Heavy Ion Theory

Probing the States of Matter in QCD

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When we find the answer, do we remember the question?

High energy heavy ion programs at CERN & BNL:

$$\boxed{\textbf{produce \& study the QGP predicted by QCD}}$$

Can one make a new state of matter by nuclear collisions?

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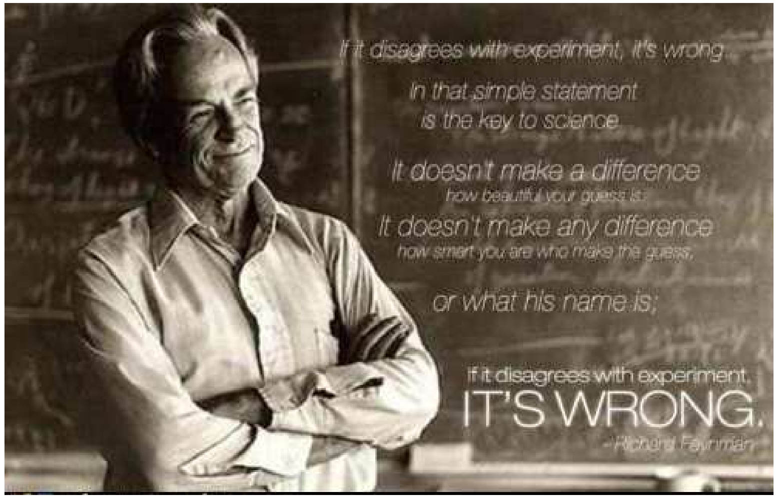


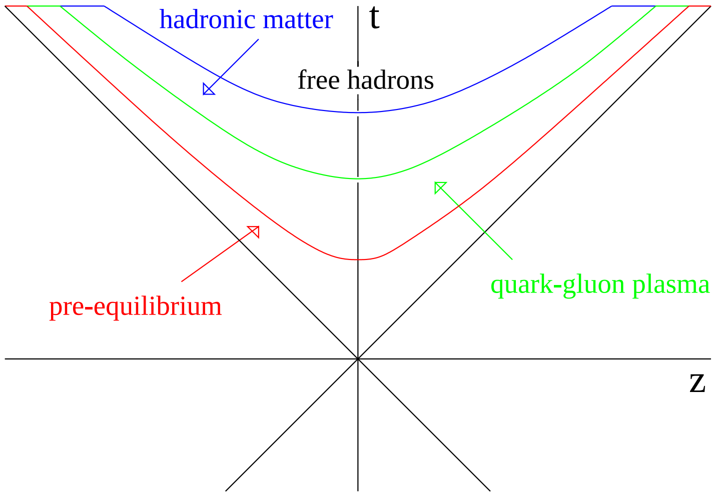
Richard Feynman:

If I throw my watch
against the wall,
I get a broken watch
and not
a new state of matter.

nuclear collisions are complex phenomena

- initial static configuration
  – parton structure, shadowing, color glass...
- non-equilibrium evolution
  – parton scattering, energy loss, expansion, equilibration, heating & cooling
- pre-equilibrium phenomena
  – difficult to access in terms of first principle QCD

complete description
from non-equilibrium
early stages to expected
equilibrium QGP
necessarily complex &
model-dependent



Split of Paradigms:

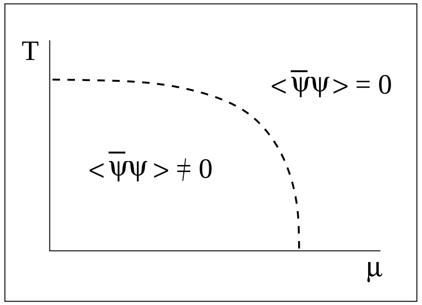
- model complete evolution process;
  check model vs. signals from different collisions stages;
- calculate specific features in equilibrium QCD medium,
  measure these in high energy heavy ion collisions;

