High p_T Quarkonia (and open heavy flavor) in heavy ion collisions

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August 14, 2012

[arXiv:1203:0329[hep-ph]] with Ivan Vitev

Quarkonia at high p_T

- Form Q-$\bar{Q}$ pairs early in the collision
- Most studies use thermal quarkonium wavefunctions
- Formation time for quarkonia in vacuum $t_{\rm form} \sim \frac{1}{E_b} \sim \frac{1}{m_Q v^2}$ (For example, $t_{\rm form}[J/\psi] \sim 1.03\text{fm}$, $t_{\rm form}[\Upsilon] \sim 0.24\text{fm}$)
- Formation time for a "thermally equilibriated" quarkonium $t_{\rm formTE} \sim \frac{1}{\tilde{E}_{b\rm TE}} \gg t_{\rm form}$ (For example, $t_{\rm formTE}[J/\psi](T_c) \sim 24\text{fm}$, $t_{\rm formTE}[\Upsilon](T_c) \sim 1\text{fm}$)

Quarkonia at high p_T

- 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
- In this first attempt we ignore the quenching and other dynamics of the color-octet state

Open heavy flavor at high p_T

- Non-equilibrium fragmentation/dissociation dynamics may give higher suppression for high p_T open heavy flavor
- The differences from Quarkonia are that
  1. The dissociation time smaller
  2. Therefore an important contribution due to partonic level jet quenching
  3. After dissociation, the heavy quark can refragment to form mesons
- *(Sharma, Vitev, Zhang (2009))*

Production

- To calculate the p+p baseline and the initial yields in A+A we use non-relativistic quantum chromodynamics (NRQCD)
- The production cross-section 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 *(Bodwin, Braaten, LePage, Cho, Leibovich, Fleming ...)*
- $\langle\mathcal{O}(Q\bar{Q}([^3S_1]_1) \to J/\psi)\rangle$ etc. are non-perturbative matrix elements that have to be fitted to experiments
- The picture is that you create short distance $Q\bar{Q}$ states which evolve to J/ψ wavefunctions

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
  2. Coherent multiple scattering
  3. Transverse momentum broadening as a model for the Cronin effect
- Not yet well understood for quarkonia

Propagation through the medium

- Form a short distance $Q\bar{Q}$ object, a "proto-quarkonium"
- The "proto-quarkonium" forms a quarkonium on a time-scale $t_{\rm form}$
- The quarkonia dissociate on a time-scale $t_{\rm diss}$

In equations

- We solve the rate equations

$$\frac{d\,N^{\mathrm{hard}}_{Q\bar{Q}}(t;p_T,\alpha)}{dt} = -\frac{1}{t_{\mathrm{form}}(t;p_T,\alpha)} N^{\mathrm{hard}}_{Q\bar{Q}}(t;p_T,\alpha)$$

$$\frac{d\,N^{\mathrm{meson}}_{Q\bar{Q}}(t;p_T,\alpha)}{dt} = \frac{1}{t_{\mathrm{form}}(t;p_T,\alpha)} N^{\mathrm{hard}}_{Q\bar{Q}}(t;p_T,\alpha) - \frac{1}{t_{\mathrm{diss.}}(t;p_T,\alpha)} N^{\mathrm{meson}}_{Q\bar{Q}}(t;p_T,\alpha)$$

$$\frac{d\,N^{\mathrm{diss.}}_{Q\bar{Q}}(t;p_T,\alpha)}{dt} = \frac{1}{t_{\mathrm{diss}}(t;p_T,\alpha)} N^{\mathrm{meson}}_{Q\bar{Q}}(t;p_T,\alpha)$$

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

Rate equations of open heavy flavor

- *(Adil, Vitev)*

$$\partial_t f^Q(p_T,t) = \frac{-f^Q(p_T,t)}{\langle \tau_{\rm form}(p_T,t)\rangle} + \frac{1}{\langle \tau_{\rm diss}(\frac{p_T}{\bar{x}},t)\rangle} \int_0^1 \frac{dx}{x^2}\phi_{Q/H}(x) f^H(\frac{p_T}{x},t)$$

$$\partial_t f^H(p_T,t) = \frac{-f^H(p_T,t)}{\langle \tau_{\rm diss}(p_T,t)\rangle} + \frac{1}{\langle \tau_{\rm form}(\frac{p_T}{\bar{z}},t)\rangle} \int_0^1 \frac{dz}{z^2} D_{H/Q}(z) f^Q(\frac{p_T}{z},t)$$

$$f^Q(p_T,t) = \frac{d\sigma^Q(t)}{dyd^2p_T}\ , \quad f^Q(p_T,t=0) = \frac{d\sigma^Q_{PQCD}}{dyd^2p_T}$$

$$f^H(p_T,t) = \frac{d\sigma^H(t)}{dyd^2p_T}\ , \quad f^H(p_T,t=0) = 0$$

- A reasonable estimate for partonic energy loss is obtained by allowing partonic energy loss for $\tau_p = \tau_{\rm form}(1+\frac{L-\tau_{\rm form}}{L})$ *(Sharma, Vitev, Zhang).*

