Charmonium mass in hot and dense hadronic matter from QCD sum rules

Kenji Morita[1] (kmorita@yukawa.kyoto-u.ac.jp) and Su Houng Lee[2]

[1]*Yukawa Institute for Theoretical Physics, Kyoto University, Japan*

[2]*Institute of Physics and Applied Physics, Yonsei University, Korea*

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Introduction

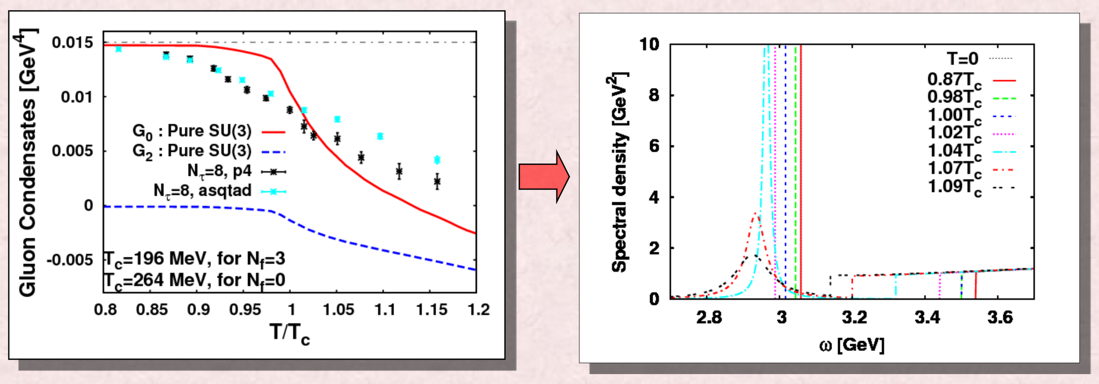
◆ Charmonium : Sensitive to the confinement nature of QCD

- Success of the Cornell potential in mass spectrum : linear confinement force
- QCD sum rules description : gluon condensate $\left\langle \frac{\alpha_s}{\pi} G^a_{\mu\alpha} G^{a\alpha}_{\nu} \right\rangle$
- In-medium modification signals deconfinement
  - ▸ Decrease of string tension : mass reduction (Hashimoto, Miyamura, et al., '86)
  - ▸ QGP – Debye screening leads to "Suppression" (Matsui-Satz, '86)
  - ▸ Lattice QCD : J/ψ survival beyond T_c suggested by MEM spectral function (Asakawa-Hatsuda, '04)

◆ QCD sum rule approach at finite temperature

- Decrease of the gluon condensate is translated into in-medium modification

  (K.M and S.H.L : PRL100, PRC77, PRD82)



- This work : extension to finite chemical potential

  effect of mass shift in the statistical hadronization scenario

Resonance gas model for gluon condensates

◆ Gluon Condensates from Finite T Lattice QCD

- We need both scalar and twist-2 gluon condensates for inputs in QCDSR.

$$\langle T^\mu_\mu \rangle = \left\langle \frac{\beta(g)}{2g} G^a_{\mu\nu} G^{a\mu\nu} \right\rangle + \sum_i m_i \langle \bar{q}_i q_i \rangle = \varepsilon - 3p$$

Gluonic part : M_0

$$T^{\mu\nu} = -G^{a\mu\alpha} G^{a\nu}_{\alpha} + \frac{i}{2} \bar{q} (\gamma^\mu D^\nu + \gamma^\nu D^\mu) q = (\varepsilon + p) u^\mu u^\nu$$

M_2

- How to subtract quark contribution?

◆ Resonance gas model with LDA

- We extend the linear density approximation for the nuclear matter to a resonance gas.

$$M_0^{\text{n.m.}} = \rho m_N^0 \qquad M_2^{\text{n.m.}} = \rho A_G m_N$$

$$\Rightarrow \quad M_0^{\text{had}} = \sum_{i=\text{hadrons}} \rho_i m_i^0 \qquad M_2^{\text{had}} = \sum_{i=\text{hadrons}} \rho_i m_i A_G^i.$$