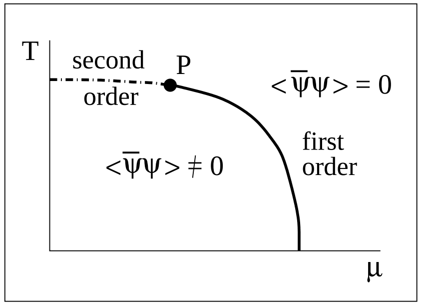
  if they don't agree:
  the collision medium is not the equilibrium QGP of QCD

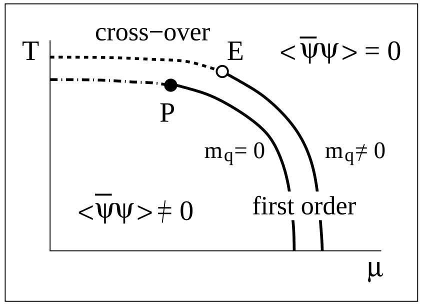
Contents

1 Hadrosynthesis: The Abundance of the Species

Two-phase structure of QCD matter in chiral limit ($m_q = 0$), two quark flavors [Pisarski & Wilczek; Stephanov, Rajagopal & Shuryak]



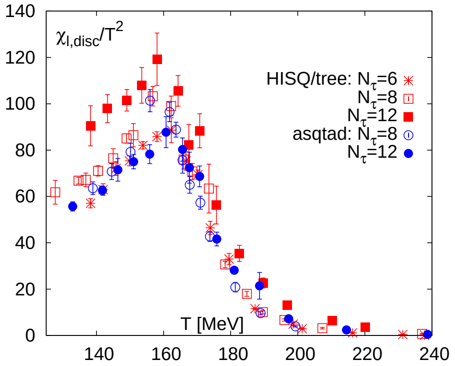




small finite quark mass acts like a weak external field

determine transition temperature T_c for physical case (2+1 quark flavors) through peak of chiral susceptibility

[Bazavov et al. (hotQCD)]



continuum limit of lattice QCD at $\mu = 0$:

$$\boxed{T_c = 154 \ \pm \ 9 \text{ MeV}}$$

transition from deconfined to confined medium
→ interacting hadron system

resonance dominance (*dual resonance model*):

interacting hadron gas = ideal gas of hadronic resonances

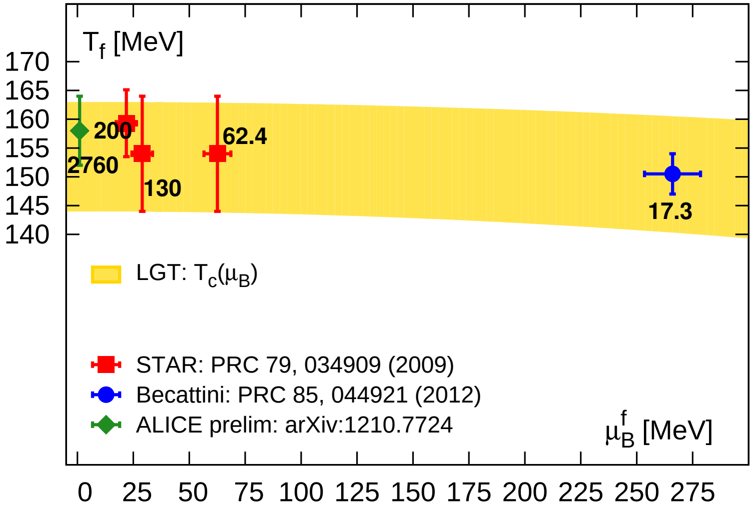
[Beth & Uhlenbeck; Dashen, Ma & Bernstein]

⇒ relative abundances of hadron species i & j given by phase space ratio at temperature T, baryochemical potential μ

$$\frac{N_i}{N_j} = \left(\frac{d_i}{d_j}\right)\left(\frac{m_i}{m_j}\right)^2 \frac{K_2(m_i/T_f)\cosh(B_i\mu/T)}{K_2(m_j/T_f)\cosh(B_j\mu/T)}$$

data agree: abundances of all species in AA collision at fixed $\sqrt{s}$ lead to unique freeze-out parameters T_f, μ_f

striking observation:

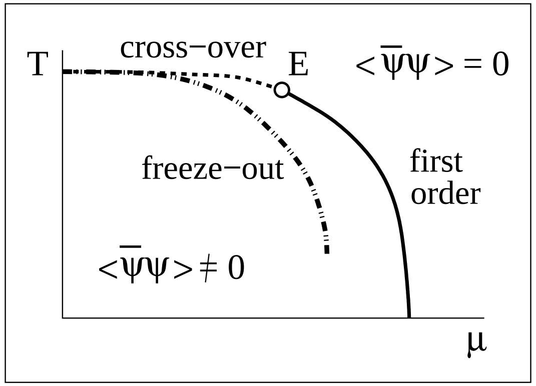


for $\mu_f \simeq 0$, the freeze-out temperature T_f coincides with the transition temperature T_c;

the medium formed in nuclear collisions hadronises at the transition temperature of QCD matter

NB: increase of collision energy leads to
decrease of baryochemical potential μ
due to nuclear transparency; tool to vary μ

at larger μ, non-resonant baryon-baryon interactions cause drop of freeze-out below transition line



support claim “hadronic matter through nuclear collisions”: consider fluctuations of conserved quantum numbers (e.g. baryon number, charge, ...) in an ideal resonance gas; determined by higher derivatives of free energy (cumulants)

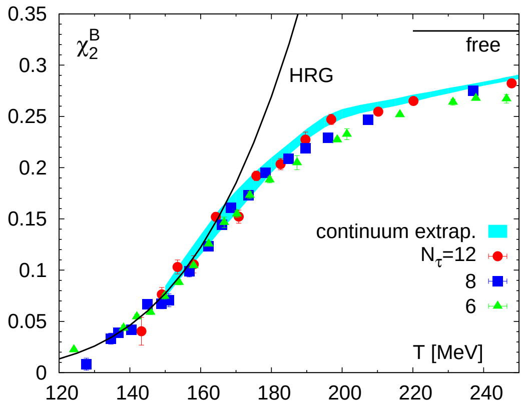
$$\frac{f(T,\mu)}{T^4} = \frac{1}{\pi^2}\sum_i d_i (m_i/T)^2 K_2(m_i/T)\cosh(B_i\mu/T),$$

$$\chi_B^{(n)}(T,\mu) = \partial^n(f/T^4)/\partial(\mu/T)^n$$

example: $\chi_B^{(2)} \sim \langle N_B^2 - \langle N_B\rangle^2\rangle$, etc.

resulting $\chi_B^{(2)}(T, \mu = 0)$
at $\mu = 0$ is in accord
with lattice QCD calculation

[Bazavov et al. (hotQCD)]

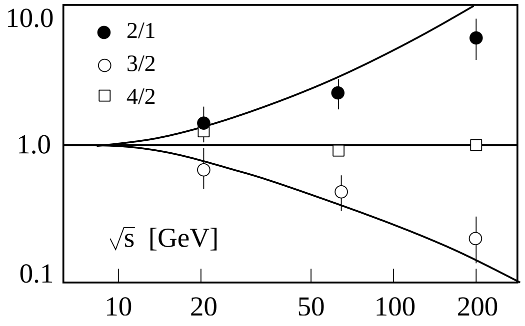


since all baryons have $B = \pm 1$, get ratios

$$\frac{\chi_B^{(3)}}{\chi_B^{(1)}} = \frac{\chi_B^{(4)}}{\chi_B^{(2)}} = \ldots = 1 \qquad \frac{\chi_B^{(2)}}{\chi_B^{(1)}} = \coth(\mu/T), \ \frac{\chi_B^{(3)}}{\chi_B^{(2)}} = \tanh(\mu/T), \ldots$$

for lower order cumulants,
this behavior is in accord
with STAR data from RHIC

[Aggarwal et al. (STAR)]



Conclusion:

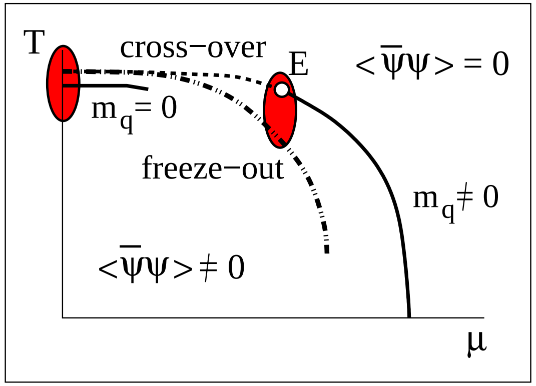
nuclear collisions ⇒ $\sim$ equilibrium hadronic resonance gas,
for $\mu = 0$ at the transition temperature predicted by QCD

But:

are there no traces of critical behavior near transition?
are there deviations from ideal gas, diverging correlations,...?

2 Critical Behavior: Fluctuations and Correlations

only remnants of critical behavior:
— near $\mu = 0$, $m_q \neq 0$
— near critical endpoint,
freeze-out $\neq$ transition line
look for reflections of divergence



simpler case: Ising model

$$\mathcal{H} = -J \sum_{\{i,j\}} s_i s_j - H \sum_i s_i$$

$$Z(T,H) = \prod_{i=1}^{N^3} \sum_{s_i=\pm 1} \exp\{-\beta \mathcal{H}\} \qquad f(T,H) = -\frac{T}{V} \log Z(T,H)$$

consider derivatives of $f(T,H)$ with respect to T and H

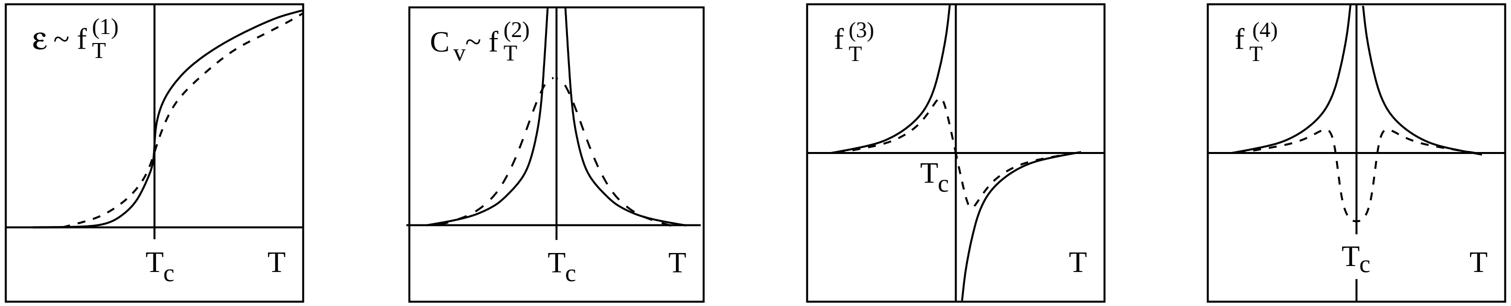
$$f_T^{(n)}(T, H=0) = \left(\frac{\partial^n f(T,H)}{\partial T^n}\right)_{H=0}$$

here $f_T^{(1)}(T,H=0) \sim \epsilon(T,H=0)$ — energy density
$f_T^{(2)}(T,H=0) \sim C_v(T,H=0)$ — specific heat

singular behavior for $T \to T_c$:

$$C_v \sim |t|^{-\alpha} \qquad t \equiv \frac{T - T_c}{T_c}$$

and so on... singular behavior is damped by external field H



crucial feature reflecting criticality:

non-monotonic higher cumulants

similar pattern for derivatives re H,

$$f_H^{(n)}(T, H=0) = \left(\frac{\partial^n f(T,H)}{\partial H^n}\right)_{H=0}$$

giving magnetisation

$$m(t, H=0) \sim f_H^{(1)}(T, H=0) = \left(\frac{\partial f(T,H)}{\partial H}\right)_{H=0} \sim |t|^{-\beta}, \quad t<0$$

isothermal susceptibility

$$\chi_T(t, H=0) \sim f_H^{(1)}(T, H=0) = \left(\frac{\partial^2 f(T,H)}{\partial H^2}\right)_{H=0} \sim |t|^{-\gamma}, \quad t < 0$$

and so on.

