Strangeness, Charm and Charmonia at High Temperatures

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Deconfined strange and charm quarks in HIC

constituent quark number scaling of strange hadron elliptic flow


strangeness enhancement

Deconfined strange and charm quarks in HIC

D meson elliptic flow

J/Ψ elliptic flow

partonic nature of strange & charm degrees of freedom in QGP

J/Ψ suppression

Influence of chiral crossover on deconfinement? 

- Liberation of quark DoF, $N^0_c \rightarrow N_c \Rightarrow$ rise in quark number fluctuations
- Up & down, quarks deconfine around the chiral crossover
- Imprint of the chiral nature of the crossover
- Strange quark deconfines above the chiral crossover?
- Strange quark too heavy to be influenced by the chiral nature of the crossover?
- Charm quarks remain confined well above the chiral crossover?
- Chiral symmetry plays no role in charm quark deconfinement?

Chiral crossover: $T_c = 154(9) \text{ MeV}$

Need to look for proper observables

probe quantum numbers associated with sDoF & cDoF ...

higher order

baryon(B)/charge(Q)–strangenessness(S) correlations

B/Q/S–charm(C) correlations

\[ \chi_{mn} = \frac{\partial^{m+n} P}{\partial^m \mu_x \partial^n \mu_y} \]

\[ \chi^{XY}_{0n} \equiv \chi^n Y \]

\[ \hat{\mu}_x = \mu_x / T \]

\[ P = p / T^4 \]

… and construct observables from combinations of higher order S/C fluctuations, B/Q–S, B/Q/S–C correlations such that these observables are only sensitive to the quantum numbers associated with DoF irrespective of their masses

Strangeness in an uncorrelated hadron gas

\[ P_{S}^{HRG} = P_{|S|=1,M}^{HRG} \cosh(\hat{\mu}_S) + P_{|S|=1,B}^{HRG} \cosh(\hat{\mu}_B - \hat{\mu}_S) + P_{|S|=2,B}^{HRG} \cosh(\hat{\mu}_B - 2\hat{\mu}_S) + P_{|S|=3,B}^{HRG} \cosh(\hat{\mu}_B - 3\hat{\mu}_S) \]

\[ P_{S}^{HRG} : \text{partial pressure of all } |S|\neq0 \text{ hadrons} \]

\[ P_{|S|=1,M}^{HRG} : \text{partial pressure of } |S|=1 \text{ mesons} \]

\[ P_{|S|=1,B}^{HRG} : \text{partial pressure of } |S|=1 \text{ baryons} \]

\[ P_{|S|=2,B}^{HRG} : \text{partial pressure of } |S|=2 \text{ baryons} \]

\[ P_{|S|=3,B}^{HRG} : \text{partial pressure of } |S|=3 \text{ baryons} \]

Strange hadrons: \( m_S^{\text{had}} \gg T \)

Using classical (Boltzmann) approx

up to 4th order

S fluctuations & B–S correlations

\[ \chi_2^S \quad \chi_4^S \quad \chi_{11}^{BS} \quad \chi_{31}^{BS} \quad \chi_{22}^{BS} \quad \chi_{13}^{BS} \]

Boltzmann (classical) approx works very well for strange hadrons, deviations < 3%
Strangeness in an uncorrelated hadron gas

up to 4th order
S flucn & B–S corrln.
6 known (LQCD)

separate conrt. of strange mesons & baryons
4 unknown

$P_{|S|=1,M}^{HRG}$: partial pressure of $|S|=1$ mesons
$P_{|S|=1,B}^{HRG}$: partial pressure of $|S|=1$ baryons
$P_{|S|=2,B}^{HRG}$: partial pressure of $|S|=2$ baryons
$P_{|S|=3,B}^{HRG}$: partial pressure of $|S|=3$ baryons

$M(s_1, s_2) = \chi_2^S - \chi_2^{BS} + s_1 S_1 + s_2 S_2$

$B_1(s_1, s_2) = \frac{1}{2} \left( \chi_4^S - \chi_2^S + 5 \chi_{13}^{BS} + 7 \chi_{22}^{BS} \right) + s_1 S_1 + s_2 S_2$

