Equations of state for strongly interacting matter and Intensity Interferometry of thermal photons

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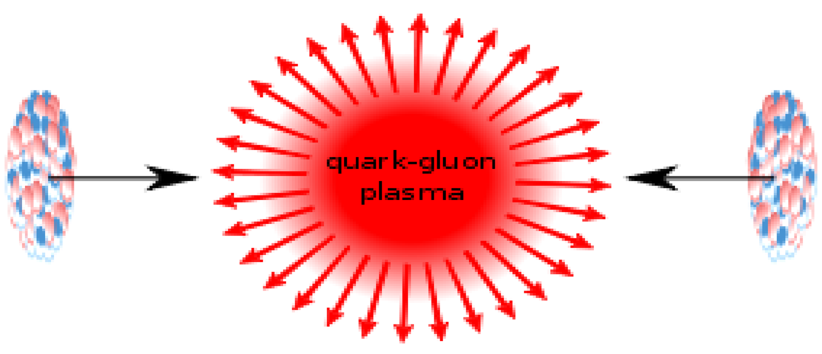
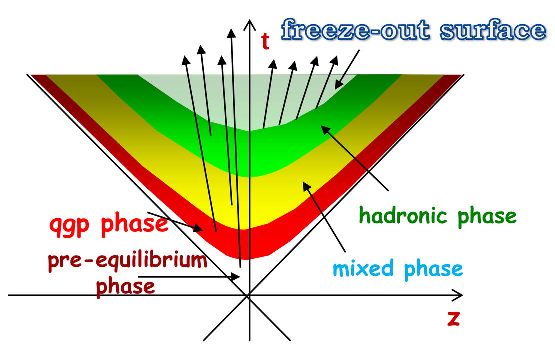
Introduction



Theoretical studies over the last decades and recent heavy ion experiments at RHIC have confirmed that *a strongly interacting, deconfined* state of quarks and gluons is formed when two nuclei collide at relativistic energies. This state of matter is called quark-gluon plasma (QGP). [See for details, QGP white paper, Nucl. Phys. A 757, 1 (2005)]



Relativistic hydrodynamics has been used as an efficient tool to describe space-time evolution of the system from the initial thermalisation to the kinetic freeze-out.

Conservation of energy-momentum $\partial_\mu T^{\mu\nu} = 0 \quad (\mu,\nu = 0,\ldots,3)$

Conservation of local charge $\partial_\mu j_i^{\mu} = 0 \quad i = 1,..,n \quad \mu = 0,\ldots,3$

- In order to solve these equations, we need an extra relation between the local thermodynamic quantities like: energy density, pressure of the thermally equilibrated system. This is called the 'Equation of state' (EOS) for the strongly interacting system.
- We find an equation of state for the hot hadronic matter based on hadron resonance gas model.
- It consists of all baryons having mass < 2 GeV and all mesons having mass < 1.5 GeV along with Hagedorn resonances in the mass range (2 GeV < m < 12 GeV) in thermal and chemical equilibrium.
- The density of Hagedorn states is taken as :

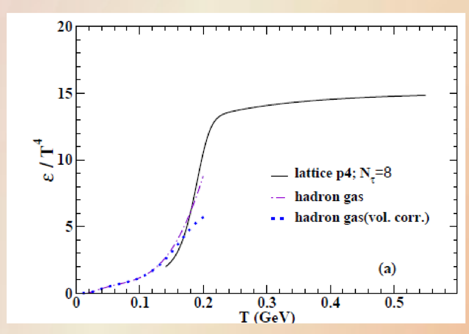
$$\rho_{HS} = A\frac{\exp(m/T_H)}{(m^2+m_0^2)^{5/4}}$$