response functions (C_v, χ_T, ...) related to fluctuations

$$\text{of energy}: \; C_v(T, H=0) \sim \langle(\sum_{i,j} s_i s_j)^2\rangle - \langle\sum_{i,j} s_i s_j\rangle^2$$

$$\text{of spin}: \; \chi_T(t, H=0) \sim \langle(\sum s_i)^2\rangle - m^2$$

divergence of response function $\sim$ divergence of fluctuations
$\sim$ divergence of correlation lengths $\xi(t) \sim |t|^{-\nu}$

response functions diverge with correlations: $\chi_T(t) \sim \xi^{\gamma/\nu} \sim \xi^2$

singular behavior specified by critical exponents α, β, γ, ν, ...

QCD thermodynamics

$$f_{\text{Ising}}(T; H) \;\rightarrow\; f_{\text{QCD}}(T, \mu_B, \mu_Q, \mu_S; m_q)$$

– one symmetry-respecting variable T → four T, μ_B, μ_Q, μ_S

– external field $H \rightarrow m_q$

look for non-monotonic behavior of response functions as signal of critical behavior

– near $\mu = 0$ for O(4) criticality remnants at small m_q

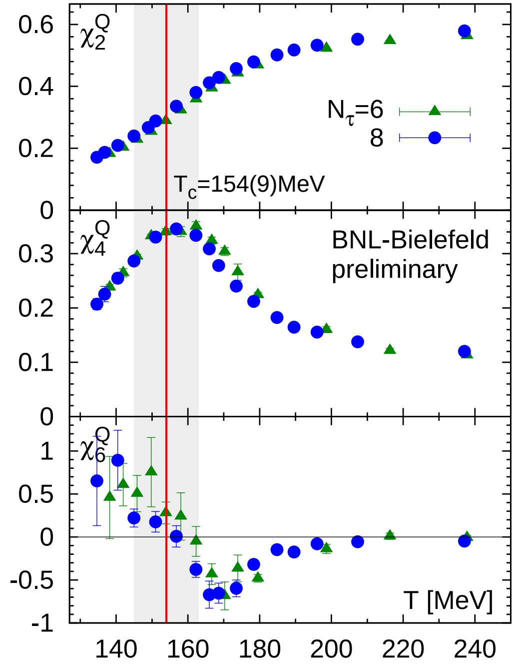
– near critical endpoint for Z_2 criticality at freeze-out just below transition line

- $\mu = 0$:

  does QCD at 2+1 physical quark masses show signs of critical behavior?

recent lattice results for charge fluctuation cumulants: critical behavior apparent for physical quark masses

[C. Schmidt et al. (Bielefeld-BNL)]



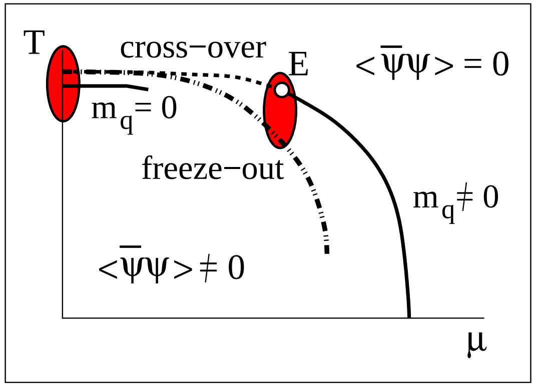
sufficiently high statistics data at LHC could settle issue:

— $\chi_Q^{(6)} \to 0$ **at** T_c **vs. strong increase of HRG**

— $\chi_Q^{(8)}$ **becomes negative at** $\sim T_c$ **vs. strong increase of HRG**

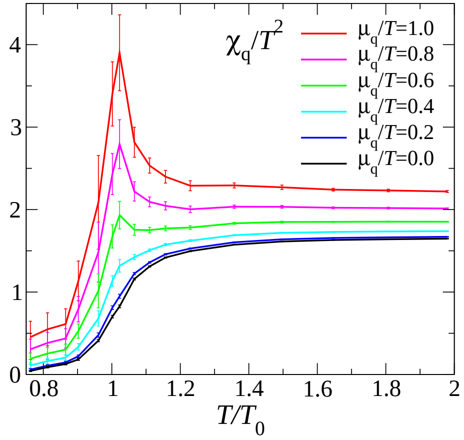
- $\mu \neq 0$, critical endpoint

again look for non-monotonic behavior of cumulants at freeze-out "near" transition