$B_2(s_1, s_2) = -\frac{1}{4} \left( \chi_4^S - \chi_2^S + 4 \chi_{13}^{BS} + 4 \chi_{22}^{BS} \right) + s_1 S_1 + s_2 S_2$

$B_3(s_1, s_2) = \frac{1}{18} \left( \chi_4^S - \chi_2^S + 3 \chi_{13}^{BS} + 3 \chi_{22}^{BS} \right) + s_1 S_1 + s_2 S_2$

uncorrelated hadron gas:

$M(s_1, s_2) \rightarrow P_{|S|=1,M}^{HRG}$ for all $(s_1, s_2)$

$B_i(s_1, s_2) \rightarrow P_{|S|=i,B}^{HRG}$

irrespective of hadron mass spectrum

$S_1 = S_2 = 0$

2 constraints

$P_{|S|=1,M}^{HRG}$ : partial pressure of $|S|=1$ mesons
$P_{|S|=1,B}^{HRG}$ : partial pressure of $|S|=1$ baryons
$P_{|S|=2,B}^{HRG}$ : partial pressure of $|S|=2$ baryons
$P_{|S|=3,B}^{HRG}$ : partial pressure of $|S|=3$ baryons

$S_1 = S_2 = 0$

irrespective of hadron mass spectrum

$P_{|S|=1,M}^{HRG}$ : partial pressure of $|S|=1$ mesons
$P_{|S|=1,B}^{HRG}$ : partial pressure of $|S|=1$ baryons
$P_{|S|=2,B}^{HRG}$ : partial pressure of $|S|=2$ baryons
$P_{|S|=3,B}^{HRG}$ : partial pressure of $|S|=3$ baryons

irrespective of hadron mass spectrum
Strangeness in an uncorrelated hadron gas

\[ S_1 = \chi_{31}^{BS} - \chi_{11}^{BS} \]
\[ S_2 = \left( \frac{\chi_S^2 - \chi_S^4}{3} \right) - 2 \left( \chi_{13}^{BS} + 2 \chi_{22}^{BS} + \chi_{31}^{BS} \right) \]

if sDoF are (uncorrelated) hadrons with \( S=1,2,3 \) and \( B=0,1 \)
irrespective of the hadron masses

\[ S_1 = 0, \quad S_2 = 0 \]

for example:

\[ S_1 = \chi_{31}^{BS} - \chi_{11}^{BS} = (B^3 - B) \times f(m_{S}^{\text{had}}) \]

\[ S_1 = 0 \text{ for } B = 0,1 \]

if sDoF are quarks then \( B=1/3 \): \( S_1 \neq 0 \)

similarly:

\[ \chi_4^B - \chi_2^B = (B^4 - B^2) \times f(m_{u,d,S}^{\text{had}}) \]
Are there strange hadrons above the chiral crossover?

\[ T \lesssim T_c : \text{sDoF have } B=0,1 \]

\[ \chi_2^B - \chi_4^B : \text{light quark analog of } S_1 \]

sDoF behave similarly as the light quark DoF

\[ \chi_2^B - \chi_4^B : \text{light quark analog of } S_1 \]

no strange hadrons for

\[ T \geq T_c \]

\[ T \geq T_c : \text{sDoF have fractional } B \]

BNL-Bi:
Extensions to charm sector

\[ C_1 = \chi^\text{BC}_{31} - \chi^\text{BC}_{11} \]

\[ C_2 = \left( \chi^2 - \chi^4 \right)/3 - 2\left( \chi^\text{BC}_{13} + 2\chi^\text{BC}_{22} + \chi^\text{BC}_{31} \right) \]

\[ C_3 = 3\left( \chi^\text{BC}_{13} - 2\chi^\text{BC}_{22} + \chi^\text{BC}_{31} \right) + \left( \chi^\text{QC}_{11} - 3\chi^\text{QC}_{13} + 3\chi^\text{BC}_{22} - \chi^\text{BC}_{31} \right)/2 \]

if sDoF are (uncorrelated) hadrons with \( C = 1, 2, 3 \) & \( Q = 0, 1, 2 \) and \( B = 0, 1 \) irrespective of the hadron masses

\[ C_1 = 0, \ C_2 = 0, \ C_3 = 0 \]

for example:

\[ C_1 = \chi^\text{BC}_{31} - \chi^\text{BC}_{11} = (B^3 - B) \times f\left( m^\text{had}_C \right) \]

depends on the hadron mass spectrum

\[ C_1 = 0 \text{ for } B = 0, 1 \]

if sDoF are quarks then \( B = 1/3 \): \( C_1 \neq 0 \)
Are there charmed hadrons above the chiral crossover?

