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Quarkonium Suppression in Nuclear Collisions: An Update

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Heavy Flavor and Electromagnetic Probes in Heavy Ion Collisions

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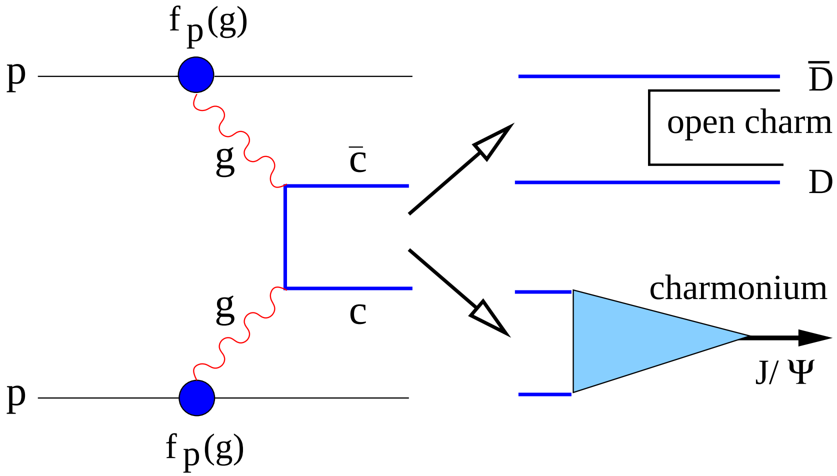
Carlos Lourenço: When we find the answer,
we may have forgotten the question.

How can we study quark deconfinement in the laboratory
and measure the temperature of the quark-gluon plasma?

- Theory:
  the QGP modifies quarkonium binding differently at different temperatures & for different quarkonia.
- Experiment:
  quarkonium production in AA collisions (medium) is different from that in pp collisions (no medium)
- Phenomenology:
  the whole process begins with $c\bar{c}/b\bar{b}$ production

Charm production in hadron-hadron collisions:



– fixed partitioning of total $c\bar{c}$ into open and hidden charm:

$\sim 90\%$ open, $\sim 10\%$ hidden

– fixed partitioning of hidden charm into different charmonia

$$\sigma_{hh \to J/\psi}(s) = g_{c\bar{c} \to J/\psi}\, \sigma_{hh \to c\bar{c}}(s) \quad \text{(color evaporation)}$$

– fixed partitioning of open charm into different D etc.

$$\sigma_{hh \to D^+}(s) = g_{D^+}\, \sigma_{hh \to c\bar{c}}(s) \quad \text{(statistical hadronisation)}$$

– observed J/ψ receives feed-down from higher excitations

60 % direct (1S), 30 % from χ_c(1P), 10 % from ψ'(2S)

similar pattern for bottomonia; basic question:

how are these pp features modified in AA collisions?

NB: ∃ two questions: [HS, arXiv:1303.3493; Adv. High Energy Phys. 2013 (2012) 242910]

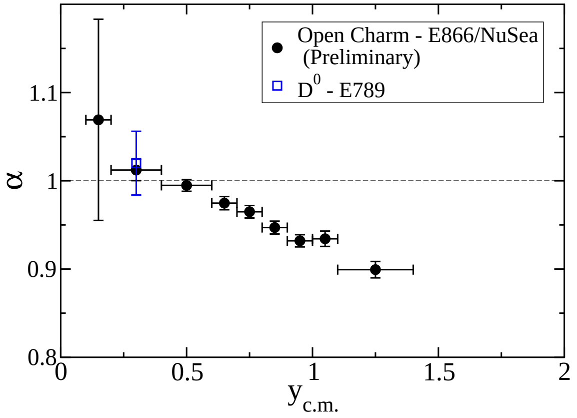
1. how is heavy flavor ($c\bar{c}/b\bar{b}$) production modified?
2. how is the subsequent quarkonium formation modified?

