Thermal Quarkonia in heavy ion collisions

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January 30, 2015

Timescales

- As we increase the temperature of the thermal medium, quarkonia in thermal equilibrium with the medium will be less bound due to screening effects and dissociation processes
- At high enough temperatures they will “melt”. In lattice calculations shows up as a broadening of spectral functions
- In the heavy ion environment multiple time scales relevant
- Interplay between formation rates, dissociation rates and the expansion rate of the medium

Dissociation rates

- Weak coupling thermal field theory calculations using a hierarchy of scales $m_Q \gg T \gg \Lambda_{QCD}$ expected to be valid at high temperature give widths $\Gamma \sim g^2 T$
- The widths are related to the imaginary part of the potential as well as the screening of charge
- *(Petreczky et. al., Laine et. al., Brambilla et. al., Rothkopf et. al.)*

Usual procedure

- The $Q\bar{Q}$ formed on time scales $\sim 1/m_Q$
- Quarkonia formed on time scales $t_\mathrm{f} \sim 1/E_b$
- Write down the rate equation for the yields of quarkonia by using the width from dissociation rates or from the complex eigen-energies
- *(Hees et. al., Strickland et. al.)*

Formation rates

- No firm theory
- A rough estimate gives $1/E_b \sim 1/(mv^2) \sim 1/(m\alpha)$ for vacuum binding energies
- Should one use "thermal" binding energies or vacuum binding energies? The formation times for the "thermal" binding states is much longer
- For a boosted (high p_T) quarkonium, even larger in the lab frame

A model for high p_T quarkonium propagation

- Following is a model for $p_T \gtrsim$ 3MeV quarkonia *(Vitev, Sharma)*
- Partonic process create color-octet and color-singlet "pre-quarkonia" on a short time scale of $1/m_Q$
- The production cross-section in pp collisions is

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

- $d\sigma(Q\bar{Q}([^3S_1]_1))$... are short distance cross-sections that can be calculated in perturbative QCD
- $\langle\mathcal{O}(Q\bar{Q}([^3S_1]_1) \to J/\psi)\rangle$... are non-perturbative matrix elements that have to be fitted to experiments *(Braaten, LePage, Cho, Leibovich....)*

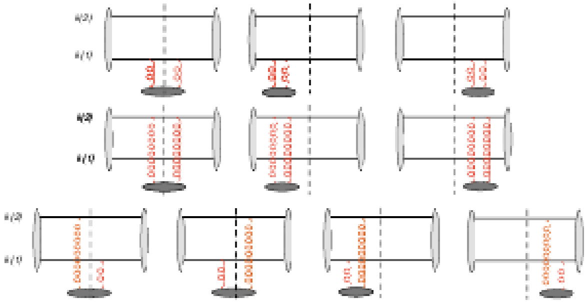
Basic model

- For pp collisions in NRQCD the details of hadronization from the short distance state do not matter
- For the AA collisions, the dynamics are important. We assume that for $t_f \sim 1/E_b$, a meson is formed. This is a simplification
- The color-octet component undergoes energy loss during this time
- Collisions with the thermal gluons dissociate this meson on a time scale t_{diss}
- Rate equations give the evolution of the quarkonium yields

Dissociation rate

- The dissociation rate given most easily in light cone coordinates with z chosen to be in the direction of the motion of the quarkonium
- The collision with thermal gluons affects the wavefunction perpendicular to the motion
- The heavy quarks get a transverse momentum kick $\sim \mu = gT$ after travelling the mean free path λ

Dissociation rate



Dissociation rate

- $$P_{\rm surv.}(\chi\mu^2\xi) = \Big|\frac{1}{2(2\pi)^3}\int d^2\mathbf{k}dx\,\psi_f^*(\Delta\mathbf{k},x)\psi_i(\Delta\mathbf{k},x)\Big|^2 = \Big|\frac{1}{2(2\pi)^3}\int dx\,\mathcal{N}^2 \pi x(1-x)\Lambda^2 e^{-\frac{m_Q^2}{x(1-x)\Lambda^2}}\Big[\frac{2\sqrt{x(1-x)\Lambda^2}\sqrt{\chi\mu^2\xi+x(1-x)\Lambda^2}}{\sqrt{x(1-x)\Lambda^2}^2+\sqrt{\chi\mu^2\xi+x(1-x)\Lambda^2}^2}\Big]\Big|^2$$
- $t_{\rm diss.}(p_T,\alpha) = \frac{dP_{\rm diss.}}{dt} = -\frac{dP_{\rm surv.}}{dt}$

Formation time tables

- $\delta r \sim \frac{1}{m_Q v}$, thus $t_{\text{form}} \sim (1,2)\gamma \frac{1}{m_Q v^2}$
- The formation and decay rates for $p_T = 10$GeV for $0 - 20\%$ central collisions