\[ T \lesssim 175 \text{ MeV} : \]
\[ \text{cDoF have } B=0,1 \text{ & } Q=0,1,2 \]

no charmed hadrons for \( T \gtrsim 1.1 T_c \)

charm quarks are treated as probe particles in a bath of gluons and up, down quarks, \textit{i.e.} partially quenched charm quarks → no contribution from charm quark loop
Confined sDoF

\[ M(s_1, s_2) = \chi_2^S - \chi_2^{BS} + s_1 S_1 + s_2 S_2 \]

if sDoF are hadrons: \( S_1 = S_2 = 0 \)

\[ M(s_1, s_2) \rightarrow P^{HRG}_{|S|=1,M} \quad \text{for all} \quad (s_1, s_2) \]

\[ P^{HRG}_{|S|=1,M} : \text{partial pressure of strange mesons with vacuum masses} \]

high T: \( S_1 = S_2 \neq 0 \)

\[ M^{\text{nonint}}(s_1, s_2) \quad \text{depends on} \quad (s_1, s_2) \]

sDoF are well described by strange hadrons having vacuum masses for \( T \approx T_c \)

BNL-Bi:
Confined sDoF

\[ B_1(s_1, s_2) \]

\[ B_2(s_1, s_2) \]

\[ B_3(s_1, s_2) \]

\[ P_{\text{HRG}}^{\text{HRG}} : \text{partial pressure of } S=n \text{ baryons with vacuum masses} \]

similar conclusion for strange baryons

similar observables for cDoF: both observables give the partial pressure of charmed mesons at low $T$, but have widely different high $T$ limit $T \lesssim 175$ MeV:

$P_{\text{HRG}}^{C,\text{mes}}$ : partial pressure of open charm mesons with vacuum masses

cDoF are well described by charmed hadrons having vacuum masses for $T \lesssim 1.1T_c$
both observables give the partial pressure of charmed baryons at low T, but have widely different high T limit

\[ T \lesssim 175 \text{ MeV} : \]

\[ P^\text{HRG}_{C,\text{bar}} : \text{partial pressure of charmed baryons with vacuum masses} \]

same conclusion for charmed baryons

accidental agreement of the blue data points with \( P^\text{HRG,QM}_{C,\text{bar}} \) up to much higher T illustrate the importance of multiple observables with widely different high T limit

\[ P^\text{HRG,QM}_{C,\text{bar}} : \text{partial pressure of charmed baryons including unobserved states predicted in a Quark Model [Roberts & Pervin, IJMP A23, 2817 (2008)]} \]
Deconfined sDoF

strongly interacting sDoF for $T_c \lesssim T \lesssim 2T_c$

weakly/non-interacting quasi-quarks

$S = -1, B = 1/3, Q = -1/3$

baryon–strangeness correlation

$\chi_{mn}^{BS}/\chi_n^S = B^m S^n = (-1)^n/3^m$

charge–strangeness correlation

$\chi_{mn}^{QS}/\chi_n^S = Q^m S^n = (-1)^{m+n}/3^m$

weakly interacting strange quasi-quarks for $T \gtrsim 2T_c$

higher order B–S & Q–S corr. show stronger deviations from the weakly interacting quasi-quark picture
Deconfined sDoF

weakly/non-interacting quasi-quarks

\( S = -1, \ B = 1/3, \ Q = -1/3 \)