Heavy flavor production in nuclear collisions modified in

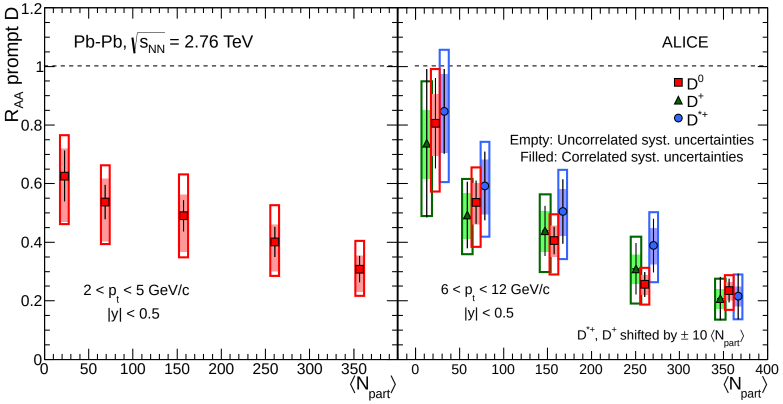
- initial state: pdf modification (shadowing), energy loss of incident partons (gluons)
- final state: energy loss of secondary partons $c, \bar{c}; b, \bar{b}$

Experimental examples:

rapidity dependence of open charm, 800 GeV fixed target pA at FNAL, $\sigma(pA) = A^{\alpha}\sigma(pp)$



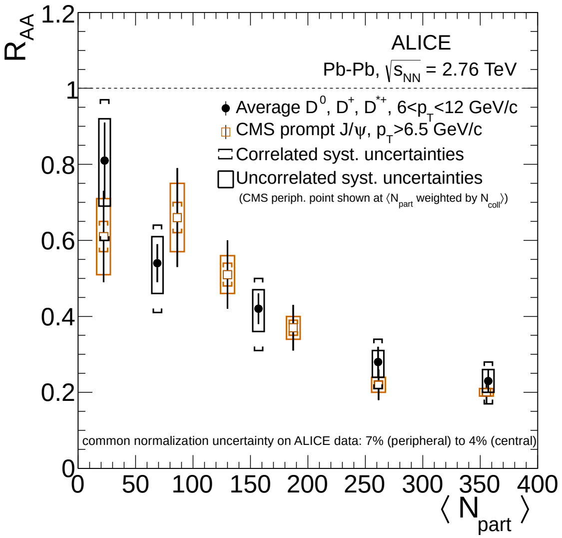
centrality dependence of open charm, 2.76 TeV $PbPb$ at RHIC, for large p_T



Such modifications are passed on to quarkonium production, but say nothing re quarkonium suppression (or enhancement).

$R_{AA}(J/\psi) \sim \sigma_{AA}(J/\psi)/N_{\rm col}\sigma_{pp}(J/\psi)$ **is modified,**
but only because the initial $c\bar{c}/b\bar{b}$ production was modified,
not because something happened to the J/ψ.

to illustrate:
if in the kinematic regime studied
the medium has no effect
on J/ψ production,
then R_{AA} for D and for J/ψ
should coincide: they do.



decrease of $R_{AA}(J/\psi)$ **does NOT mean J/ψ suppression;**
overall charm decreases in AA vs. pp, J/ψ gets same fraction.

Conclude:

to determine effects of the medium on quarkonium formation, we first have to eliminate prior effects on $c\bar{c}/b\bar{b}$ production.

Two possibilities:

- measure double ratio

$$S(J/\psi) = \frac{\{\sigma_{AA}(J/\psi)/\sigma_{AA}(D)\}}{\{\sigma_{pp}(J/\psi)/\sigma_{pp}(D)\}}$$

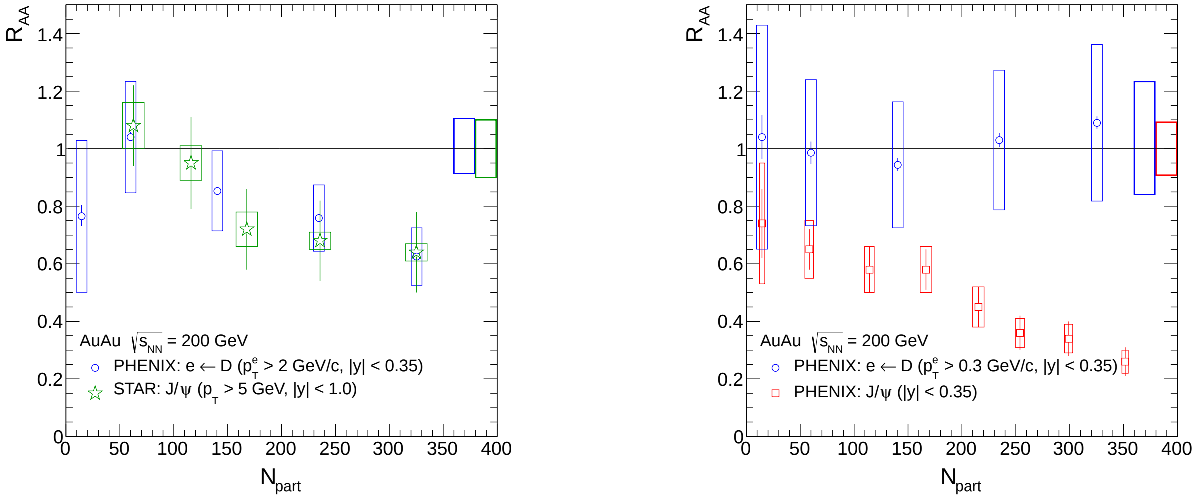
  so that modifications of $c\bar{c}/b\bar{b}$ formation cancel.

