Quarkonia in heavy ion collisions

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Topics

- Quarkonia supression at finite p_T
- A jet variable to analyze energy loss mechanisms

Quarkonia at finite p_T

- We consider both charm and bottom mesons
- At finite p_T regeneration is less important even for charm
- A framework — NRQCD — at finite p_T can be used to get the initial state and cold nuclear matter effects can be included in the formalism

Timescales

- Quarkonia in thermal equilibrium with the medium will be less bound (or unbound) due to screening effects and dissociation processes
- In the heavy ion environment multiple time scales relevant
- Interplay between formation rates and dissociation rates

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., Strickland 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 $p_T \gtrsim 3$MeV 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....)*

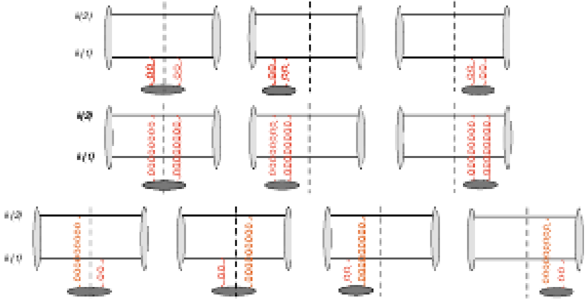
Basic model

- 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 $t_{\rm diss}$
- Rate equations give the evolution of the quarkonium yields

Dissociation rate in our calculation

- 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
- A two dimensional problem
- 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 $t_{\rm form} \sim (1,2)\gamma \frac{1}{m_Q v^2}$
- The formation and decay rates for $p_T = 10$GeV for $0-20\%$ central collisions

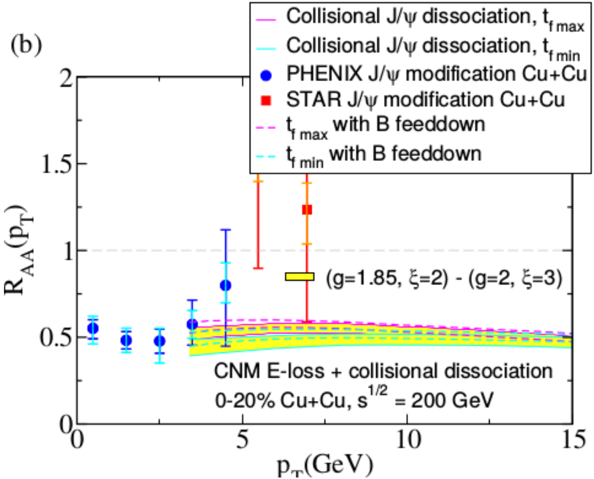
Charmonium state	J/ψ	$\chi_{c0,1,2}$
Formation time$_{\rm max}$ [fm/c]	3.3	4.4
Dissociation time [fm/c]	1.7	1.6

Bottomonium state	$\Upsilon(1)$	$\Upsilon(2)$	$\Upsilon(3)$	$\chi_{b0,1,2}(1)$	$\chi_{b0,1,2}(2)$
Formation time$_{\rm max}$ [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}

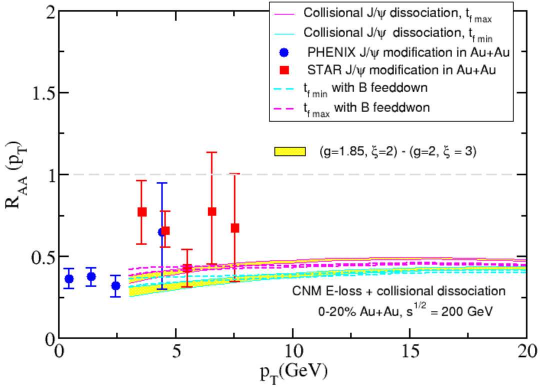
- Dissociation processes will reduce the yield of quarkonia in AA collisions over the (scaled) yield in pp collisions; some of the quarkonia form open heavy flavor mesons. $R_{AA} < 1$
- Seen for Υ as well as J/Ψ *(RHIC, LHC)*
- Complications due to cold nuclear matter effects
- The most relevant cold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