ρ : normal nuclear density

M_N^0 : Nucleon mass in the chiral limit

A_G : 2nd moment of gluon distribution function of nucleon

ρ_i : number density of hadron i

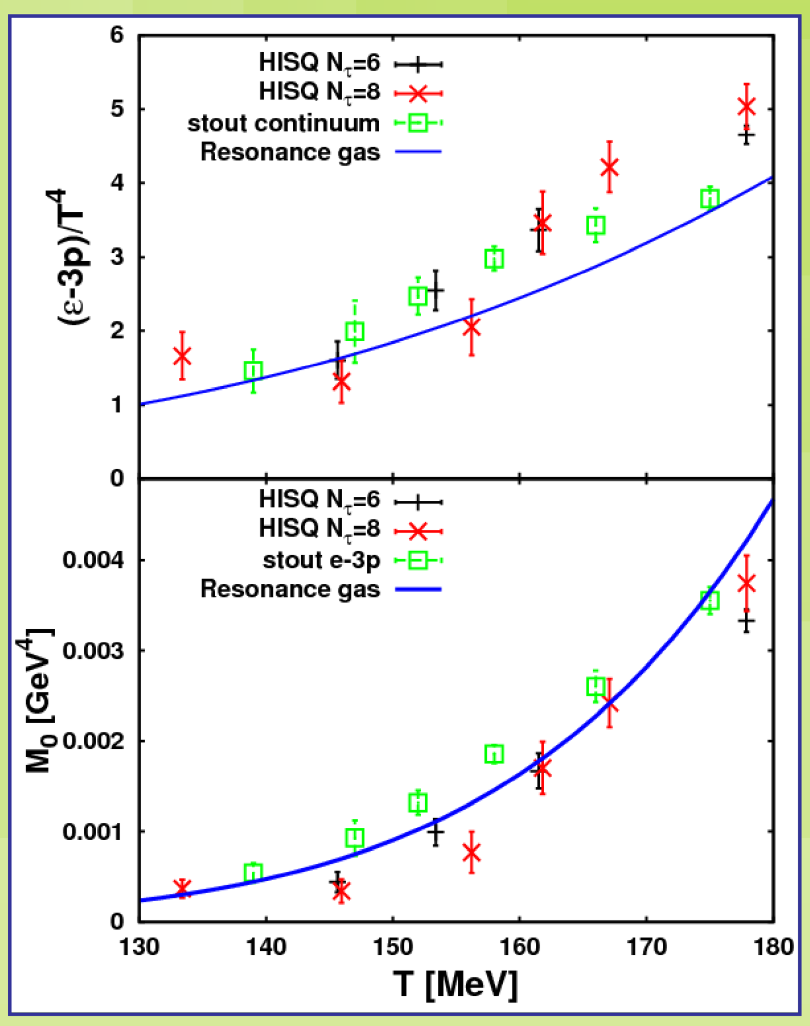
m_i^0 : mass of hadron i in the chiral limit

A_G^i : 2nd moment of gluon distribution function of hadron i

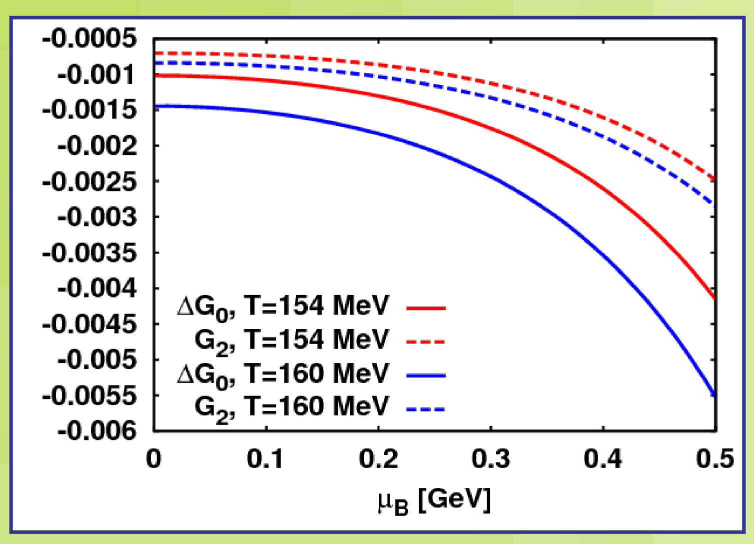
- We assume common A_G=0.9 for all hadrons.
- We use flavor SU(3) symmetry for m_i^0
- m_i^0 of heavier hadrons are assumed to be the same as physical ones, taken from PDG.

