Effective volume of correlated charm quark pair

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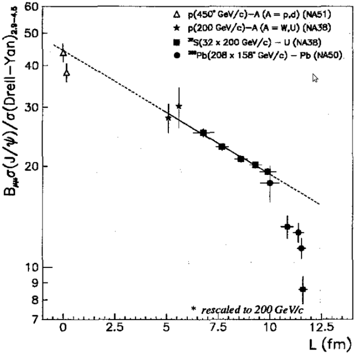
J/ψ in HIC



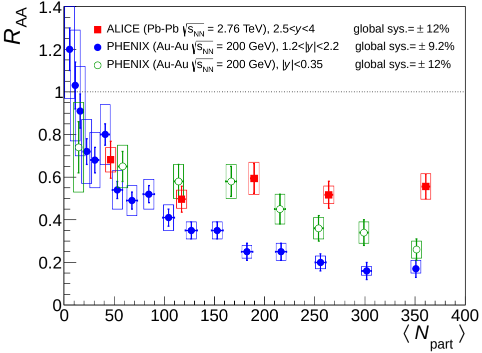
(SPS data, Nucl. Phys. A610, 404c (1996))

$J/\psi + g \rightarrow c + \bar{c}$

- Sequential dissociation (H. Satz, et al)
- Statistical model (P. Braun-Munzinger, et al)
- Transport model (P. Zhuang , R. Rapp, T. Song, et al)

J/ψ in HIC

$$R_{AA} = \frac{N^{AA}_{J/\psi}}{N^{pp}_{J/\psi} N_{coll}}$$



(Alice data, Phys. Rev. Lett. 109, 072301 (2014))

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- Y. Liu, B. Chen, N. Xu, P. Zhuang , Upsilon Production as a Probe for Early State Dynamics in High Energy Nuclear Collisions at RHIC, Phys. Lett. B697 (2011) 32-36.
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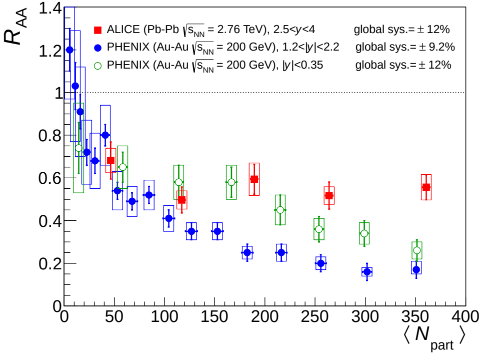
- ...

J/ψ Regeneration

$$R_{AA} = \frac{N^{AA}_{J/\psi}}{N^{pp}_{J/\psi} N_{coll}}$$



$c + \bar{c} \to J/\psi + X$

(Alice data, Phys. Rev. Lett. 109, 072301 (2014))

J/ψ Regeneration

Possible heavy quarkonium regeneration from rare heavy quarks:

- J/ψ at SPS
- J/ψ in peripheral collisions at RHIC
- Υ at SPS or RHIC
- J/ψ in p+Pb collisions at LHC
- Υ in p+Pb collisions at LHC
- ...

Outline

1. Canonical ensemble effect
2. Effective volume
3. Results from a toy model
4. Qualitative conclusions

Canonical effect of J/ψ production in the statistical model

Statistical model:

$$N_{c\bar{c}}^{dir} = \frac{1}{2} N_{open} + N_{hidden}$$

- Grand canonical ensemble:

$$N_{c\bar{c}}^{dir} = \frac{1}{2} \gamma n_{open}^{th} V + \gamma^2 n_{hidden}^{th} V$$

$$\frac{N_{hidden}}{N_{open}^2} \propto \frac{1}{V}$$

Canonical ensemble

- Canonical ensemble (rare charm limit):

$$
\begin{aligned}
N_{c\bar{c}}^{dir} &= \frac{1}{2}\gamma n_{open}^{th} V \frac{I_1(\gamma n_{open}^{th} V)}{I_0(\gamma n_{open}^{th} V)} + \gamma^2 n_{hidden}^{th} V \\
&\approx (\frac{1}{2}\gamma n_{open}^{th} V)^2 + \gamma^2 n_{hidden}^{th} V
\end{aligned}
$$

$$
\frac{N_{hidden}}{N_{open}} \propto \frac{1}{V}
$$

Canonical effect of J/ψ production in the statistical model

Statistical model:

$$N_{c\bar{c}}^{dir} = \frac{1}{2} N_{open} + N_{hidden}$$

- Grand canonical ensemble:

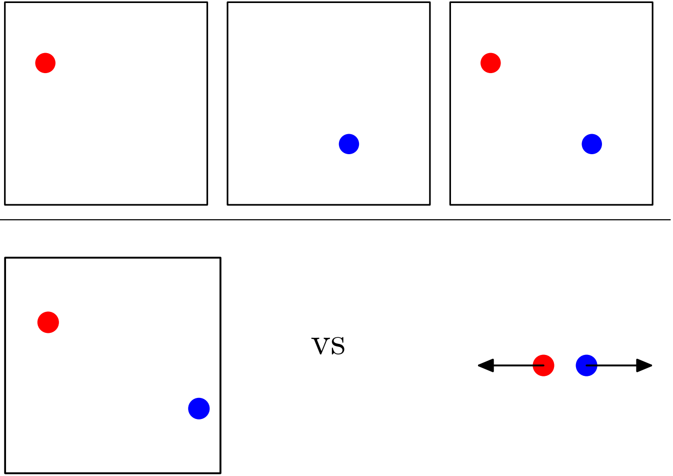
$$\frac{N_{hidden}}{N_{open}^2} \propto \frac{1}{V}$$

- Canonical ensemble (rare charm limit):

$$\frac{N_{hidden}}{N_{open}} \propto \frac{1}{V}$$

Microscopic view: $V \to$ collision rate $\to N_{hidden}$.

Heavy quark correlation and the effective volume



Approach

Set up

- gluons: Boltzmann distribution
- charm quarks:

$$\partial_t f_c + \mathbf{v} \cdot \nabla f_c \quad = \quad C_{c+g \to c+g}$$

- parameters:
  - $\sigma_{cg} = 4$ mb, isotropic
  - $m_c = 1.25$ GeV
  - $m_g = 0$
  - constant temperature T
  - initial momentum of charm quarks p_0

Approach

of collisions between c and $\bar{c}$ in Δt

$$
\begin{aligned}
\Delta N_{\text{coll}} &\propto \sigma \\
&\propto \Delta t \\
&\propto N_c \\
&\propto N_{\bar{c}} \\
&\sim \text{correlation between } c \text{ and } \bar{c}
\end{aligned}
$$

For thermalized charm quarks in volume V

$$
\Delta N_{\text{coll}}^{th} = \frac{N_c N_{\bar{c}} \sigma \Delta t}{V} g(m_c/T),
$$

where $g(z) \equiv \frac{4K_3(2z)}{zK_2^2(z)}$.

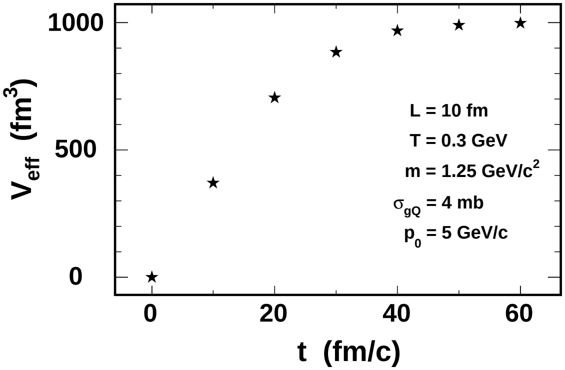
Approach

$$\Delta N_{\mathrm{coll}}^{th} = \frac{N_c N_{\bar{c}} \sigma \Delta t}{V} g(m_c/T),$$