B–Q–S correlation

\[
\frac{\chi_{BQS}^{\chi_{lmn}}}{\chi_{n}^{S}} = B^{l}Q^{m}S^{n} = \frac{(-1)^{m+n}}{3^{l+m}}
\]

weakly interacting strange quasi-quarks for \( T \geq 2T_{c} \)

strongly interacting sDoF

for \( T_{c} \leq T \leq 2T_{c} \)
Deconfined cDoF

B–C corrIn

Q–C corrIn

S–C corrIn

non-int. quarks

strongly interacting cDoF for $1.1T_c \lesssim T \lesssim 2T_c$

weakly interacting charm quasi-quarks for $T \gtrsim 2T_c$

deconfined cDoF looks very similar to deconfined sDoF
Flavor correlations in QGP

\[ \chi_{mn}^{f_1 f_2} / \chi_{m+n}^{f_2} \]

normalization by \( \chi_{m+n}^{f_2} \) partly neutralizes the flavor mass dependence

strong correlations among various flavors are almost flavor blind for \( T \gtrsim 1.1T_c \)

dominated by gluonic interactions in the deconfined phase

weak correlations among various flavors for \( T \gtrsim 2T_c \)
closed charm states cannot be probed using quantum number correlations

spatial (screening) correlation functions of charmonia

\[
C(z, T) = \int_0^\infty \frac{2 d \omega}{\omega} \int_{-\infty}^{\infty} dp_z e^{i p_z z} \rho(\omega, p_z, T)
\]

in contrast to the usual temporal correlation function

\[
C(\tau, T) = \int_0^\infty \frac{d \omega}{2\pi} \rho(\omega, 0, T) \frac{\cosh[\omega(\tau - 1/2T)]}{\sinh(\omega/2T)}
\]

spatial correlation function:

- is not limited to the physical distance of 1/T
- transport-type zero mode contribution to the spectral function does not lead to a non-decaying constant at large distances and only generates a contact term
- the kernel is T independent \(\rightarrow\) direct comparison with T=0 correlation function possible
1S charmonia

comparison of $T=/= & T=0$
spatial correlation functions
provide direct signatures for
significant thermal modifications

$1S$ charmonium states are
significantly modified for
$T \gtrsim 175 \text{ MeV}$

Yu Maezawa et al., Lattice 2013
similar significant thermal modifications of the 1P charmonium states for $T \gtrsim 175$ MeV
Screening masses of charmonia

\[ C(z, T) = \int_0^\infty \frac{2 d\omega}{\omega} \int_{-\infty}^\infty d\rho_z e^{izp_z} \rho(\omega, p_z, T) \]

- high T, non-interacting quark–antiquark pair:
  \[ C(z \to \infty, T) \sim e^{-Mz} \]
  \[ M : \text{screening mass} \]
  \[ M = 2 \sqrt{(\pi T)^2 + m_c^2} \]

- low T, well-defined mesonic bound state:
  \[ \rho(\omega, p_z) \sim \delta(\omega^2 - p_z^2 - m_{\text{mes}}^2) \]
  \[ M = m_{\text{mes}} \]

a trick: one can study the onset of T dependence of M more clearly by imposing a periodic temporal boundary conditions for the valence charm quarks along with the usual anti-periodic ones

- high T, no minimal Matsubara mode:
  \[ M = 2 m_c \]

- low T, bosonic meson bound states insensitive to fermionic b.c at the quark level:
  \[ M = m_{\text{mes}} \]
Screening masses of charmonia

thermal modifications to charmonia are not significant, well-described by their vacuum masses for $T \lesssim T_c$

significant thermal modifications and possible dissolution of charmonium states for $T \gtrsim 1.1T_c$
Recapitulation

The emerging strange / charm story from LQCD ...

- No strange hadrons for $T \geq T_c$, no open charm hadrons for $T \geq 1.1T_c$, charmonia are significantly modified for $T \geq 1.1T_c$

- For $T \leq T_c$ sDoF and cDoF are well described by hadrons having vacuum masses

- sDoF and cDoF remain strongly interacting till $T \leq 2T_c$

- sDoF and cDoF appear consistent with weakly interacting quasi-quarks for $T \geq 2T_c$
Backup slides
Influence of dynamical charm quark

preliminary results from the Wuppertal-Budapest collaboration

PoS LATTICE2011 (2011) 201

effects of dynamical charm quark negligible for $T \leq 400$ MeV