$$\begin{aligned} m_\pi^0 &= m_K^0 = 0, \\ m_{f_0}^0 &= m_\sigma^0, \\ m_\phi^0 &= m_\omega^0 = m_{K^*}^0 = m_\rho^0 = m_\rho \\ m_{a_1}^0 &= m_{K_1}^0 = m_{a_1}, \qquad \text{(from } \chi\text{PT)} \\ m_N^0 &= m_\Lambda^0 = m_\Sigma^0 = m_\Xi^0 = 750\text{MeV}, \\ m_{\Sigma^*}^0 &= m_{\Xi^*}^0 = m_\Omega^0 = m_\Delta^0 = m_\Delta \end{aligned}$$

◆ Comparison with lattice data



◆ Gluon condensates



- The higher μ_B becomes, the larger the gluon condensates changes. This fact implies a bigger mass shift at higher chemical potential

$$G_0(T) = G_0^{\text{vac}} - \frac{8}{9} M_0(T)$$

$$G_2(T) = -\frac{\alpha_s^{\text{eff}}}{\pi} M_2(T)$$

Mass shift from QCD sum rules

◆ QCD sum rules for charmonium

- Borel-transformed current correlator in deep Euclidean region (up to dim.4)

$$\mathcal{M}(M^2) = e^{-\nu} \pi A(\nu) [1 + \alpha_s(M^2) a(\nu) + b(\nu) \phi_b(T) + c(\nu) \phi_c(T)] \qquad \nu = 4m_c^2/M^2$$

▸ Medium effect can be imposed on the change of condensates at low temperatures (Hatsuda-Koike-Lee '93)

$$\phi_b = \frac{4\pi^2}{9(4m_c^2)^2} G_0(T), \quad \phi_c = \frac{4\pi^2}{3(4m_c^2)^2} G_2(T)$$

- Connection to spectral function : Dispersion relation

$$\mathcal{M}(M^2) = \int_0^\infty ds\, e^{-s/M^2} \text{Im}\tilde{\Pi}(s)$$

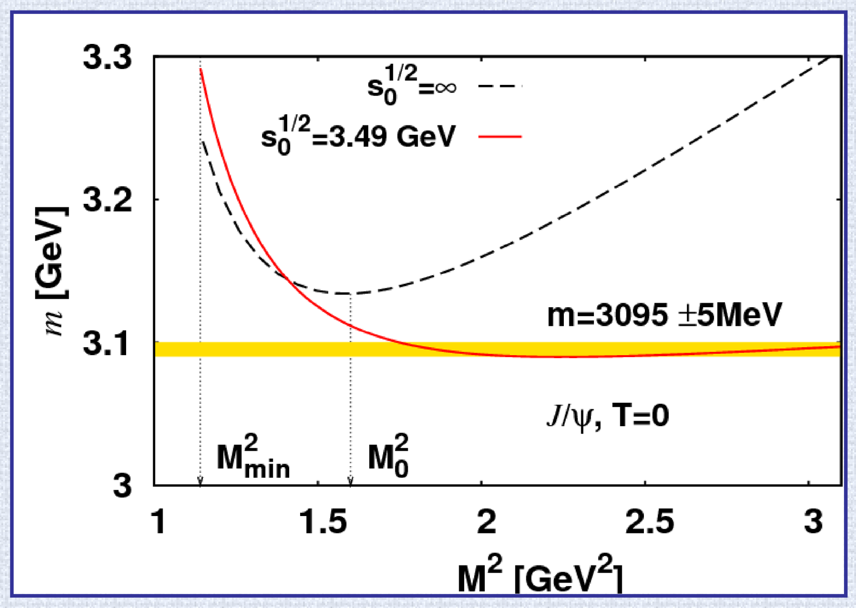
▸ We assume "pole + continuum" ansatz for the model spectral function. Result of the pole modification does not depend on the detailed structure of other parts owing to the pole dominance in the dispersion relation.

- Expression for the mass in the narrow width approximation

$$m^2_{J/\psi}(M^2) = -\frac{\frac{\partial}{\partial(1/M^2)} [\mathcal{M}(M^2) - \mathcal{M}^{\text{cont}}(M^2)]}{\mathcal{M}(M^2) - \mathcal{M}^{\text{cont}}(M^2)}.$$

▸ We use 1-loop perturbative expression for continuum.

▸ We evaluate the mass as a function of M² and search for the plateau region in which the pole dominance (70% of the dispersion integral) and the convergence of the OPE (30% relative dim.4 contribution to the total OPE) are satisfied.