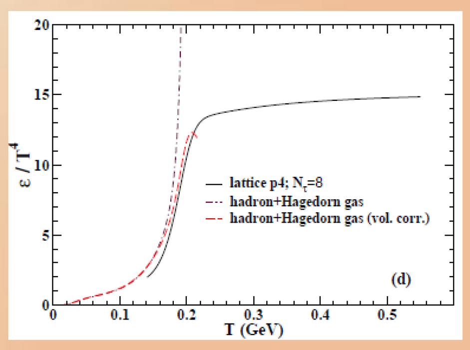
$$A = 0.5\,GeV^{3/2},\ m_0 = 0.5\,GeV$$

$$T_H = 0.196\ GeV$$

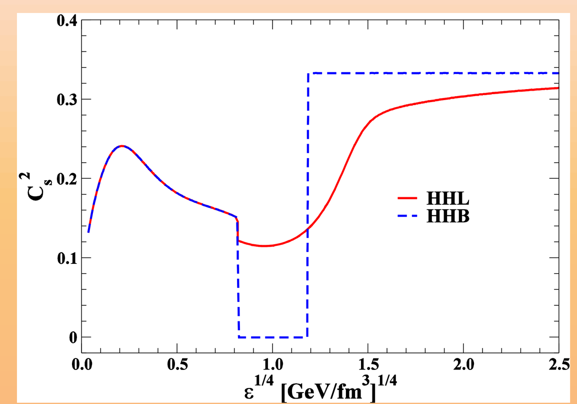
[J. Noronha-Hostler *et al.* Phys. Rev. C 81, 054909 (2010)]

- Thus the hadronic mass spectrum can be written as sum of discrete hadronic states and continuous Hagedorn states.
- Thermodynamic quantities like : pressure (p) and energy density (ε) are calculated from the grand canonical partition function, at zero baryonic chemical potential (μ_B).
- Taking account for finite volume of hadrons, the above quantities are corrected according to the formalism of Kapusta and Olive [Nucl. Phys. A 408, 478 (1983)].





- It is found that inclusion of Hagedorn resonances and finite volume correction gives the best agreement with the recent lattice QCD result [A. Bazavov et al. Phys. Rev. D 80,014504 (2009)] in the temperature range T< 200 MeV.
- We construct two EOS, HHB and HHL, where the volume corrected hadron + Hagedorn resonance gas is used for both in the range T< 165 MeV.
- The bag model inspired EOS (HHB) admits a mixed phase at T=165 MeV, where as the lattice inspired EOS (HHL) shows a sharp transition for 180 < T < 190 MeV.



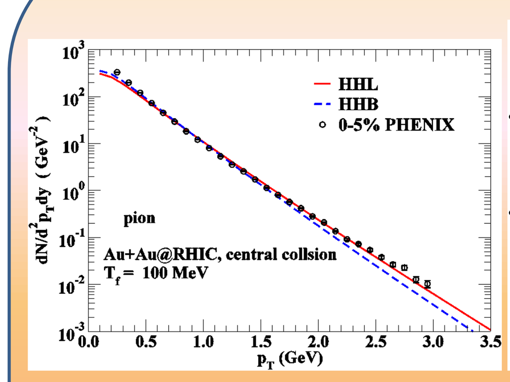
Motivation : We are looking for an observable which is sensitive to the difference of these two EOS's HHB and HHL .

We solve the ideal hydrodynamic equations for central collisions of Au+Au nuclei at 200 A GeV for the two EOS with identical initial condition.

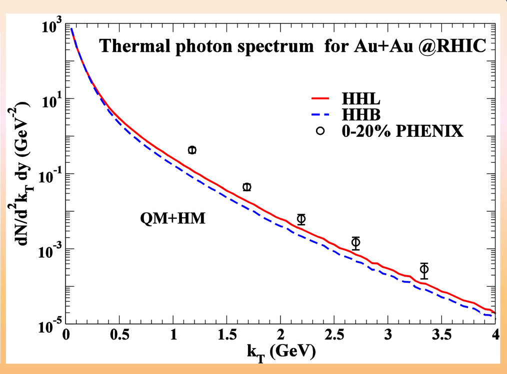
The thermal pion p_T spectra are obtained using the Cooper-Frye formula and compared with (0-5)% PHENIX data (Decay of resonances are not considered).