Dissociation

- The survival probability is given by *(Adil, Vitev (2007))*

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

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

Formation time

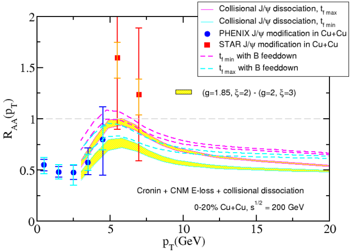
- For open heavy flavor, uncertainty principle estimates
- $\tau_f(D) \sim 1.5$[fm/c], $\tau_f(B) \sim 0.4$[fm/c]
- For quarkonia, $\delta r \sim \frac{1}{m_Q v}$, thus $t_{\mathrm{form}} \sim (0.5, 1)\gamma \frac{1}{m_Q v^2}$
- The formation and decay rates for $p_T = 10$GeV for $0 - 20\%$ central collisions

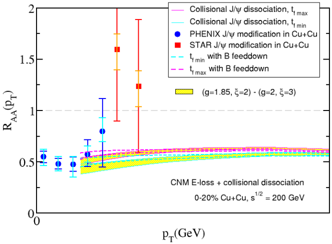
Charmonium state	J/ψ	$\chi_{c0,1,2}$
Formation time$_{\mathrm{max}}$ [fm/c]	3.35	4.40
Dissociation time [fm/c]	1.74	1.61