<u>Conclusion:</u>

— lattice QCD (in spite of technical difficulties at finite μ) predicts observable signatures of criticality



[Ejiri et al. (Bielefeld-BNL)]

— experiments (LHC, RHIC-beam energy scan) in progress

3 The QGP Temperature: Quarkonium Suppression

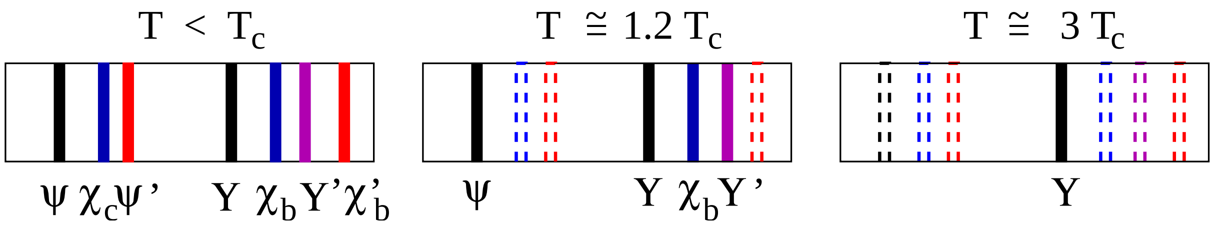
hard probes of hot early collision stage QGP:

electromagnetic radiation, jets, quarkonia

— much smaller ($R \sim 0.1 - 0.2$ fm),
— more tightly bound ($\Delta E \sim 0.6 - 1.2$ GeV)
than light quark bound states

can survive up to some temperature in hot QGP

— stepwise dissociation: first larger, more loosely bound
excited states, then ground states "melt"



"QGP Thermometer"

large quark masses → NR potential theory

$$\left\{2m_c - \frac{1}{m_c}\nabla^2 + V(r)\right\}\Phi_i(r) = M_i\Phi_i(r),$$

with Cornell potential $V(r) = \sigma\, r - (\alpha/r)$ gives excellent (spin-averaged) vacuum spectra

in hot deconfined medium, color-screened potential

$$V(r,T) \sim \sigma r \left\{\frac{1 - e^{-\mu r}}{\mu r}\right\} - \frac{\alpha}{r} e^{-\mu r},$$

with screening length $r_d(T) = 1/\mu(T))$ from lattice studies; get dissociation temperature estimates

$$T_{J/\psi} \;\simeq\; 1.3\; T_c, \quad T_\chi \;\&\; T_{\psi'} \;\simeq\; 1.1\; T_c.$$

Better: calculate directly in finite temperature lattice QCD calculate correlator

$$G_i(\tau, T) = \int d\omega\ \sigma_i(\omega, T)\ \frac{\cosh[\omega(\tau - (1/2T))]}{\sinh(\omega/2T)}.$$

at discrete points in τ; need to invert to get spectrum $\sigma(\omega, T)$:
Maximum Entropy Method (MEM)

