Quarkonium production and propagation in heavy ion collisions

Rishi Sharma

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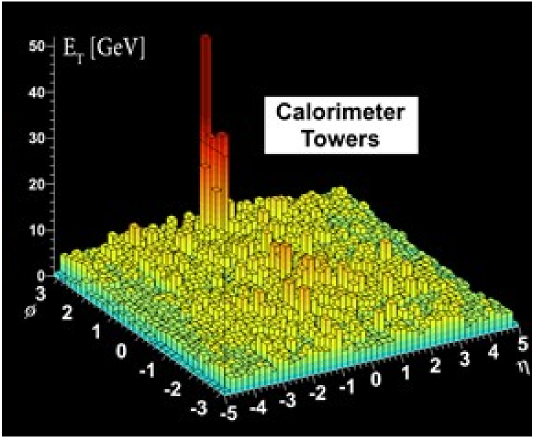
Introduction

Colliding heavy ions

- Asymptotic freedom suggests that at a high enough temperature $T > T_c \sim \Lambda_{QCD}$ matter exists in a quark gluon plasma (QGP) phase where the quarks and gluons are deconfined
- Experiments at RHIC and the LHC create the QGP for short durations of a few fm/c by colliding two heavy nuclei moving relativistically in the center of mass frame
- Our goal is to study the properties of the QGP by looking at the emitted particles

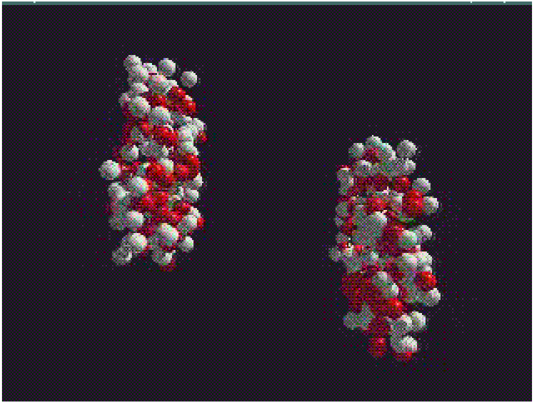
Observing particles



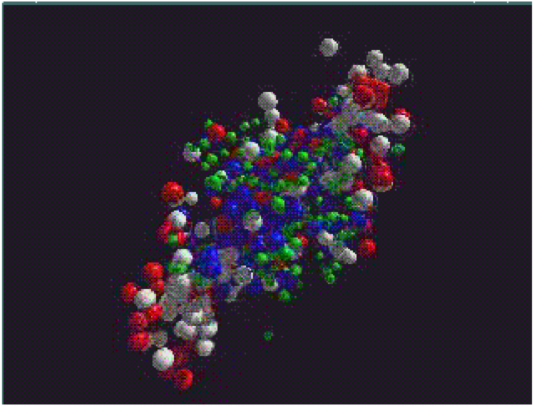
The low p_T particles, hydrodynamics

- Model the low p_T ($\lesssim 3GeV$) particles as arising from a thermalized QGP

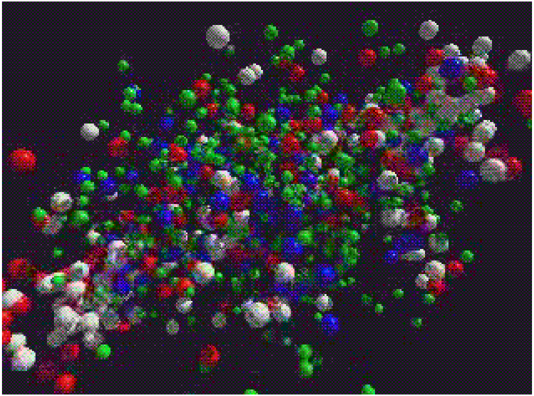
Physical picture



Physical picture



Physical picture



The low p_T particles, hydrodynamics

- This picture has been very successful at describing collective properties of the low p_T spectra
- For example, the QGP flows like a fluid with low viscosity *[Teaney et. al., Romatschke et. al., Heinz et. al.,]* (interesting connections with string theory *[Son, Starinets]*)