▸ Estimating mass by averaging over the plateau

$$\overline{m} = \frac{1}{M^2_{\max} - M^2_{\min}} \int_{M^2_{\min}}^{M^2_{\max}} dM^2 m(M^2)$$

▸ Error is given by

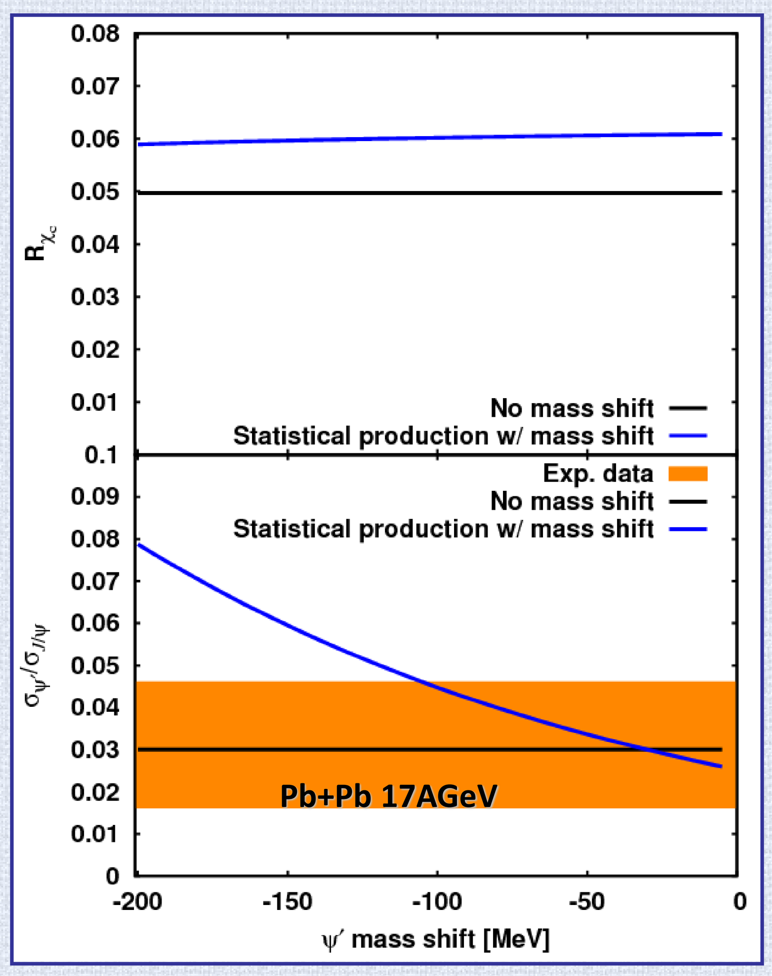
$$(\delta m)^2 = \frac{1}{M^2_{\max} - M^2_{\min}} \int_{M^2_{\min}}^{M^2_{\max}} dM^2 [m(M^2) - \overline{m}]^2$$

- Mass shift at hadronization points [T,μ_B results from A.Andronic et al., NPA772,167 ('06)]

System	RHIC Au+Au 200A GeV	RHIC Au+Au 130A GeV	SPS Pb+Pb 17.4A GeV	SPS Pb+Pb 12.3A GeV	SPS Pb+Pb 8.7A GeV
(T,μ_B) [MeV]	(160.5, 20)	(165.5, 38)	(160, 240)	(154, 298)	(156, 403)
$\delta m_{J/\psi}$ [MeV]	28±5	33±5	37±5	33±5	52±5
δm_{χ_c} [MeV]	62±6	76±6	81±6	72±6	118±6

◆ Effect on particle ratio via statistical hadronization

- We do not have to take charm conservation into account in charmonium-charmonium ratios.
- ψ' mass shift cannot be evaluated from QCD sum rules. An estimate based on second order Stark effect gives 4 times larger mass shifts than that of J/ψ.



- $R_{\chi c}$: fraction of J/ψ coming from decay of χc
- Rcc shows an enhancement independent of uncertain ψ' mass shift
- ψ' mass shift smaller than 100 MeV is consistent with exp. data at SPS Pb+Pb 17.4 GeV

Summary

◆ **We estimated the gluon condensates of resonance gas utilizing the linear density approximation.**

◆ **The condensates decreases as chemical potential increases.**

◆ **We use QCD sum rules to calculate the charmonium mass with inputs from the T and μ_B dependent gluon condensates**

◆ **Downward mass shift causes change in the particle ratio at hadronization**