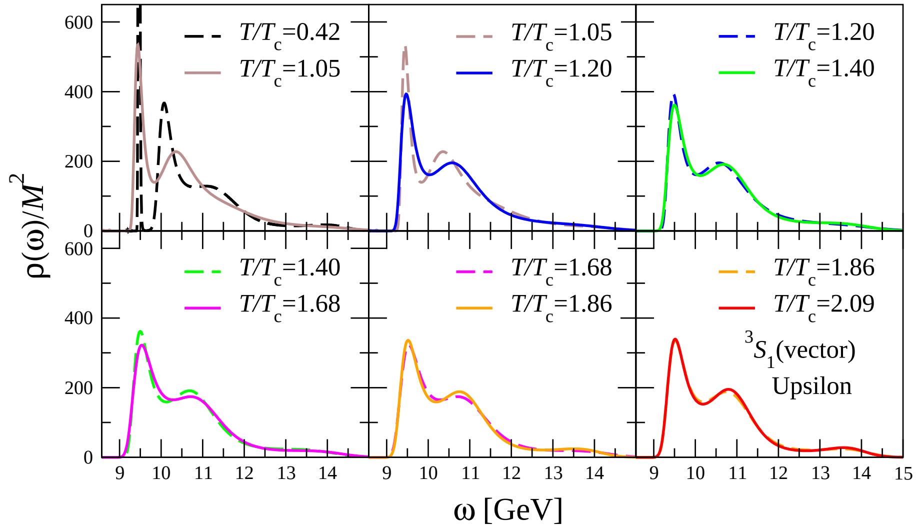
so far, only preliminary information: [Ding et al.]

— limited no. τ points,
— two - three temperatures only

some estimates:

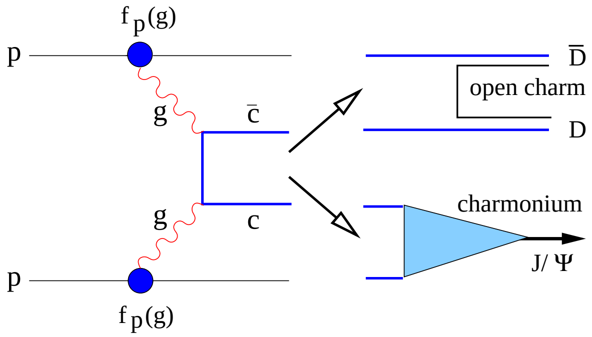
state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	1.5	1.1	1.1	> 4.0	1.8	1.60	1.2	1.1

recent NRQCD studies with temperature scan for Υ



[Aarts et al.]

apply to nuclear collisions;
production scheme in *pp*



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

– fixed partitioning of hidden charm into different charmonia
(color evaporation)

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

– fixed partitioning of open charm into different D etc.
(statistical hadronisation)

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

– 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:

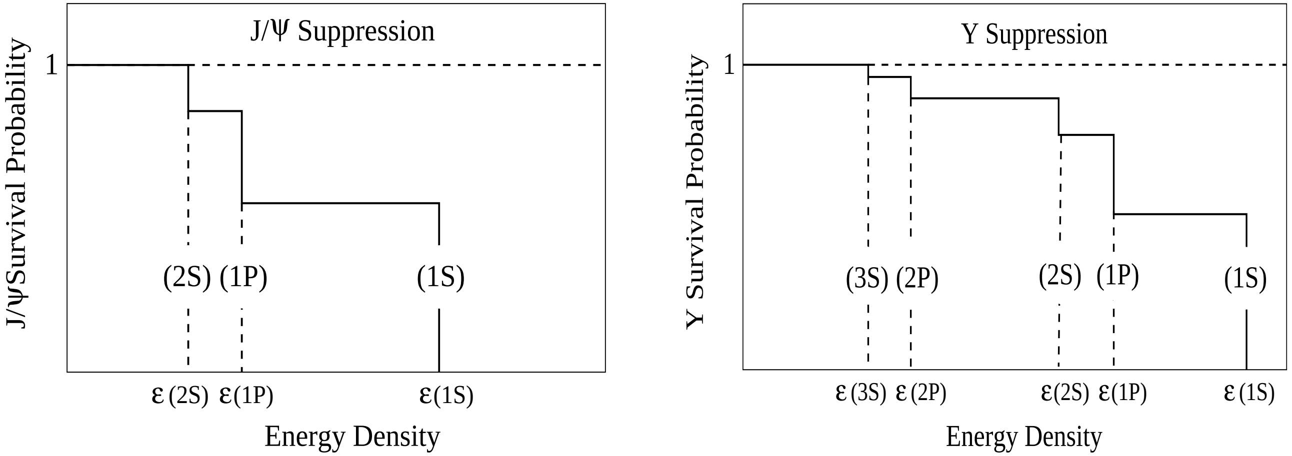
how are these features modified in nuclear collisions?

hot QGP prevents quarkonium binding, leads to suppression of quarkonium production [Matsui & HS]

— with increasing temperature (energy density), first production of excited states suppressed, then ground state

— for J/ψ production, first feed-down contributions, then direct ground state suppressed

Sequential Quarkonium Production



suppression thesholds calculable in QCD

what is J/ψ survival probability $S_{J/\psi}$? calibration?

