

Quarkonium production and propagation in heavy ion collisions

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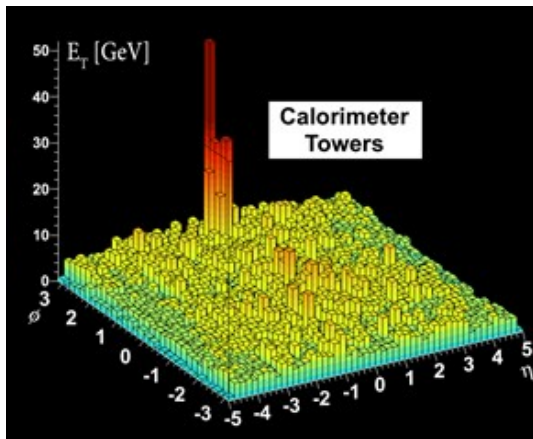
[arXiv:1203.0329 [hep-ph]] with Ivan Vitev

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

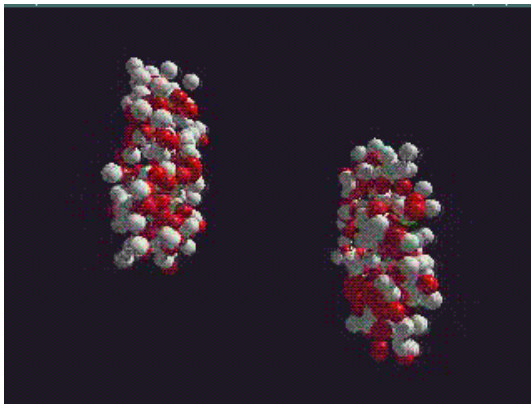
Observing particles



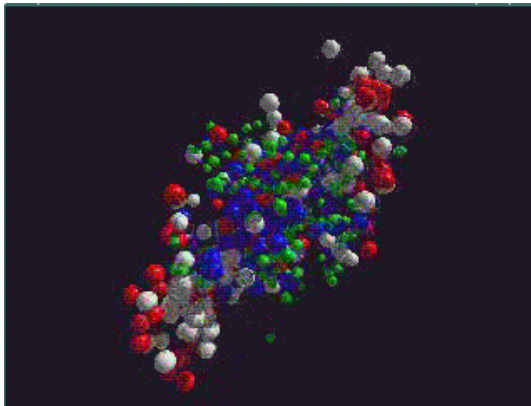
The low p_T particles, hydrodynamics

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

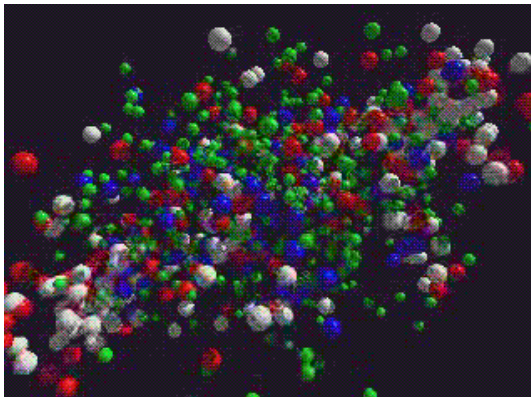
Physical picture



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. $R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{N_{\text{coll}}dN^{pp}/dp_T}$

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 $\frac{\alpha_s}{r} \rightarrow \frac{\alpha_s e^{-m_D r}}{r}$
- ▶ At a large enough temperature $r_{\text{meson}} \sim m_D$, and “melting” occurs [*Matsui, Satz (1986)*]

Motivation

Quarkonia at high p_T

- ▶ Formed early in the collision
- ▶ Most studies [*Rapp, Hees et. al., Strickland et. al.*] assume thermal equilibration 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 – 20GeV) 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

$$\begin{aligned} |J/\psi\rangle = & |Q\bar{Q}([{}^3S_1]_1)\rangle + \mathcal{O}(v)|Q\bar{Q}([{}^1S_0]_8g)\rangle \\ & + \mathcal{O}(v^2)|Q\bar{Q}([{}^3S_1]_8gg)\rangle + \mathcal{O}(v^1)|Q\bar{Q}([{}^3P_0]_8g)\rangle \\ & + \mathcal{O}(v^1)|Q\bar{Q}([{}^3P_1]_8g)\rangle + \mathcal{O}(v^1)|Q\bar{Q}([{}^3P_2]_8g)\rangle + \dots \end{aligned}$$