Results for Cu+Cu at RHIC

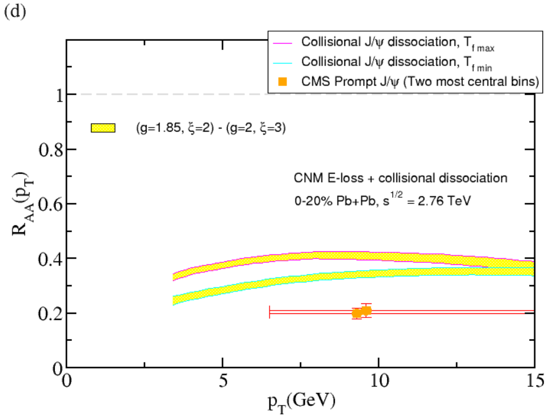


RS and Ivan Vitev Phys. Rev. C (2012)

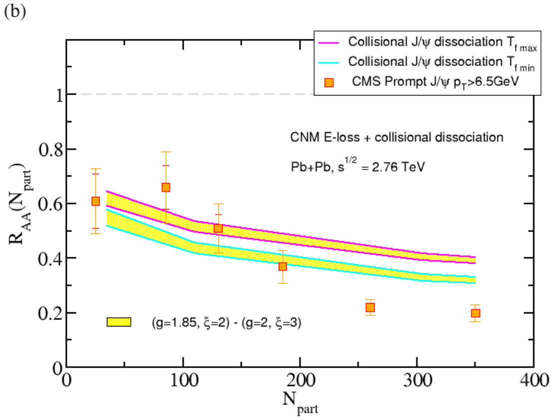
Results for Au+Au at RHIC



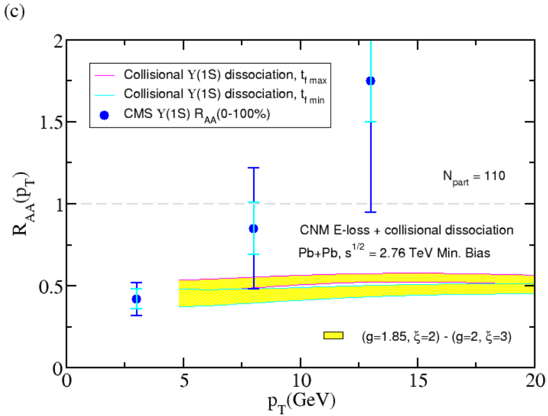
R_{AA} at the LHC



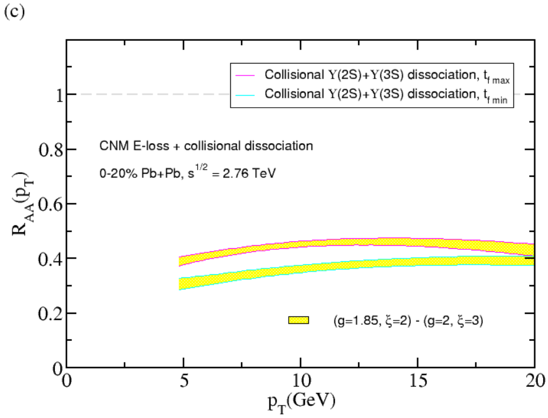
R_{AA} versus N_{part} at the LHC



R_{AA} for $\Upsilon(1S)$ at the LHC



R_{AA} for $\Upsilon(2S)$ at the LHC



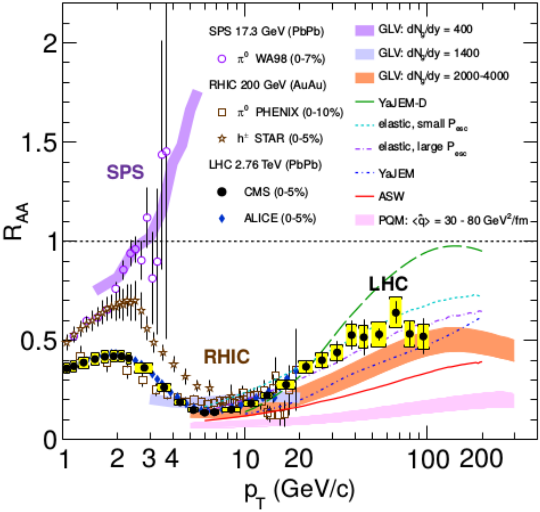
Summary

- The biggest uncertainty comes from the formation time
- For the color singlet component can be handled by eolving the Schroedinger equation. The color octet contribution is more challenging
- Dissociation by itself not sufficient: require thermalization effects on the wavefunction

Jet variable

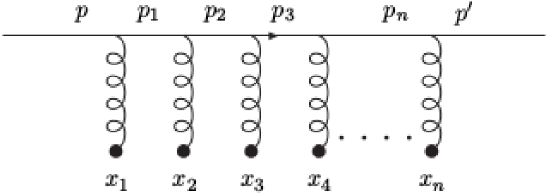
- A jet variable to analyze energy loss mechanisms
- (Jain, Gavai, Sharma [1509:04671])