The high p_T particles

- Energetic particles created very early in the heavy ion collision and propagate through the thermal medium
- As they pass through the medium, their properties are affected. For example
  - Energetic partons may lose energy
  - Bound states may dissociate
- Manifests as a modification from the properties in p+p collisions. $R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{N_{\rm coll} dN^{pp}/dp_T}$

Quarkonia

- Bound states of light quarks in QCD, for example protons, are of size $1/\Lambda_{QCD}$ can be thought of having a binding energy $\sim \Lambda_{QCD}$
- For heavy quarks, different situation because $M_Q \gg \Lambda_{QCD}$
- Roughly, $Q\bar{Q}$ states bound by a potential $V(r) \sim -\frac{\alpha_s}{r}$
- The charmed mesons J/ψ
- The bottom mesons Υ
- Color screening $\frac{\alpha_s}{r} \to \frac{\alpha_s e^{-m_D r}}{r}$
- At a large enough temperature $r_{\mathrm{meson}} \sim m_D$, and “melting” occurs *[Matsui, Satz (1986)]*

Motivation

Quarkonia at high p_T

- Formed early in the collisison
- Most studies *[Rapp, Hees et. al., Strickland et. al.]* assume thermal equilibriation of the $Q - \bar{Q}$ interaction and calculate the suppression in low p_T yields
- But for a short distance object with a short formation time, the assumption may not hold
- In this talk, we will assume that the wavefunctions of the quarkonia are not thermalized and see if we can describe RHIC and LHC high p_T $(5 - 20\text{GeV})$ yields in a consistent framework

Formalism and calculation

Production

- The picture for the initial production of Q and $\bar{Q}$ is given by non relativistic qcd (NRQCD) *(Braaten, Bodwin, LePage, Cho, Leibovich, Godbole, Roy, Sridhar, Gupta, Cooper, Nayak ..)*
- Contributions ordered in the small parameter v

$$\begin{aligned} |J/\psi\rangle =& |Q\bar{Q}([{}^3S_1]_1)\rangle + \mathcal{O}(v)|Q\bar{Q}([{}^1S_0]_8 g)\rangle \\ &+ \mathcal{O}(v^2)|Q\bar{Q}([{}^3S_1]_8 gg)\rangle + \mathcal{O}(v^1)|Q\bar{Q}([{}^3P_0]_8 g)\rangle \\ &+ \mathcal{O}(v^1)|Q\bar{Q}([{}^3P_1]_8 g)\rangle + \mathcal{O}(v^1)|Q\bar{Q}([{}^3P_2]_8 g)\rangle + \cdots \end{aligned}$$

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

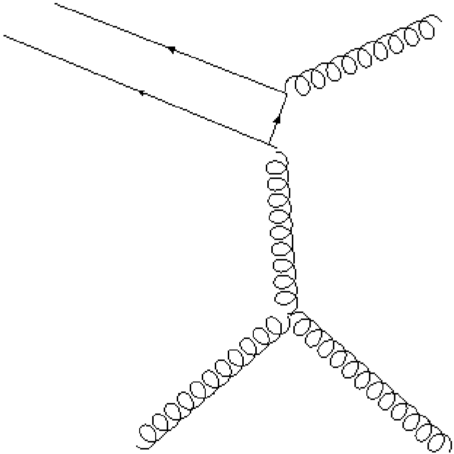
Production

- Form a short distance $Q\bar{Q}$ object, a "proto-quarkonium" which can be both in the color-singlet and the color-octet state
- The "proto-quarkonium" forms a quarkonium on a time-scale t_{form} with probabilities given by the color-octet and the color-singlet matrix elements respectively

