}$)</th>
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<tr>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>$\chi_b(3P)$</td>
</tr>
</tbody>
</table>

iEBE-VISHNU simulator (1+2D) C. Shen et al. (2014)

- Viscous second order Israel Stewart event-by-event hydrodynamics
**Time evolution of quarkonium states**

- Very rough analogy with a radioactive decay chain

\[
\frac{dN}{dt} = \lambda N - \lambda N
\]

- Competition between the energetic, heavy quark pairs ("partons") binding into quarkonia vs. dissociating into free quarks

\[
f_{\text{Parton}} = \sum g_\bar{Q}Q(\text{spin, color})
\]

\[
f_{\text{Quarkonia}} = \sum_{\text{States}} J/\psi, \psi(2s), \chi_c \\
... \Upsilon(1s), \Upsilon(2s), \Upsilon(3s), \chi_b(1S), \chi_b(2S)...
\]

- Dynamics reduces to a kinetic approximation

\[
\partial_t f_{\text{Parton}}(E, t) = -\frac{1}{\langle \tau_{\text{form}}(E, t) \rangle} f_{\text{Parton}}(E, t) \\
+ \frac{1}{\langle \tau_{\text{diss}}(E, t) \rangle} f_{\text{Quarkonia}}(E, t)
\]

\[
\partial_t f_{\text{Quarkonia}}(E, t) = +\frac{1}{\langle \tau_{\text{form}}(E, t) \rangle} f_{\text{Parton}}(E, t) \\
- \frac{1}{\langle \tau_{\text{diss}}(E, t) \rangle} f_{\text{Quarkonia}}(E, t)
\]

Initial conditions: perturbatively produced, QQ-bar states

\[
f_{\text{Parton}}(E, t = 0) = \frac{dN_{\text{Parton}}}{dp_T} \\
f_{\text{Quarkonia}}(E, t = 0) = 0
\]

This is the effect of the medium

Well-understood asymptotic limits
Effects of the medium

- Formation time – a bit of a misnomer. Typical time for the onset of interactions – take it to be $O(1 \text{ fm})$

- Dissociation time – includes thermal wavefunction effect and collisional broadening

$$P_{f \leftarrow i}(\chi \mu_D^2 \xi, T) = \left| \frac{1}{2(2\pi)^3} \int d^2k \, dx \, \psi_i^*(\Delta k, x) \psi_i(\Delta k, x) \right|^2$$

$$= \left| \frac{1}{2(2\pi)^3} \int dx \, \text{Norm}_f \text{Norm}_i \pi \, e^{-\frac{m_Q^2}{x(1-x)\Lambda(T)^2}} \, e^{-\frac{m_Q^2}{x(1-x)\Lambda_0^2}} \right|^2$$

$$\times \frac{2[x(1-x)\Lambda(T)^2][\chi \mu_D^2 \xi + x(1-x)\Lambda_0^2]}{[x(1-x)\Lambda(T)^2] + [\chi \mu_D^2 \xi + x(1-x)\Lambda_0^2]}$$

Dissociation time

$$\frac{1}{t_{\text{diss.}}} = -\frac{1}{P_{f \leftarrow i}(\chi \mu_D^2 \xi, T)} \frac{dP_{f \leftarrow i}(\chi \mu_D^2 \xi, T)}{dt}$$

- Initial wavefunction $\sim$ vacuum
- Collisional broadening
- Thermal narrowing

S. Aronson et al. (2017)
• The model predicts slow change of $R_{AA}$ for mid-peripheral to central collisions. Applicable at moderate high $p_T$ under the fragmentation region.