The thermal photon yield is obtained by integrating the rates from QGP and hadronic matter over the space-time volume of the system and the data for single photons of 0-20% centrality bin are shown for comparison. We have not included prompt photon contribution.

QGP photon rate: Arnold et al. JHEP, 12,009 (2001).
Hadronic photon rate : Turbide et al. PRC 69, 014903 (2004).



[PHENIX] Phys. Rev. C 69,034909 (2004)

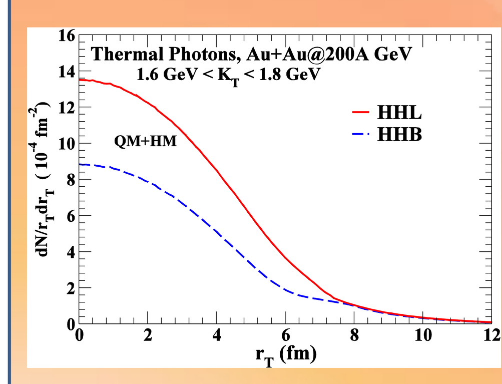


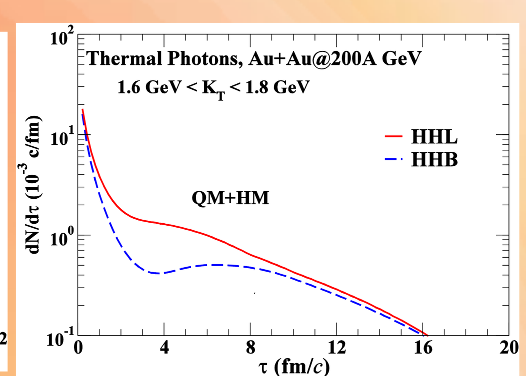
[PHENIX] Phys. Rev. Lett. 104, 132301 (2010)

- Both the EOS gives reasonable description of particle distributions, though the HHL EOS is slightly preferred.
- The inverse slope of the spectra for HHL EOS is larger than the same for the HHB EOS.
- We verified the thermal photon spectrum is quite close to the earlier photon calculation.

These results suggest that both the particle and thermal photon spectra can not distinguish between the two equations of state.

- We also study the spatial and temporal variation of the photon emission source for a typical momentum K_T~1.7 GeV.





We find that the HHL EOS leads to a larger production of photons at smaller radial distances as well as intermediate times compared to HHB.

- This difference holds out a hope that we may see a difference in the intensity correlation of thermal photons for the two EOS.

A recent study in this field has been done by D. K. Srivastava & R. Chatterjee, Phys. Rev. C 80, 054914 (2009)

The correlation function between two photons of momenta k_1 and k_2 is defined as:

$$C(k_1,k_2) = [E_1E_2\frac{dN}{d^3k_1d^3k_2}]/[E_1\frac{dN}{d^3k_1}E_2\frac{dN}{d^3k_2}]$$

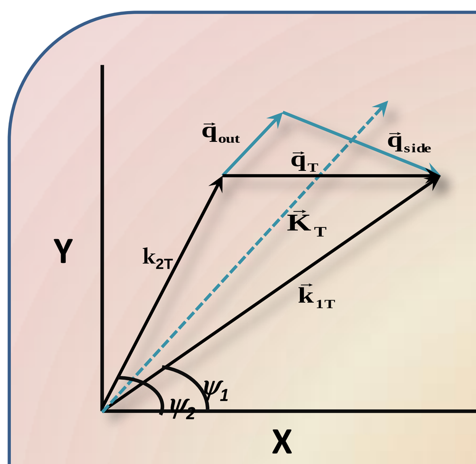
This can be written in terms of source function S as:

$$C(q,K) = 1 + \frac{1}{2}\frac{\left|\int d^4x\, S(x,K)e^{ix.q}\right|^2}{\int d^4x\, S(x,k_1)\int d^4x\, S(x,k_2)}$$

Where S is the photon production rate per unit volume $\frac{EdN}{d^4x d^3k}$

$$\vec{q} = \vec{k}_1 - \vec{k}_2 \quad \text{and} \quad \vec{K} = (\vec{k}_1 + \vec{k}_2)/2$$

For details see : S. De, D. K. Srivastava , and Rupa Chatterjee J. Phys. G 37, 115004 (2010).