- measure ratios of excited states to ground state,

$$R(\Upsilon'/\Upsilon) = \frac{\sigma_{AA}(\Upsilon')}{\sigma_{AA}(\Upsilon)}$$

  so that again modifications of $c\bar{c}/b\bar{b}$ formation cancel.

RHIC Data



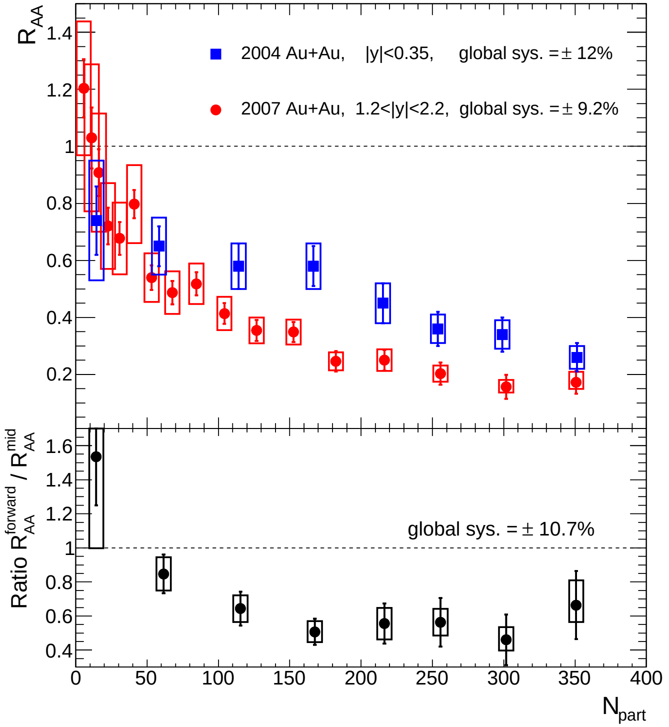
Data from PHENIX & STAR: J/ψ vs. open charm production at high & low transverse momenta (thanks to Torsten Dahms)

at high p_T, strong $c\bar{c}$ suppression, no additional effect on J/ψ;
at low p_T, up to 80 % J/ψ suppression:

here ∃ no medium effect on $c\bar{c}$ production,
only on charmonium binding.

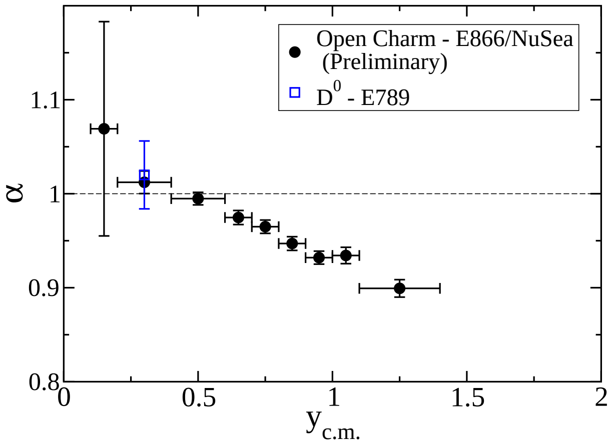
Complementary aspect: so-called “RHIC puzzle”

“more J/ψ suppression” in forward than in central production, based on R_{AA}



Could it be that there are just fewer $c\bar{c}$ pairs produced at forward than at mid rapidity?