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

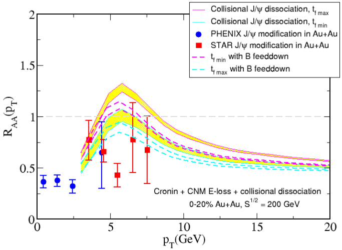
Quarkonia results

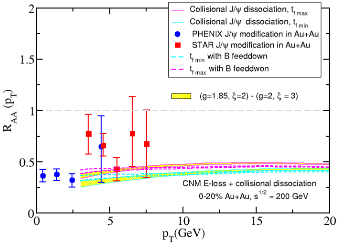
Results for Cu+Cu at RHIC



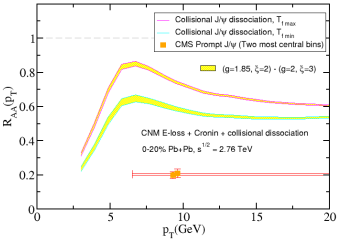


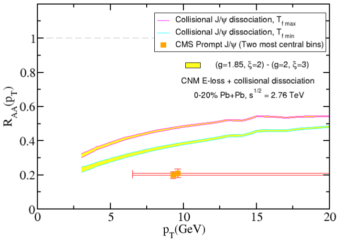
Results for Au+Au at RHIC



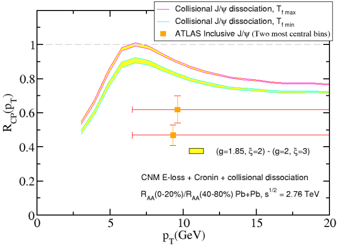


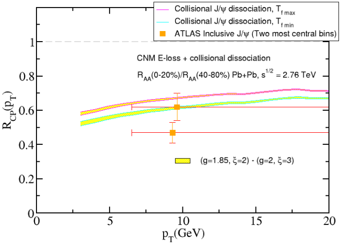
Results for Pb+Pb at the LHC



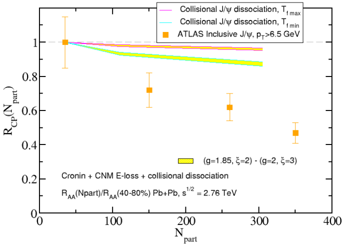


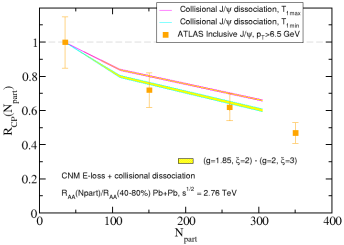
Central versus peripheral at the LHC



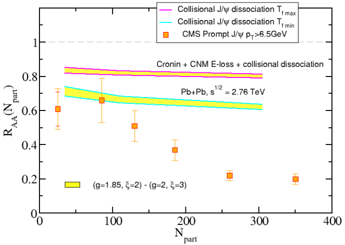


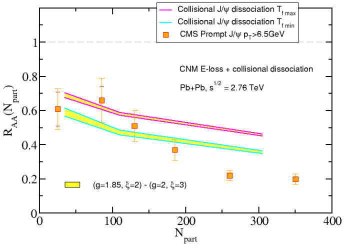
R_{CP} versus centrality at the LHC





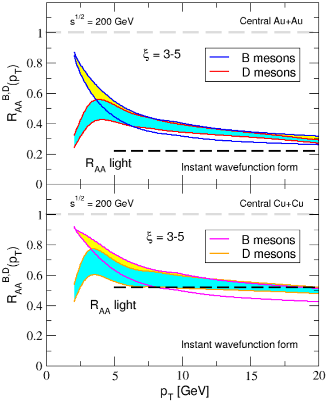
R_{AA} versus centrality at the LHC

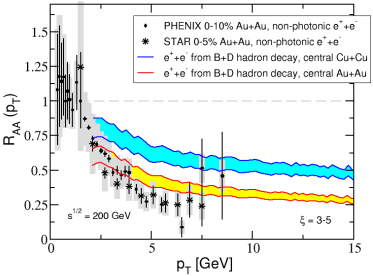




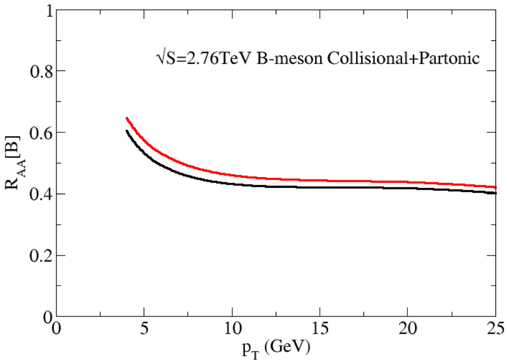
Open heavy flavor results

B and *D* meson results at RHIC





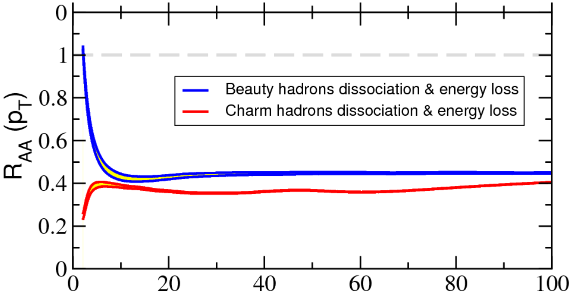
B meson results at the LHC



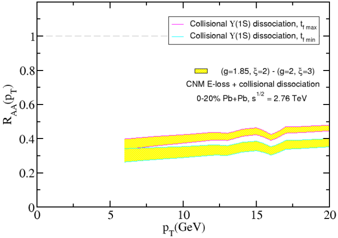
Conclusions

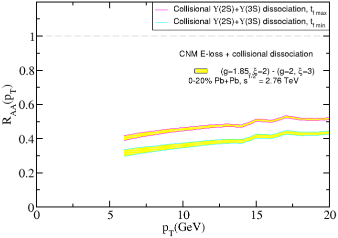
- LHC's ability to measure differential observables in the transverse momentum p_T for large p_T is very useful for discriminating models
- Appears that transverse momentum broadening is not present. Comparison with d+Au data at RHIC supports this conclusion
- Dissociation picture phenomenologically successful for open heavy flavor
- For small $N_{\rm part}$, consistent with LHC J/ψ yields
- LHC results, in particular for central Pb+Pb suggest thermalization of the wavefunction
- In future, a better framework to handle the formation process
- Handling the evolution of the color octet component is another challenge for the future

B and D meson results at the LHC



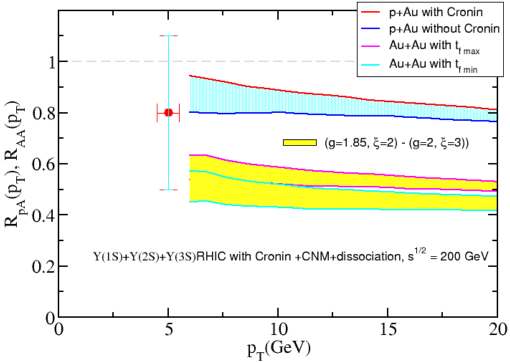
Υ, R_{AA}



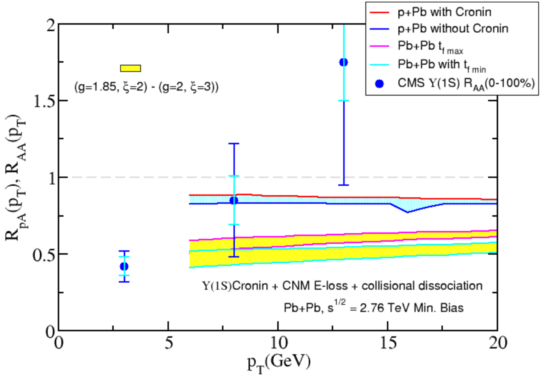


- $\frac{\Upsilon(2S+3S)}{\Upsilon(1S)}|_{pp} = 0.76^{+0.16}_{-0.14} \pm 0.12$, $\frac{\Upsilon(2S+3S)}{\Upsilon(1S)}|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$
- $\frac{R_{AA}(\Upsilon(2S+3S))}{R_{AA}(\Upsilon(1S))} = 0.32^{+0.19}_{-0.15} \pm 0.03$