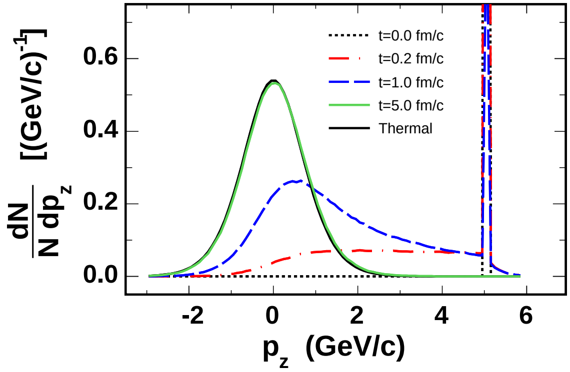
We define the effective volume

$$V_{\mathrm{eff}} = \lim_{\substack{N_c, N_{\bar{c}} \to \infty \\ \Delta t \to 0 \\ \sigma \to 0}} \frac{N_c N_{\bar{c}} \sigma \Delta t}{\Delta N_{\mathrm{coll}}} g(m_c/T).$$

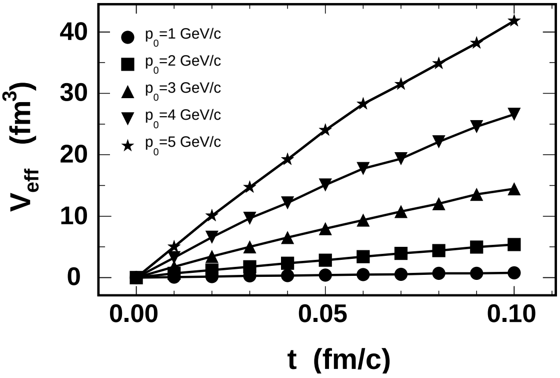
Box Test


1000
500
0
0
20
40
60
t (fm/c)
V_eff (fm^3)
L = 10 fm
T = 0.3 GeV
m = 1.25 GeV/c^2
σ_gQ = 4 mb
p_0 = 5 GeV/c

p_z distribution of the charm quark

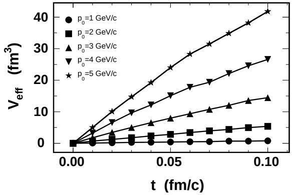


Short Time



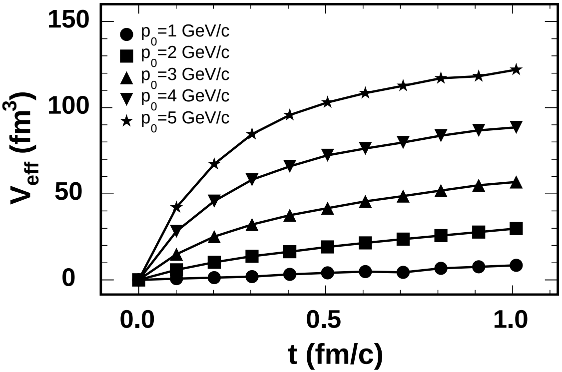
40
30
20
10
0
0.00
0.05
0.10
V_{eff} (fm^3)
t (fm/c)
p_0=1 GeV/c
p_0=2 GeV/c
p_0=3 GeV/c
p_0=4 GeV/c
p_0=5 GeV/c

Short Time

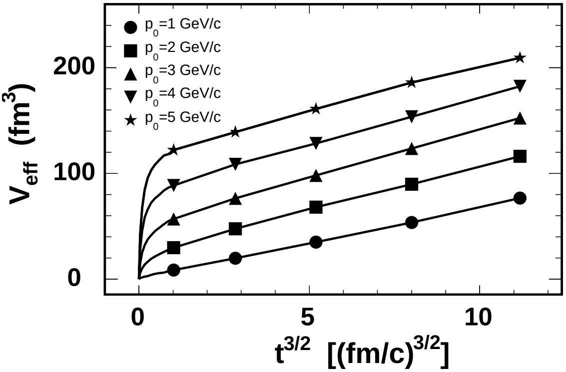


$$N_{J/\psi} \propto \int \frac{\Delta N_{Q\bar{Q}}}{\Delta t} dt \propto \int \frac{1}{V_{\rm eff}} dt \propto \int \frac{1}{t} dt$$