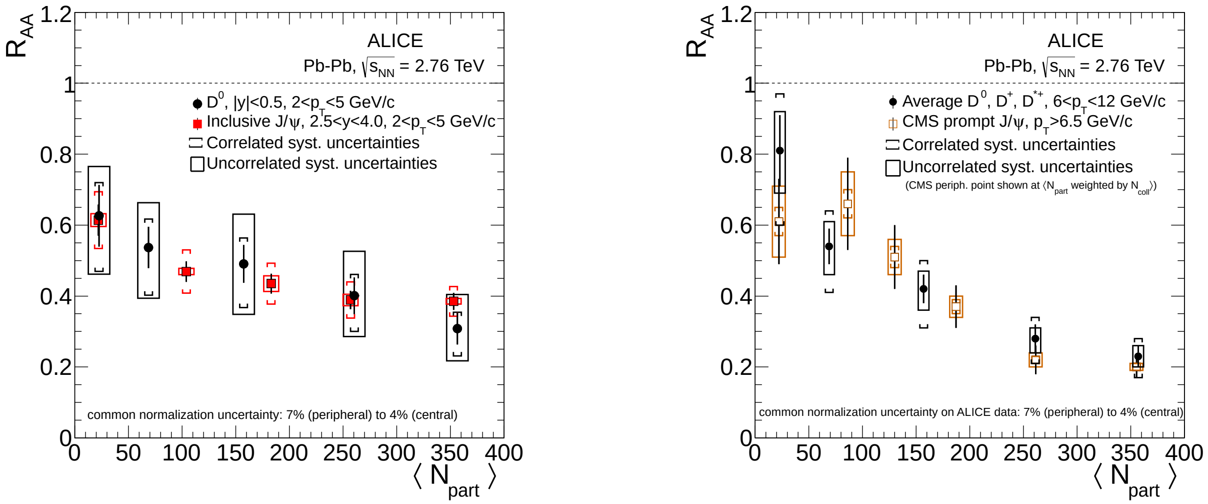
Check by looking at open charm production in pA collisions



Rapidity dependence of open charm production in $\boldsymbol{pA}$ at 800 GeV, with parametriztion $\boldsymbol{\sigma_{pA} = A^{\alpha}\sigma_{pp}}$.
(thanks to Mike Leitch)

The puzzle seems not so puzzling with correct calibration; but need to check quantitatively by more detailed studies of open charm production in $\boldsymbol{pA}$ collisions

LHC Data

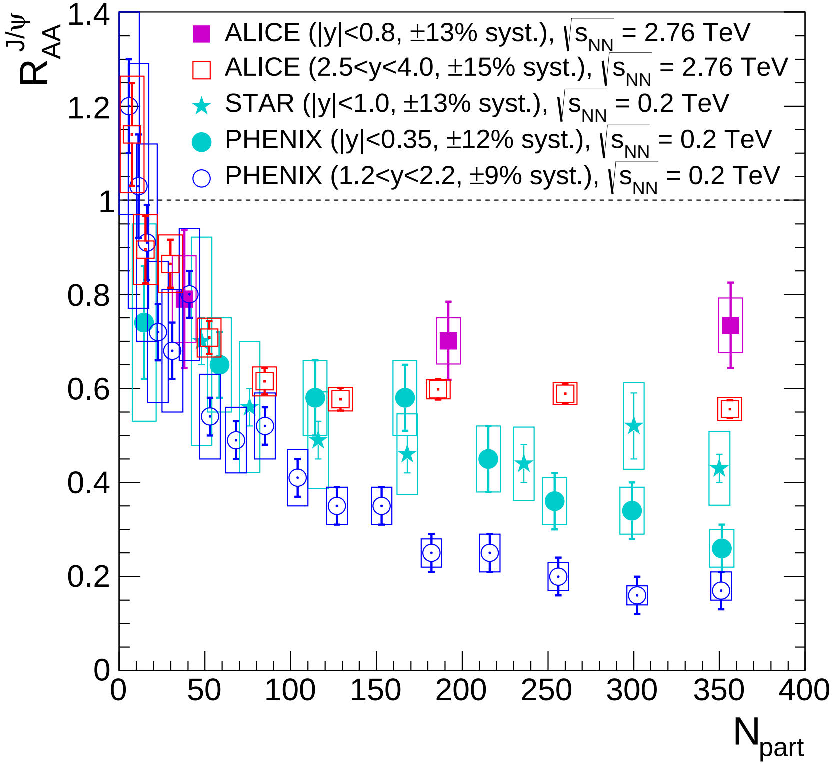


Data from ALICE & CMS: J/ψ vs. open charm production at intermediate & high transverse momenta (thanks to Zaida Conesa del Valle)

in AA at high P_T, as many $c\bar{c}$ pairs make J/ψ as in scaled pp, but there just are fewer now to begin with

hence here neither J/ψ suppression nor enhancement.

low P_T?