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

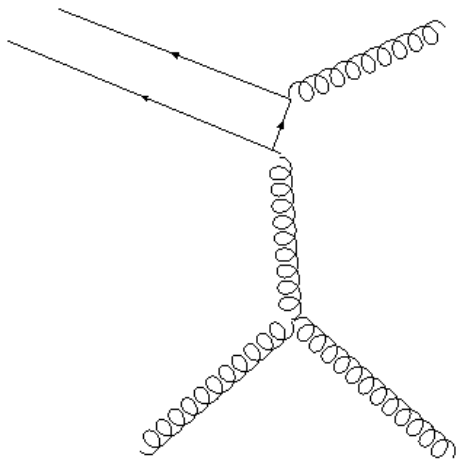
Production

- ▶ 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

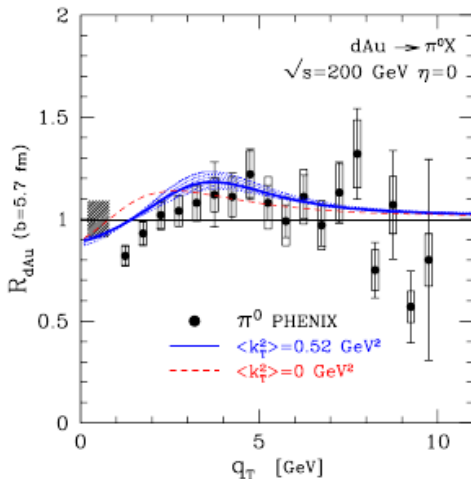
Cold nuclear matter effects

- ▶ 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 $\zeta_{q,g} \approx 0.12, 0.27\text{GeV}^2$. A proposed mechanism for nuclear shadowing
 3. Transverse momentum broadening. A proposed mechanism for the Cronin effect
- ▶ Enhanced by system size $L \sim A^{1/3}1.2\text{fm}$. 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



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

Propagation through the QGP

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

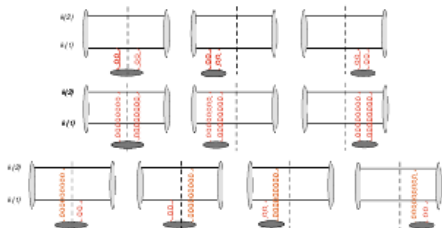
$$\begin{aligned}\frac{d N_{Q\bar{Q}}^{\text{hard}}(t; p_T, \alpha)}{dt} &= -\frac{1}{t_{\text{form}}(t; p_T, \alpha)} N_{Q\bar{Q}}^{\text{hard}}(t; p_T, \alpha) \\ \frac{d N_{Q\bar{Q}}^{\text{meson}}(t; p_T, \alpha)}{dt} &= \frac{1}{t_{\text{form}}(t; p_T, \alpha)} N_{Q\bar{Q}}^{\text{hard}}(t; p_T,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

- ▶ The initial conditions are

$$N_{Q\bar{Q}}^{\text{hard}}(t=0; p_T, \alpha) = N_{NRQCD}^{\text{hard}}(p_T, \alpha) \text{ and}$$

$$N_{Q\bar{Q}}^{\text{meson}}(t=0; p_T, \alpha) = N_{Q\bar{Q}}^{\text{diss.}}(t=0, p_T, \alpha) = 0$$

Dissociation



- ▶ The survival probability is given by

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

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

Dissociation

- ▶ The survival probability is given by

$$P_{\text{surv.}}(\chi\mu^2\xi) = \left| \frac{1}{2(2\pi)^3} \int dx \mathcal{N}^2 \right. \\ \left. \pi x(1-x)\Lambda^2 e^{-\frac{m_Q^2}{x(1-x)\Lambda^2}} \left[\frac{2\sqrt{x(1-x)\Lambda^2}\sqrt{\chi\mu^2\xi + x(1-x)\Lambda^2}}{\sqrt{x(1-x)\Lambda^2} + \sqrt{\chi\mu^2\xi + x(1-x)\Lambda^2}} \right] \right|^2$$

- ▶ 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
- ▶ $\xi \sim \text{few}$ is an enhancement factor from the power law tail of the differential scattering cross section

Formation time tables

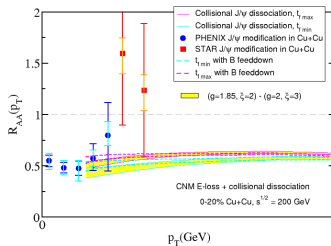
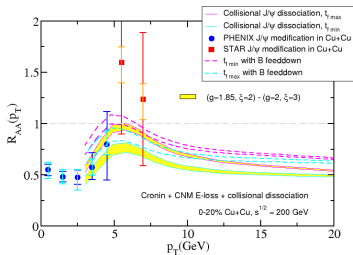
- ▶ $\delta r \sim \frac{1}{m_Q v}$, thus $t_{\text{form}} \sim (0.5, 1)\gamma \frac{1}{m_Q v^2}$
- ▶ The formation and decay rates for $p_T = 10\text{GeV}$ for 0 – 20% central collisions

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

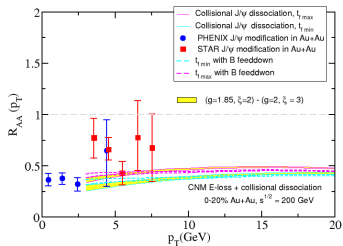
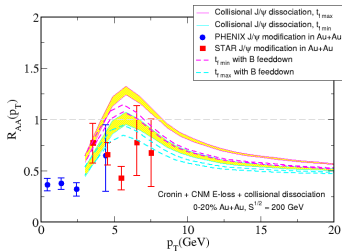
Bottomonium state	$\Upsilon(1)$	$\Upsilon(2)$	$\Upsilon(3)$	$\chi_{b0,1,2}(1)$	$\chi_{b0,1,2}(2)$
Formation time _{max} [fm/c]	1.44	2.85	4.17	2.36	3.45
Dissociation time [fm/c]	3.30	2.23	1.93	1.93	2.06