NB: overall $c\bar{c}$ production dependent on collision energy, details (shadowing, parton energy loss, ...)

crucial question:

- **are relative fractions going into hidden/open heavy flavor, into ground state vs. excited states modified by medium?**

$$S_{J/\psi} = \left(\frac{J/\psi}{c\bar{c}}\right)_{AA} \Big/ \left(\frac{J/\psi}{c\bar{c}}\right)_{pp} = \frac{R_{AA}(J/\psi)}{R_{AA}(D)}$$

nuclear modification $R_{AA}(J/\psi) \sim N_{AA}(J/\psi)/n_{\rm col}N_{pp}(J/\psi)$

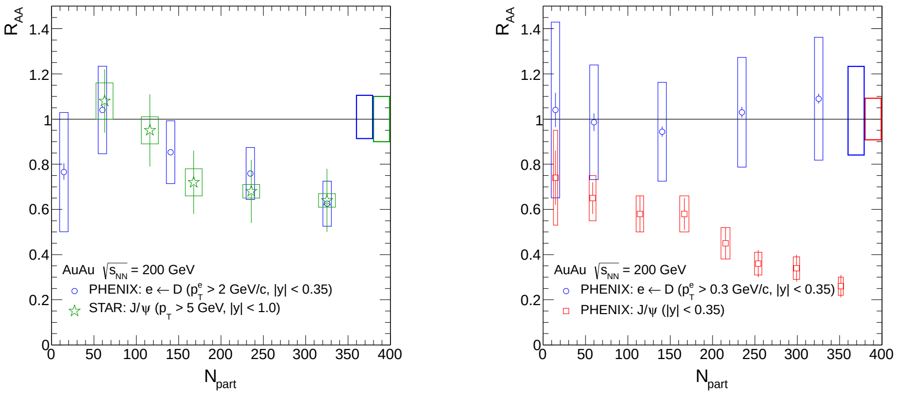
NB: open charm ~ production of a given D, etc.

difficulty for past twenty years: no open charm data

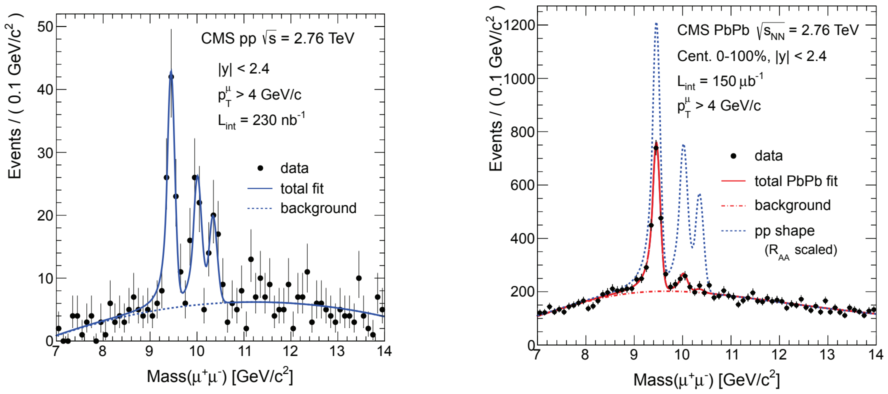
model construction for J/ψ survival → model-dependence

now new data from RHIC and LHC:

RHIC
J/ψ production



LHC
Υ production



Conclusions

- **Nuclear collisions produce hadronic medium in thermal equilibrium at transition temperature of statistical QCD.**
- **Critical behavior at transition is encoded in fluctuations calculated in QCD, in principle measurable for baryon number, charge, strangeness.**
- **Suppression thresholds for quarkonium states determine temperature of QGP, calculable in QCD and measurable for charmonia (?) and bottomonia.**