• For Upsilon $p_T$ integrated results available. Mean $p_T \sim 5$ GeV (for 3S even 7 GeV)
Phenomenological results – transverse momentum

- Both ground and excited quarkonium states with consistent feed down – which is $p_T$ dependent!
- We have centrality and $p_T$ predictions for 5.02 TeV around midrapidity

Approximately flat $p_T$ dependence

• Good separation the suppression of the ground and excited
• In calculating the min bias results we found that the result is dominated by the first few centrality bins

\[ R_{AA}^{\text{min bias}}(p_T) = \frac{\sum_i R_{AA}(b_i) W_i}{\sum_i W_i} \]

\[ W_i = \int_{b_i \text{ min}}^{b_i \text{ max}} N_{\text{coll}}(b) \pi b \, db \]

• Suppression of excited states is very important to clarify the mechanism of quarkonium production and suppression

If at very high \( p_T \) fragmentation dominates and there is energy loss – suppression of ground and excited states will be the same. We have not seen that yet

S. Aronson et al. (2017)
• Xenon collisions provide a smaller system but results are similar to lead at smaller centralities. E.g. 0-10% Xe+Xe ~ 10-30% Pb+Pb

• At the same centrality the differences are subtle. 10% for the ground states, 30% for the first excited states

• At forward rapidities the slightly smaller densities are offset by cold nuclear matter effects. Very slightly larger suppression overall

Results are preliminary

R. Sharma et al. in preparation (2018)
Heavy quarks and quark pairs in the vacuum and the medium

$\mathcal{L}_{\text{QCD}} = \bar{\psi} (i \not{D} - m) \psi \quad iD^\mu = \partial^\mu + gA^\mu \quad A^\mu = A^\mu_\text{c} + A^\mu_\text{s} + A^\mu_\text{G}$

Feynman rules depend on the scaling of $m$. The key choice is $m/p^+ \sim \lambda$

Result: $\text{SCET}_{M,G} = \text{SCET}_M \times \text{SCET}_G$

Quarkonia produced by gluon splitting for example, together with quark fragmentation. The key is to understand the mass dependence in parton showers

\[ \left( \frac{dN}{dx d^2k_{\perp}} \right)_{g\to QQ} = T_R \frac{\alpha_s}{2\pi^2} \frac{1}{k_{\perp}^2 + m^2} \left[ x^2 + (1-x)^2 + \frac{2x(1-x)m^2}{k_{\perp}^2 + m^2} \right] \]
\[ \left( \frac{dN}{dx d^2k_{\perp}} \right)_{Q\to Qg} = C_F \frac{\alpha_s}{\pi^2} \frac{1}{k_{\perp}^2 + x^2m^2} \left[ 1 - x + x^2/2 \frac{1}{x} - \frac{x(1-x)m^2}{k_{\perp}^2 + x^2m^2} \right] \]

- You see the dead cone effects
- You also see that it depends on the process – it not simply $x^2m^2$ everywhere: $x^2m^2, (1-x)^2m^2, m^2$
Main results: in-medium splitting & parton energy loss

Organizing principle – build powers of the scattering cross section in the medium

Full massive in-medium splitting functions now available

Can be evaluated numerically

Representative example

\[
\left(\frac{dN_{\text{med}}}{dx d^2k_{\perp}}\right)_{Q \rightarrow Qg} = \frac{\alpha_s}{2\pi^2} C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2q_{\perp} \frac{1}{\sigma_{el}} \frac{d\sigma_{\text{med}}}{d^2q_{\perp}} \left\{ \left(1 + \frac{(1-x)^2}{x}\right) \left[ \frac{B_1}{B_1^2 + \nu^2} \right. \right. \\
\left. \left. \times \left( \frac{B_1}{B_1^2 + \nu^2} - \frac{C_1}{C_1^2 + \nu^2} \right) (1 - \cos[(\Omega_1 - \Omega_3)\Delta z]) + \frac{C_1}{C_1^2 + \nu^2} \cdot \left( \frac{2}{C_1^2 + \nu^2} - \frac{A_1}{A_1^2 + \nu^2} \right) \right. \right. \\
\left. \left. \left. - \frac{A_1}{A_1^2 + \nu^2} \cdot \left( \frac{D_1}{D_1^2 + \nu^2} - \frac{A_1}{A_1^2 + \nu^2} \right) (1 - \cos[\Omega_4\Delta z]) \right. \right. \\
\left. \left. \left. + \frac{1}{N_c} \frac{B_1}{B_1^2 + \nu^2} \cdot \left( \frac{A_1}{A_1^2 + \nu^2} - \frac{B_1}{B_1^2 + \nu^2} \right) (1 - \cos[(\Omega_1 - \Omega_2)\Delta z]) \right. \right. \\
\left. \left. + x^3m^2 \left[ \frac{1}{B_1^2 + \nu^2} \cdot \left( \frac{1}{B_1^2 + \nu^2} - \frac{1}{C_1^2 + \nu^2} \right) (1 - \cos[(\Omega_1 - \Omega_2)\Delta z]) + \ldots \right] \right. \right\} \right\}
\]