Intermediate Time

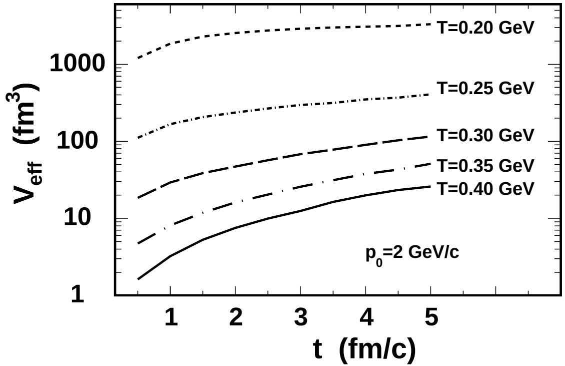


Long Time

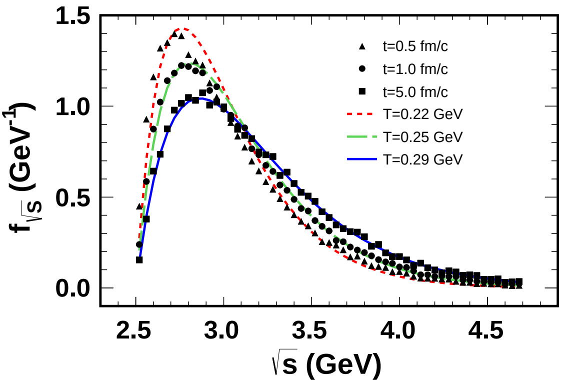


p0=1 GeV/c
p0=2 GeV/c
p0=3 GeV/c
p0=4 GeV/c
p0=5 GeV/c
200
100
0
0
5
10
Veff (fm3)
t3/2 [(fm/c)3/2]

T dependence



$\sqrt{s_{Q\bar{Q}}}$ distribution of colliding Q-$\bar{Q}$ pair

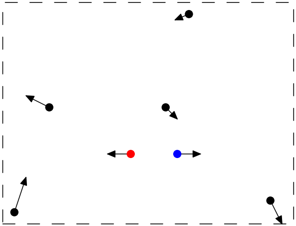


Qualitative conclusions

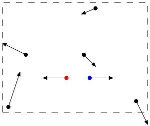
In rare charm events:

1. Charm quark correlation, instead of the volume of the fireball, plays an important role in charmonium regeneration;
2. The regeneration of charmonia depends on the temperature and initial momentum sensitively;
3. Regenerated charmonia only contribute to the low momentum region even if the charm quark distribution is far from equilibrium.

Proof of the linear behavior



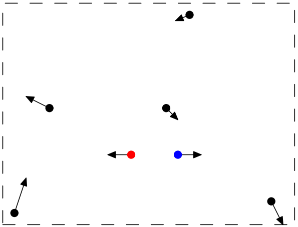
$$x' = \lambda x$$
$$t' = \lambda t$$



$$\Delta N_{Q\bar{Q}}(t, \Delta t, \sigma_{Q\bar{Q}}, \sigma_{gQ}, f_g) \quad = \quad \Delta N_{Q\bar{Q}}(t', \Delta t', \sigma'_{Q\bar{Q}}, \sigma'_{gQ}, f'_g)$$

$$\Delta N_{Q\bar{Q}} \propto \Delta t,$$
$$\Delta N_{Q\bar{Q}} \propto \sigma_{Q\bar{Q}},$$
$$\Delta N_{Q\bar{Q}} \propto \sigma_{gQ} f_g,$$
$$\Delta N_{Q\bar{Q}} \propto \sigma_{g\bar{Q}} f_g$$

Proof of the linear behavior



$$x' = \lambda x$$
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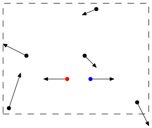

$$\begin{aligned}\Delta N_{Q\bar{Q}}(t, \Delta t, \sigma_{Q\bar{Q}}, \sigma_{gQ}, f_g) &= \Delta N_{Q\bar{Q}}(t', \Delta t', \sigma'_{Q\bar{Q}}, \sigma'_{gQ}, f'_g) \\ &= \lambda \Delta N_{Q\bar{Q}}(\lambda t, \Delta t, \sigma_{Q\bar{Q}}, \sigma_{gQ}, f_g)\end{aligned}$$

$$\frac{1}{\lambda}\Delta N_{Q\bar{Q}}(t, \Delta t, \sigma_{Q\bar{Q}}, \sigma_{gQ}, f_g) = \Delta N_{Q\bar{Q}}(\lambda t, \Delta t, \sigma_{Q\bar{Q}}, \sigma_{gQ}, f_g)$$