Leading particle



- *(CMS (2012))*

Effect of the medium: momentum broadening



- An energetic parton traversing through the medium gets kicks transverse to its motion
- *(BDMPSZ (1997))*

Momentum broadening

- In certain approximate scenarios, the probability distribution function for momentum broadening transverse to the leading parton direction,

$$\mathcal{P}(k_\perp) \approx \exp(-\frac{k_\perp^2}{\hat{q}L}) \,, \quad (1)$$

  which corresponds to diffusion in momentum space.
- $\hat{q} = (\Delta k_\perp)^2/L$
- $\hat{q} = \frac{\mu^2}{\lambda}$, where $\mu \sim gT$

Energy loss

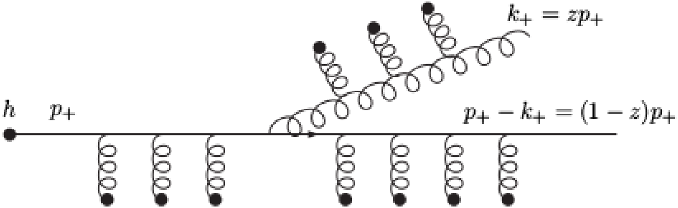


Fig. 5. The medium-induced gluon radiation diagram.

- Transverse kicks drive the parton offshell, and it radiates gluons: leading to energy loss

Models of energy loss

- GLV *Gyulassy, Levai, Vitev (1999, 2001)*, DGLV *Djordevic, GLV (2004)*, WHDG *Wicks, Horowitz, DG (2005). Momentum broadening occurs due to screened gluon exchange with stationary charge centres. Density of scatterers determined by the medium T*
- AMY *Arnold, Moore, Yaffe (2001, 2002)*. An effective theory with $p_{\mathrm{parton}} \gg T \gg gT$
- ASW *Armesto, Salgado, Wiedemann (2000, 2003)*. $\hat{q}$ is treated as a parameter. Large values are required to get experimentally observed suppressions. Sometimes computed using AdS/CFT techniques *Rajagopal, Liu, Wiedemann (2005)*
- HT *Wang, Guo, Majumder et. al. (2000).* $\hat{q}$ is a non-perturbative parameter determined by gluon correlators

Jet observables

- Models predict a specific distribution of partons in jets
- Can we use the distribution of particles in the reconstructed jets to analyze quenching?
- *eg. Vitev, Wicks, Zhang (2008), Renk (2009)*
- For example, the thrust is defined as

$$T = \sum_i \frac{|(\hat{n}^{\mathrm{jet}} \cdot \vec{p}_i)|}{Q} \tag{2}$$

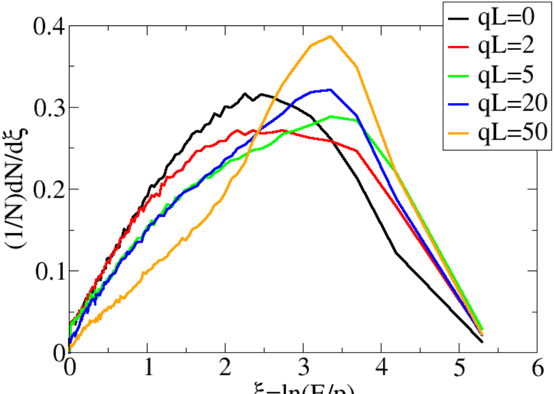
  where $\hat{n}^{\mathrm{jet}}$ is the jet direction, $\{\vec{p}_i\}$ are the momenta of the particles in the jet, and Q is centre of mass energy of the colliding e^+e^-
- $T \to 1$ for pencil like events and smaller for wider events

Jet observables

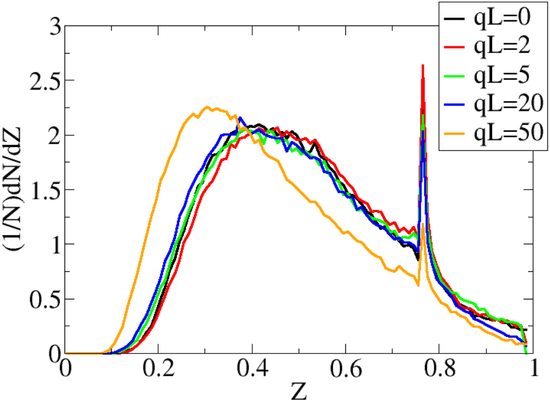
- Define
$$Z = -1/\log(\sum_i \exp(-p_T^{\rm jet}/(\hat{n}_T^{\rm jet} \cdot \vec{p}_i))) \qquad (3)$$
- If only one particle carries the momentum of the jet $Z = 1$
- If many thermal particles carry the momentum of the jet $Z \sim -\frac{1}{p_T^{\rm jet}/T \log(p_T^{\rm jet}/T)} \ll 1$
- Similar in nature to the fragmentation function of the jet but the most energetic particles in the jet play the most important role
- Stray, low energy background particles do not contribute. Useful for the heavy-ion environment