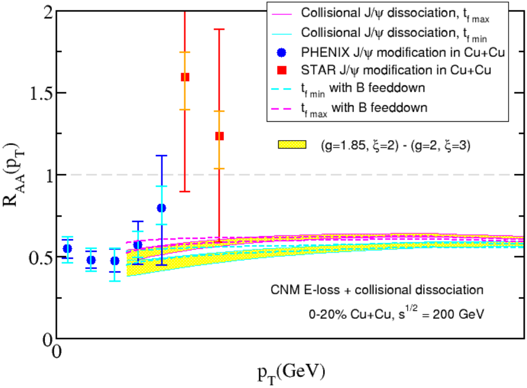
Charmonium state	J/ψ	$\chi_{c0,1,2}$
Formation time$_{\text{max}}$ [fm/c]	3.3	4.4
Dissociation time [fm/c]	1.7	1.6

Bottomonium state	$\Upsilon(1)$	$\Upsilon(2)$	$\Upsilon(3)$	$\chi_{b0,1,2}(1)$	$\chi_{b0,1,2}(2)$
Formation time$_{\text{max}}$ [fm/c]	1.4	2.9	4.2	2.4	3.5
Dissociation time [fm/c]	3.3	2.2	1.9	1.9	2.0

Implications for R_{AA}

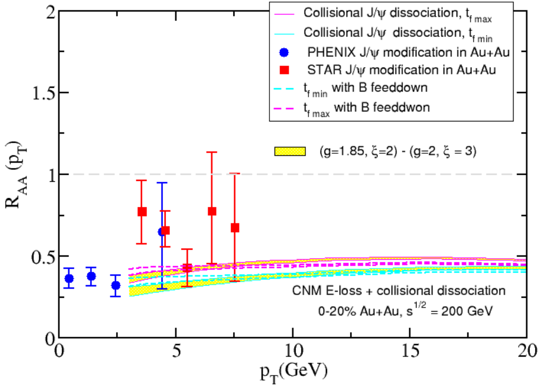
- Dissociation processes will reduce the yield of quarkonia in AA collisions over the (scaled) yield in pp collisions; some of the quarkonia form open heavy flavor mesons. $R_{AA} < 1$
- Seen for Υ as well as J/Ψ *(RHIC, LHC)*
- Complications due to cold nuclear matter effects
- The most relevant cold nuclear matter effect taken into account is cold nuclear matter energy loss

Results for Cu+Cu at RHIC

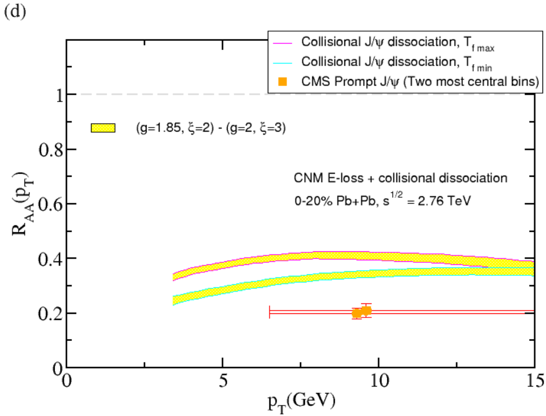


RS and Ivan Vitev Phys. Rev. C

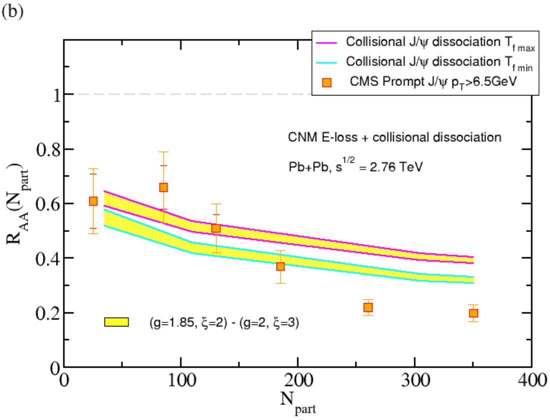
Results for Au+Au at RHIC



R_{AA} at the LHC



R_{AA} versus N_{part} at the LHC



Summary

- The biggest uncertainty comes from the formation time
- Cold nuclear matter effects also give some suppression
- For small p_T, consequences of thermal equilibrium

Implications for relative yields

- If the formation and dissociation processes are rapid enough for the ground state as well as the excited states, the ratios of their yields should thermalize
- A simple model: the quarkonum bound states thermalize between each other till a freezeout point
- For this purpose more useful to compare the relative yields *(CMS JHEP04(2014)103, 2.76TeV, mid-rapidity)*

$$r[\Upsilon(2S)] = \frac{N_{\mathrm{PbPb}}[\Upsilon(2S)]}{N_{\mathrm{PbPb}}[\Upsilon(1S)]} = 0.09 \pm 0.02 \pm 0.02 \pm 0.01$$
$$r[\Upsilon(3S)] = \frac{N_{\mathrm{PbPb}}[\Upsilon(3S)]}{N_{\mathrm{PbPb}}[\Upsilon(1S)]} < 0.04 \text{ (95\% confidence limit)} \tag{1}$$

- $\frac{N(\psi(1))}{N(\psi(2))} = (\frac{m_1}{m_2})^{3/2} e^{(E_2 - E_1)/T}$
- Assuming freezeout occurs relatively late