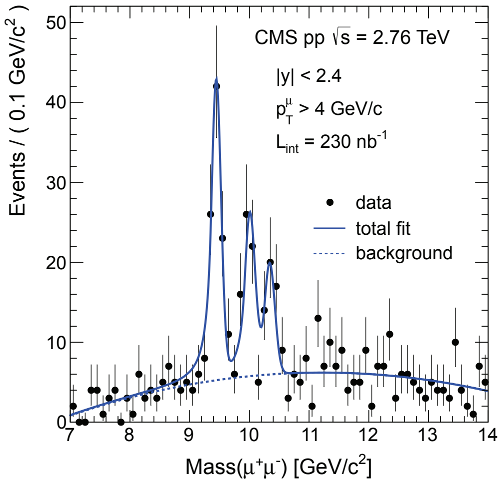


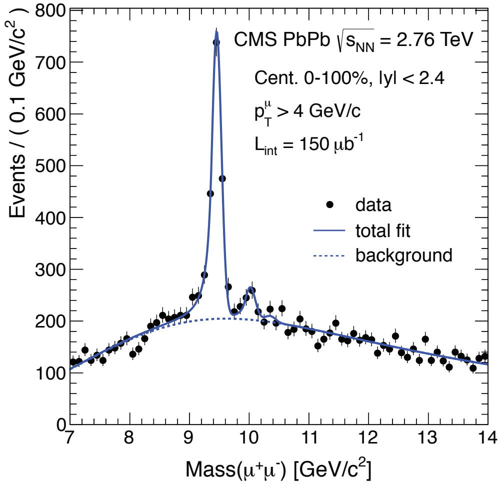
NB: cannot compare these data to any model of in-medium quarkonium behavior;
first need to know what happens to open charm:
shifted to low P_T or overall suppressed re scaled pp?

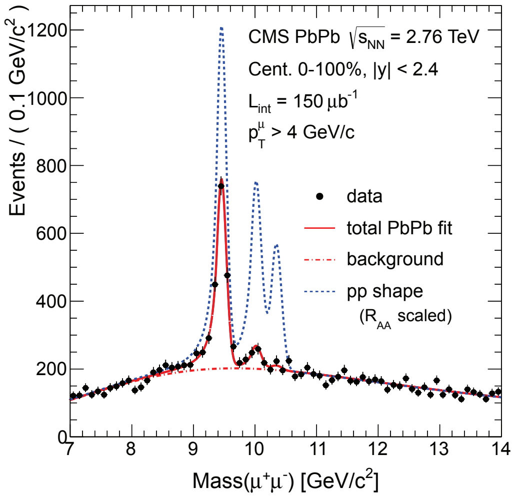
Second Probe: excited vs. ground state

ratio of excited to ground state in AA: $\Upsilon(1S) : \Upsilon(2S) : \Upsilon(3S)$

does the presence of a medium change this from pp?
initial state effects cancel here as well; example





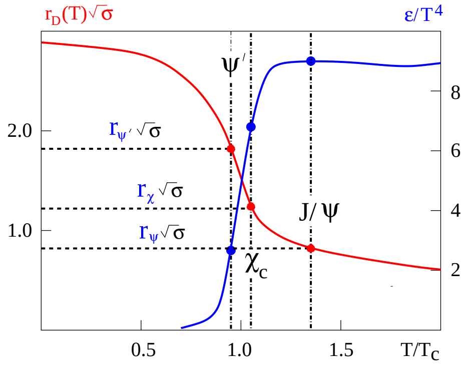


Evidence of sequential suppression?...pA results?

Quarkonium Dissociation in a hot QGP: A New Approach

- QGP consists of deconfined color charges, hence
  $\exists$ color screening for $Q\bar{Q}$ state
- screening radius $r_D(T)$ decreases with temperature T
- if $r_D(T)$ falls below binding radius r_i of $Q\bar{Q}$ state i,
  Q and $\bar{Q}$ cannot bind, quarkonium i cannot exist
- quarkonium dissociation points T_i, from $r_D(T_i) = r_i$,
  specify temperature of QGP

when force range/screening radius become less than binding radius, Q and $\bar{Q}$ cannot "see" each other