Analysis

- Partitioned the energy of the leading gluon into multiple gluons chosen from the gluon distribution *Armesto et. al. (2009)*. Simulated 200, 000 events
- Tools QPYTHIA [0907.1014], QHERWIG [0909.5118] *Armesto et. al.*
- Different distributions for different centralities



100GeV

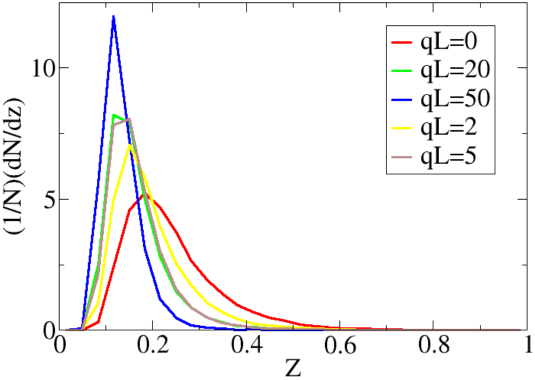


- $l = 2,\ \hat{q} = 1,\ 10;\ l = 5,\ \hat{q} = 1,\ 10$
- *(Jain, Gavai, Sharma [1509:04671])*

Main features

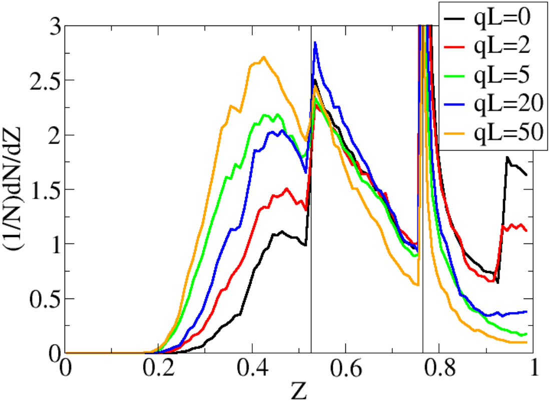
- Two particle peak at $Z = 0.7652$. It we partition 1 as x and $1 - x$, $Z \geq 0.7652$. Furthermore for $x \in (0.3, 0.7)$, $Z \approx 0.7652$
- Expect hadronization to smooth out this peak
- Specific prediction of how the distribution shifts left with increasing centrality

80GeV after hadronization



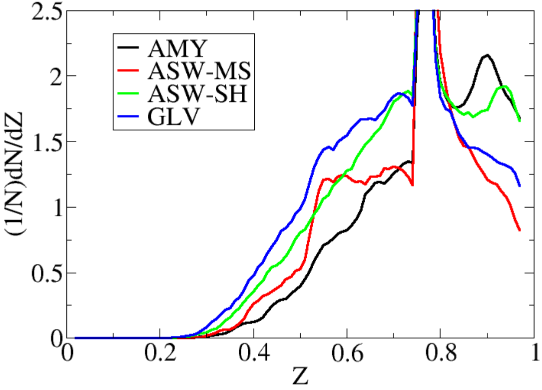
- Using *QPYTHIA* (*Armesto et. al. (2009)*) to hadronize

Curiosity for $p_T = 10\text{GeV}$



- Two particle peak at $Z = 0.528$
- Hadronization analysis not possible for such low momenta

Models



- All the different models tuned such that R_{AA} is 0.25 for $L = 5$fm. (*Armesto et. al. (2012)*)

Conclusions

- For a specific model (*Armesto et. al. (2009)*), the peak of the zeal distribution is lowered by a factor 2 as we go from peripheral to central collisions
- Seems capable of distinguishing models, but eventually will boil down to error bars
- To do
  1. Hadronization systematics
  2. Background event subtraction
  3. Experimental data
  4. Comparison with other analyses (eg. jet cone radius dependence)
- Can be used for the analysis of heavy quark jets