\[A_\perp = k_\perp, \quad B_\perp = k_\perp + xq_\perp, \quad C_\perp = k_\perp - (1-x)q_\perp, \quad D_\perp = k_\perp - q_\perp, \quad \Omega_1 - \Omega_2 = \frac{B_1^2 + \nu^2}{p_0^2x(1-x)}, \quad \Omega_1 - \Omega_3 = \frac{C_1^2 + \nu^2}{p_0^2x(1-x)}, \quad \Omega_4 = \frac{A_1^2 + \nu^2}{p_0^2x(1-x)}, \]

\[\nu = m \quad (g \rightarrow Q\bar{Q}), \quad \nu = x\tilde{m} \quad (Q \rightarrow Qg), \quad \nu = (1-x)m \quad (Q \rightarrow gQ), \]
How to pin down the mass dependence

- Look at jet substructure. The first observable is the jet splitting function
  - Allows to write down factorization theorems, no non-global logs elimination
  - Directly related to the splitting functions / parton showers
  - Eliminates background, medium, etc

A. Larkoski et al. (2014)

\[ z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \left( \frac{\Delta R_{12}}{R_0} \right)^{\beta} \]

- Groomed subjet distribution using "soft drop"

- Look for a regime where: \( x^2 m^2, (1-x)^2 m^2, m^2 \leq k_T^2 \) If we translate \( k_T \) into angle, relate it to the jet splitting kinematics for \( z_g \sim 1/2 \)

Y.T. Chien et al. (2017)

pp - 1 propagator, AA – 2 propagators

Q to Qg

\[ \left( \frac{1}{k_\perp^2 + x^2 m^2} \right) \times \left( \frac{1}{k_\perp^2 + x^2 m^2} \right) \sim \frac{1}{x^4 m^4} c \]

g to QQbar

\[ \left( \frac{1}{k_\perp^2 + m^2} \right) \times \left( \frac{1}{k_\perp^2 + m^2} \right) \sim \frac{1}{m^4} c \]

light partons

\( \sim 1/x^2 \)
Inverting the mass hierarchy of jet quenching effects

- At RHIC jet energies, and at lower jet energies at the LHC there is a unique reversal of the mass hierarchy effects on $b > c \geq u,d$.

- Can help place constraints on the parton mass dependence of in-medium showers – not only open heavy flavor but also $J$.

H. Li et al. (2018)
Quarkonia at high $p_T$ provide complementary probes of the medium. More sensitive to the temperature (than transport coefficients). Described their evolution by kinetic rate equations.

NRQCD baseline and feed down for all J/$\psi$ and $\Upsilon$ states performed. Approximately constant $p_T$ dependence of the suppression. Found slight tension between the ground and excited states’ description.

Centrality dependence rather flat, hence the suppression in Xe+Xe is quite similar at the same centrality to the one in Pb+Pb.

Excited states’ suppression provide constraints on the picture of parton fragmentation in quarkonia and energy loss. Developed an effective theory of heavy quark propagation in QCD matter. Obtained heavy quark splitting functions, relevant to open heavy flavor and quarkonia at high $p_T$.

The most important mass dependence ("dead cone" effect) in parton showers can be studies with b-jets substructure. The region of interest can be identified with a unique reversal of the mass hierarchy of jet quenching effects.