Results

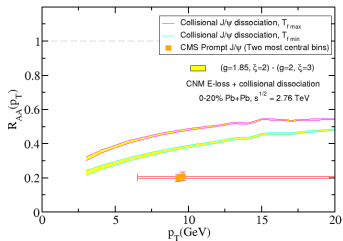
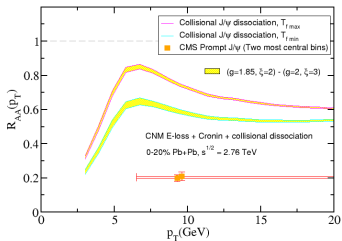
Results for Cu+Cu at RHIC



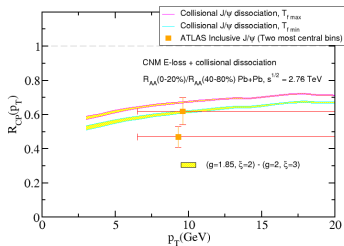
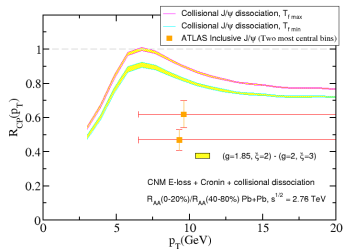
Results for Au+Au at RHIC



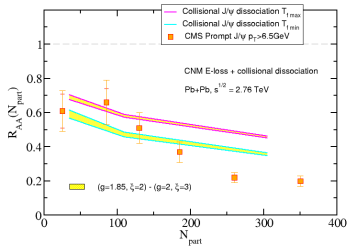
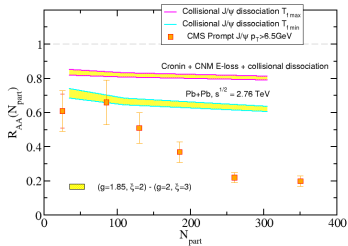
Results for Pb+Pb at the LHC



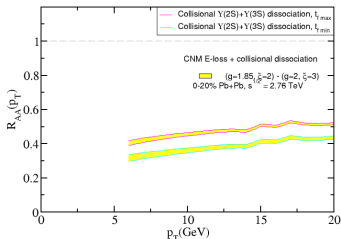
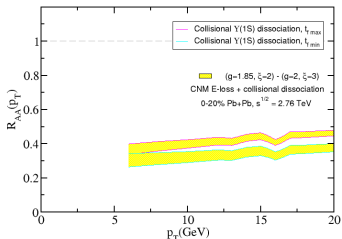
Central versus peripheral at the LHC



R_{AA} versus centrality at the LHC



Υ , R_{AA}



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

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

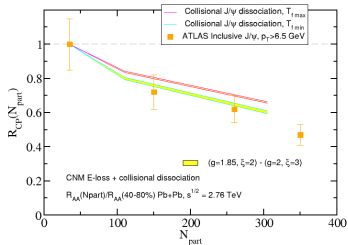
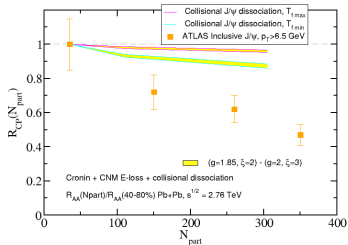
Centrality v/s N_{part}

<i>centrality</i>	N_{part}
0 – 20%	307
20 – 40%	130
40 – 80%	35
0 – 100% (Min. Bias)	110

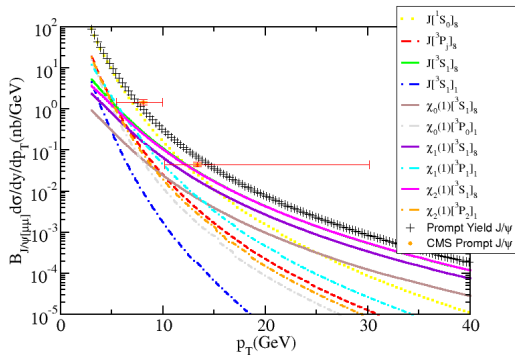
Medium parameters

for LHC 0-20%	PbPb	$dN_{dy}(g) = 2260$ (b=4.5)
for RHIC 0-20%	AuAu	$dN_{dy}(g) = 925$ (b=4.3)
for RHIC 0-20%	CuCu	$dN_{dy}(g) = 235$ (b=3.5)

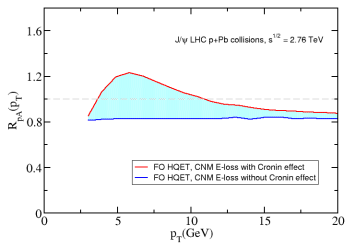
R_{CP} versus centrality at the LHC



Production in p+p collisions



R_{pPb} at the LHC



Υ suppression at the LHC