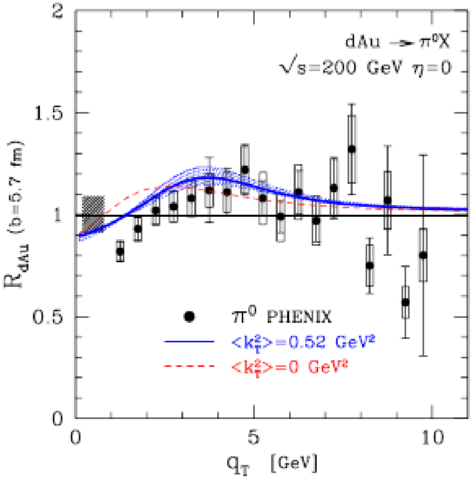
Cold nuclear matter effects

- The yields in A+A collisions is modified from p+p because of (a) cold nuclear matter (CNM) effects (b) QGP propagation
- For the CNM effects consider
  1. Initial state energy loss $\phi(x) \rightarrow \phi(\frac{x}{1-\epsilon})$ where ϕ is the parton distribution function for an incident parton
  2. Coherent multiple scattering $\phi(x) \rightarrow \phi(x[1 - \zeta_d^2 \frac{(A^{1/3}-1)}{(-t+m_d^2)}])$ where $\zeta_{q,g} \approx 0.12, 0.27\mathrm{GeV}^2$. A proposed mechanism for nuclear shadowing
  3. Transverse momentum broadening. A proposed mechanism for the Cronin effect
- Enhanced by system size $L \sim A^{1/3} 1.2\mathrm{fm}$. Affect conclusions about effects of the QGP
- Well studied for light partons, but not so well for quarkonium production

An example



An example of the Cronin effect



- $\phi(x) \to \frac{1}{2\pi\Delta k_\perp^2[A]} \exp(-k_\perp^2/\Delta k_\perp^2[A])\phi(x)$
- $\Delta k_\perp^2[A] = \Delta k_\perp^2[0] + 2\mu^2 \frac{L[A]}{\lambda}$

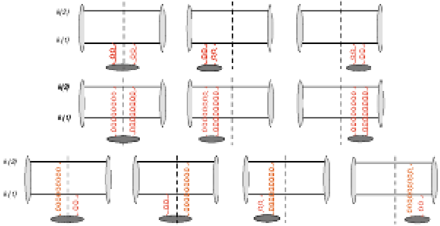
Propagation through the QGP

- The quarkonia dissociate on a time-scale $t_{\rm diss}$ due to the QGP
- We solve the rate equations

$$\begin{aligned}
\frac{d\,N_{Q\bar{Q}}^{\rm hard}(t;p_T,\alpha)}{dt} &= -\frac{1}{t_{\rm form}(t;p_T,\alpha)}N_{Q\bar{Q}}^{\rm hard}(t;p_T,\alpha)\\
\frac{d\,N_{Q\bar{Q}}^{\rm meson}(t;p_T,\alpha)}{dt} &= \frac{1}{t_{\rm form}(t;p_T,\alpha)}N_{Q\bar{Q}}^{\rm hard}(t;p_T,\alpha)\\
&\quad -\frac{1}{t_{\rm diss.}(t;p_T,\alpha)}N_{Q\bar{Q}}^{\rm meson}(t;p_T,\alpha)\\
\frac{d\,N_{Q\bar{Q}}^{\rm diss.}(t;p_T,\alpha)}{dt} &= \frac{1}{t_{\rm diss}(t;p_T,\alpha)}N_{Q\bar{Q}}^{\rm meson}(t;p_T,\alpha)
\end{aligned}$$

- The initial conditions are $N_{Q\bar{Q}}^{\rm hard}(t=0;p_T,\alpha) = N_{NRQCD}^{\rm hard}(p_T,\alpha)$ and $N_{Q\bar{Q}}^{\rm meon}(t=0;p_T,\alpha) = N^{\rm diss.}Q\bar{Q}(t=0,p_T,\alpha) = 0$

Dissociation



- The survival probability is given by

$$P_{\mathrm{surv.}} = \left| \frac{1}{2(2\pi)^3} \int d^2\mathbf{k} dx \, \psi_f^*(\Delta\mathbf{k}, x) \psi_i(\Delta\mathbf{k}, x) \right|^2$$

- $t_{\mathrm{diss.}}(p_T, \alpha) = \frac{dP_{\mathrm{diss.}}}{dt} = -\frac{dP_{\mathrm{surv.}}}{dt}$

Dissociation

- The survival probability is given by

$$P_{\mathrm{surv.}}(\chi\mu^2\xi) = \Big| \frac{1}{2(2\pi)^3} \int dx\, \mathcal{N}^2$$

$$\pi x(1-x)\Lambda^2 e^{-\frac{m_Q^2}{x(1-x)\Lambda^2}} \Big[\frac{2\sqrt{x(1-x)\Lambda^2}\sqrt{\chi\mu^2\xi + x(1-x)\Lambda^2}}{\sqrt{x(1-x)\Lambda^2}^2 + \sqrt{\chi\mu^2\xi + x(1-x)\Lambda^2}^2} \Big] \Big|^2$$