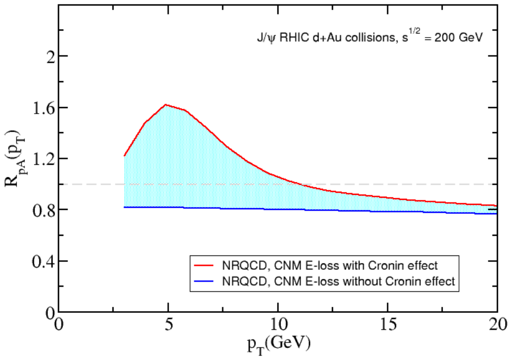
Υ suppression at RHIC



Υ suppression at the LHC



R_{pAu} at the RHIC



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	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)

Matrix elements for J/ψ (systematic analysis)

Operator	RV
$J/\psi([3S_1]_1)$	$1.2\ \text{GeV}^3$
$J/\psi([3S_1]_8)$	$2.57\times10^{-3}\text{GeV}^3$
$J/\psi([1S_0]_8)$	$2.05\times10^{-2}\text{GeV}^3$
$J/\psi([3P_0]_8)$	$4.48\times10^{-2}\text{GeV}^5$
$\chi_c([3P_0]_1)$	$3.67\times10^{-1}\text{GeV}^5$
$\chi_c([3S_1]_8)$	$1.86\times10^{-3}\text{GeV}^3$

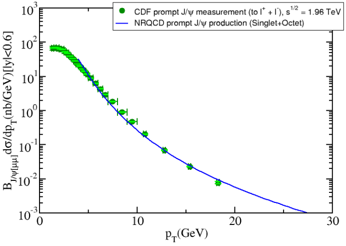
- Error in $\chi_c([3S_1]_8)$, 1% with $\chi^2/dof = 4.6$
- Error in $J/\psi([x]_8)$, 3% with $\chi^2/dof = 5.3$

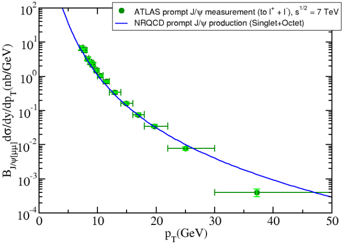
Matrix elements for J/ψ in the paper

Operator	RV	BK
$[3S_1]_1$	1.2 GeV^3	
$[3S_1]_8$	$3.31\times10^{-3}\text{GeV}^3$	$3.12\times10^{-3}\text{GeV}^3$
$[1S_0]_8$	$7.14\times10^{-2}\text{GeV}^3$	$4.5\times10^{-2}\text{GeV}^3$
$[3P_0]_8$	$-8.25\times10^{-3}\text{GeV}^5$	$-12.1\times10^{-3}\text{GeV}^5$

(Buchensohn Kniehl (2010))

Production in p+p collisions





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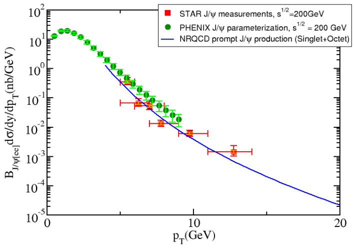
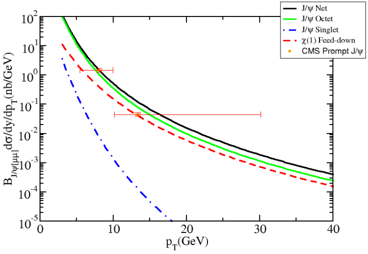
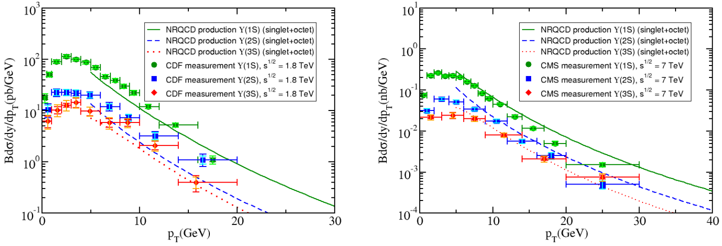




Production in p+p collisions



- Detailed error analysis in future. $\chi^2/dof \sim 8$