Now: a new approach based on emergent entropic QGP force

Verlinde 2011, Kharzeev 2014, HS 2014

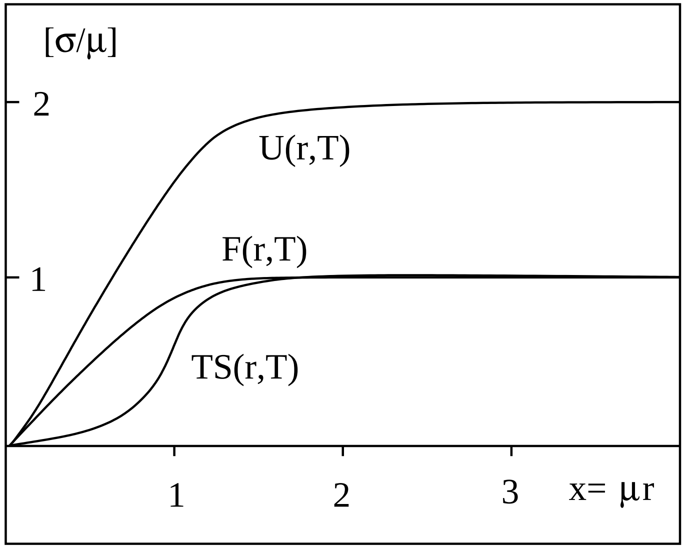
Consider difference of thermodynamic potentials for QGP with and without a heavy $Q\bar{Q}$ pair (Schwinger screening)

$$F(r,T) = \sigma r \left[\frac{1 - e^{-\mu r}}{\mu r}\right] = \frac{\sigma}{\mu}[1 - e^{-\mu r}]$$

$$TS(r,T) = -T\left(\frac{\partial F(r,T)}{\partial T}\right) = \frac{\sigma}{\mu}\left[1 - (1 + \mu r)e^{-\mu r}\right]$$

$$U(r,T) = F + TS = \frac{\sigma}{\mu}\left[2 - (2 + \mu r)e^{-\mu r}\right]$$

behavior as $f(x = \mu r)$



$Q\bar{Q}$ pair is subject to overall force

$$M(r,T) = \left(\frac{\partial U(r,T)}{\partial r}\right) = \left(\frac{\partial F(r,T)}{\partial r}\right) + T\left(\frac{\partial S(r,T)}{\partial r}\right)$$

$\Uparrow$ **dynamic** $\qquad$ $\Uparrow$ **entropic**

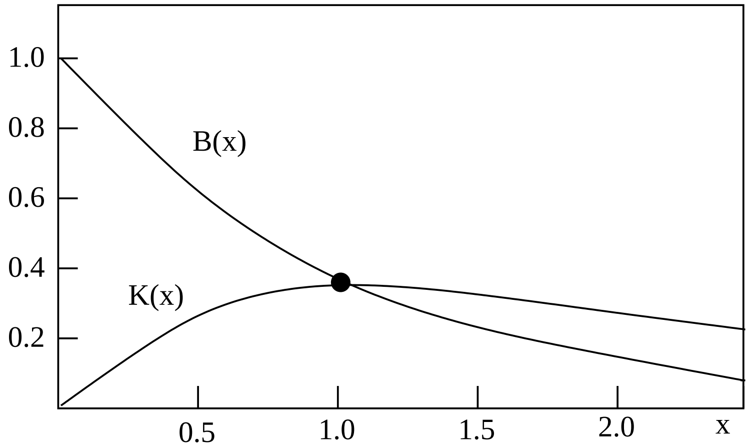
force

dynamic force ($x = \mu r$)

$$B(r,T) = \sigma e^{-x}$$

entropic force:

$$K(r,T) = \sigma \mu r e^{-\mu r} = \sigma x e^{-x}$$



When entropic force $\geq$ dynamic (binding) force:
no more binding possible

$$B(x) = K(x) \quad \Rightarrow \quad x = 1 \quad \Rightarrow \quad r_b = r_D$$

When color screening radius $<$ in-medium binding radius,
entropic force exceeds binding force:
quarkonium dissociation - emergent phenomenon.

- new physics:

– dynamic force ∼ QFT, gauge bosons, ...

– entropic force ∼ collective effect in many-body system

not the end of the story: so far, only behavior in hot QGP

what happens in critical temperature region of QGP?
Entropic force:

$$K(x) \Rightarrow [\sigma x e^{-x}] \left(\frac{T}{\mu} \frac{\partial \mu}{\partial T} \right)$$

while $B(x)$ is unaffected.

Does singular behavior of entropy at T_c mean that the entropic force destroys all hadrons there?

Conclusions

- Measurements of hidden/open heavy flavor production,
  of excited/ground state quarkonium production
  in pp, pA, AA
  will in the future provide model-independent answers
  to model-independent questions.
  But the future is still to come.

- Quarkonium dissociation can be studied as an
  emergent phenomenon,
  arising when the entropic force overcomes the dynamical binding force.