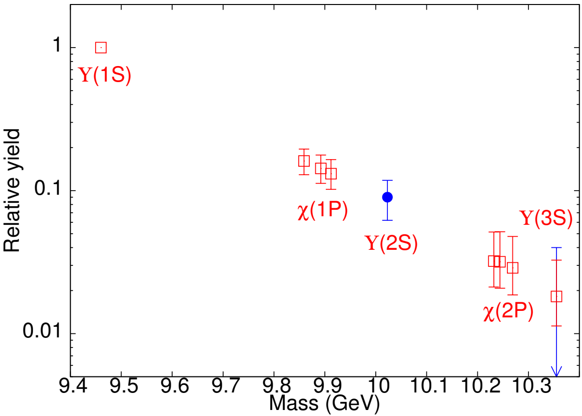
$$T_f = 222^{+28}_{-29}\mathrm{MeV} \tag{2}$$

from $\Upsilon(2S)/\Upsilon(1S)$ and $T_f < 282\mathrm{MeV}$ the corresponding

Implications for relative yields

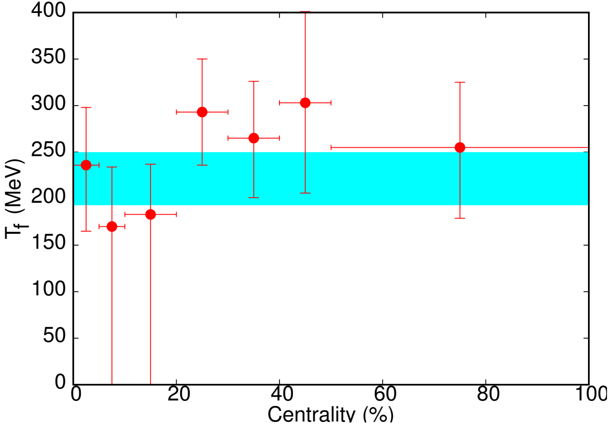
- Cold nuclear matter effects should not play a role
- Valid only for small p_T yields
- So far described a one parameter (T) model which is fitted to one data point. But observations of other states can give more information

Thermal model for bottomonia



Sourendu Gupta and RS Phys. Rev. C 89, 057901 (2014)

T_f versus centrality



(Sourendu Gupta and RS)

Remarks

- Comparing to *pp*, *pPb*
  - The yield ratios for *pp* and *pPb* not very different
  - Both are inconsistent with a thermal interpretation ($T_{12} \approx 400$MeV, $T_{13} \approx 200$MeV)
- Mean p_T not given, but using peak p_T as proxy, $p_T \sim 3.5$ giving $p_T/m_{Q\bar{Q}} \sim 0.35$

T_f versus rapidity

- We expect the freezeout to be independent of rapidity as well (caveats)
- Data for $\Upsilon(1S)$ shows $R_{AA} = 0.22 \pm 0.05 \pm 0.02 \pm 0.03$ in the central bin *(ALICE Physics Letters B 738 (2014) 361372)* for $2.5 < y < 4$
- Pushing the thermal interpretation further, we expect $\Upsilon(2S) = 0.11 \pm 0.08$ (Preliminary)

What about J/ψ?

- *(CMS 2012)*

$$r[\psi(2S)] = \frac{N_{\mathrm{PbPb}}[\psi(2S)]}{N_{\mathrm{PbPb}}[J/\psi]} = \begin{cases} 0.024 \pm 0.008 & (|y| \leq 1.6, \;\; 6.5 \leq p_T \leq 30) \\ 0.105 \pm 0.02 & (1.5 \leq |y| \leq 2.4, \;\; 3 \leq p_T \leq 30). \end{cases} \quad (3)$$

- Naiive thermal model gives $T_f = 159 \pm 31$ MeV at central rapidity (larger p_T) but 265 ± 59 MeV at larger rapidity (smaller p_T)
- Systematics with N_{part} not satisfactory either as T drops from 277MeV to 200MeV as N_{part} decreases from 310 to 35
- Attribute this to larger $p_T/m_{Q\bar{Q}}$ of the sample

What about J/ψ?

- ALICE has data for the double ratio *(arXiv:1211.2578v1)* $R_{AA}(\psi(2S))/R_{AA}(\psi(1S))$ for and p_T all the way to 0. If the *pp* baseline is given, one can analyze the systematics in a regime where we intuitively expect the simple model to work better
- Also see ALICE document (*CERN-PH-EP-2014-092)*

Summary

- A dissociation model used to describe simultaneously RHIC and LHC data on quarkonium yields at high p_T. Not thermalized enough at high T
- Formation dynamics of quarkonia in a heavy ion collision subtle and give large systematic uncertainties in model calculation of yields
- There is an interesting pattern in the low p_T yields of excited states of bottomonia at the LHC: the relative yields seem thermal with $T_f \approx 222$MeV. Seems worth checking further by looking at different y's and species
- Does it show up also in the small p_T bins for J/ψ? Experimentally challenging