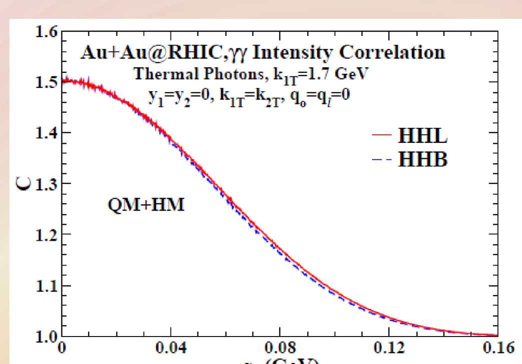
$$\vec{q}_T = \vec{k}_{1T} - \vec{k}_{2T},$$
$$\vec{K}_T = (\vec{k}_{1T} + \vec{k}_{2T})/2$$

The correlation function C is expressed in terms of the variables

$$q_{long} = k_{1z} - k_{2z} = k_{1T}\sinh y_1 - k_{2T}\sinh y_2$$

$$q_{out} = \frac{\vec{q}_T \bullet \vec{K}_T}{K_T} = \frac{(k^2_{1T} - k^2_{2T})}{\sqrt{k^2_{1T} + k^2_{2T} + 2k_{1T}k_{2T}\cos(\psi_1 - \psi_2)}}$$

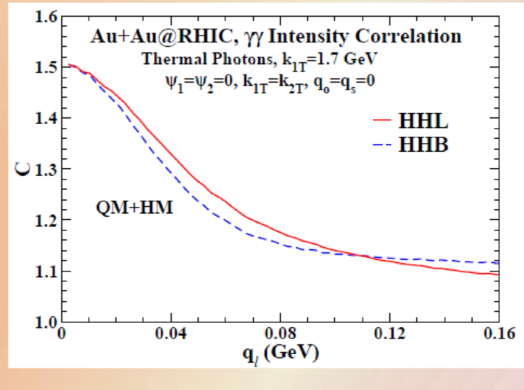
$$q_{side} = \left|\vec{q}_T - q_{out}\frac{\vec{K}_T}{K_T}\right| = \frac{2k_{1T}k_{2T}\sqrt{1-\cos^2(\psi_1-\psi_2)}}{\sqrt{k^2_{1T} + k^2_{2T} + 2k_{1T}k_{2T}\cos(\psi_1 - \psi_2)}}$$

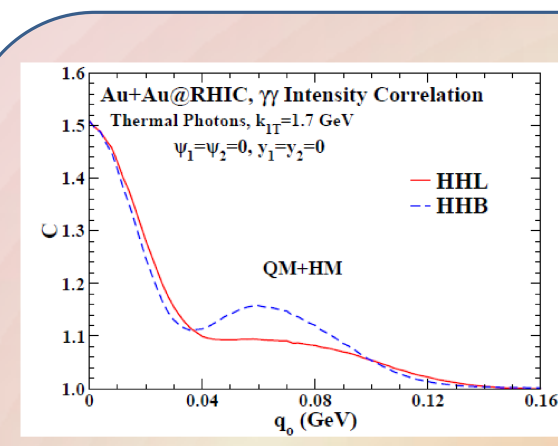


The difference is marginal.

The correlation function C is plotted against q_l , q_o and q_s for the two EOS at top RHIC energy.

For results at LHC energy, see S. De et al J. Phys. G 37, 115004 (2010).





Difference is clearly seen in the outward correlation function.

Summary and conclusions

- We have shown that inclusion of Hagedorn resonances and finite volume correction can give a rich description of hadronic matter.
- Thermal particle and thermal photon spectra are found to be quite similar for the two EOS for a given initial condition at RHIC energy.
- The outward correlation function found to distinguish between the two EOS.
- Direct photon intensity interferometry can be a valuable probe for the EOS of strongly interacting matter if verified experimentally.