- λ_Q is the mean scattering length of the quark
- $\chi = \frac{L}{\lambda_Q}$ is the average opacity, or roughly the number of collisions
- μ^2 is the typical squared transverse momentum transfer given by the Debye screening scale, $\mu = gT$ for a gluon-dominated plasma
- $\xi \sim$ few is an enhancement factor from the power law tail of the differential scattering cross section

Formation time tables

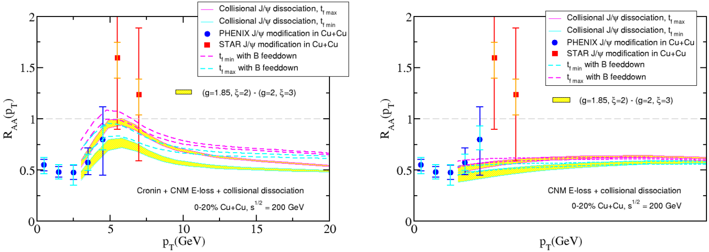
- $\delta r \sim \frac{1}{m_Q v}$, thus $t_{\mathrm{form}} \sim (0.5, 1)\gamma \frac{1}{m_Q v^2}$
- The formation and decay rates for $p_T = 10$GeV for $0 - 20\%$ central collisions

Charmonium state	J/ψ	$\chi_{c0,1,2}$
Formation time$_{\mathrm{max}}$ [fm/c]	3.35	4.40
Dissociation time [fm/c]	1.74	1.61

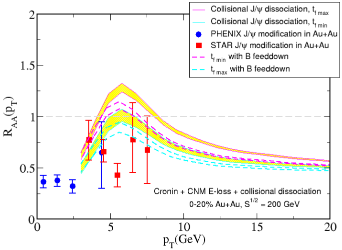
Bottomonium state	$\Upsilon(1)$	$\Upsilon(2)$	$\Upsilon(3)$	$\chi_{b0,1,2}(1)$	$\chi_{b0,1,2}(2)$
Formation time$_{\mathrm{max}}$ [fm/c]	1.44	2.85	4.17	2.36	3.45
Dissociation time [fm/c]	3.30	2.23	1.93	1.93	2.06

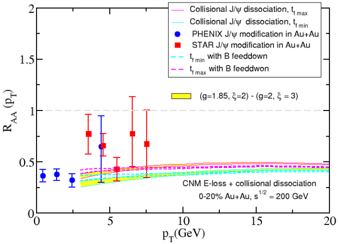
Results

Results for Cu+Cu at RHIC

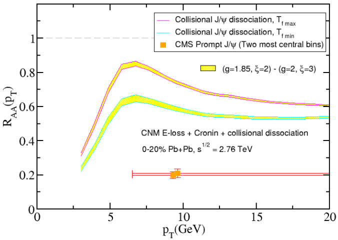


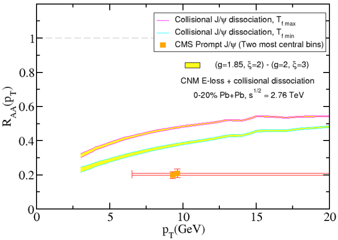
Results for Au+Au at RHIC



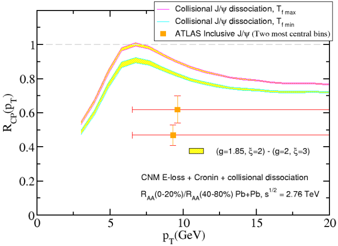


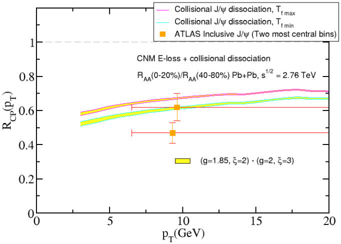
Results for Pb+Pb at the LHC



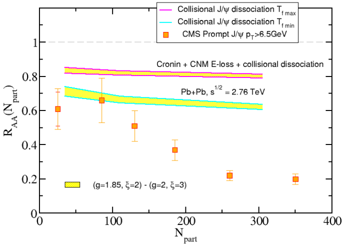


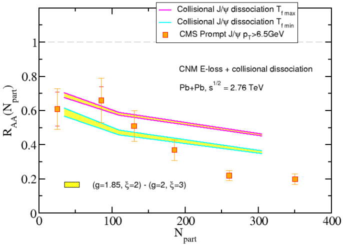
Central versus peripheral at the LHC



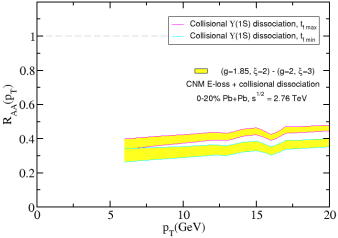


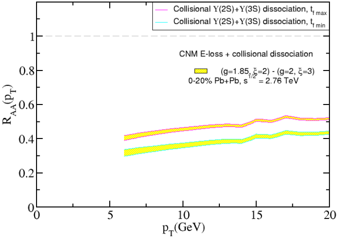
R_{AA} versus centrality at the LHC





Υ, R_{AA}





- $\frac{\Upsilon(2S+3S)}{\Upsilon(1S)}\Big|_{pp} = 0.76^{+0.16}_{-0.14} \pm 0.12,$
  $\frac{\Upsilon(2S+3S)}{\Upsilon(1S)}\Big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$
- $\frac{R_{AA}(\Upsilon(2S+3S))}{R_{AA}(\Upsilon(1S))} = 0.32^{+0.19}_{-0.15} \pm 0.03$

Conclusions

- Exciting era of high statistics, p_T differential data from the LHC
- Appears that transverse momentum broadening is not present in quarkonium production, but need comparisons with p/d+A data to eliminate the possibility
- LHC results, in particular for central Pb+Pb suggest thermalization of the wavefunction
- Rate equations not adequate to study quarkonium production and propagation. The formation process needs to be handled in a better framework

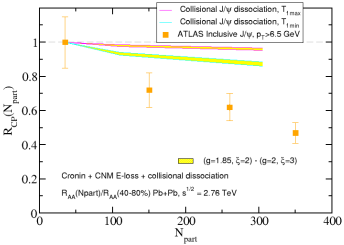
Centrality v/s N_{part}

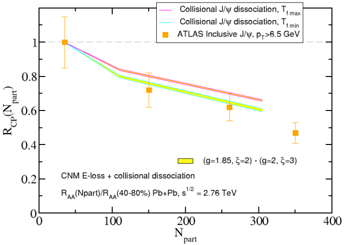
centrality	N_{part}
$0-20\%$	307
$20-40\%$	130
$40-80\%$	35
$0-100\%$ (Min. Bias)	110

Medium parameters

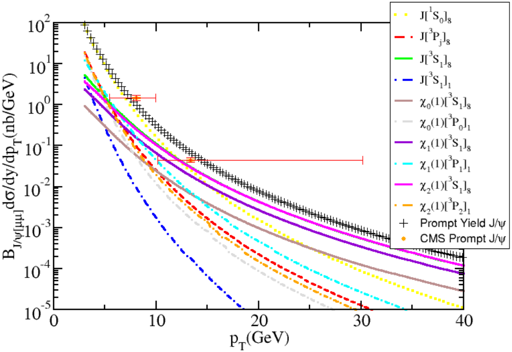
for LHC 0-20%	PbPb	dNdy(g) = 2260 (b=4.5)
for RHIC 0-20%	AuAu	dNdy(g) = 925 (b=4.3)
for RHIC 0-20%	CuCu	dNdy(g) = 235 (b=3.5)

R_{CP} versus centrality at the LHC

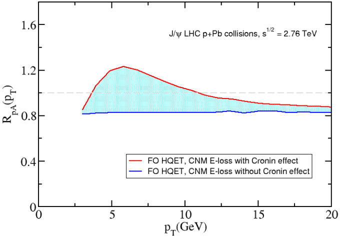




Production in p+p collisions



R_{pPb} at the LHC



Υ suppression at the LHC