QCD Equation of State at non- zero Magnetic Field using Dual QCD Formulation

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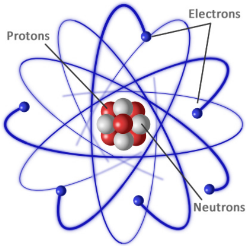
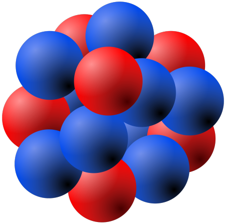
Outline

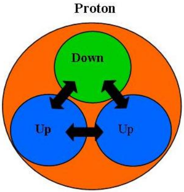
Objectives

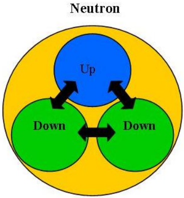
- Investigation of the topological structure of the gauge theory and dual gauge formulation.
- Analyses of the dynamical structure of the resulting dual QCD vacuum, its flux tube formation and its connection with the color confinement.
- The phase transition from hadron to QGP phase in the entire $T - \mu$ plane has been investigated in presence of non-zero magnetic field.
- The associated thermodynamical and transport coefficient of the strongly interacting quark-gluon system have been investigated in an effective way in presence of non-zero magnetic field.

Fundamental building blocks of matter and their interactions





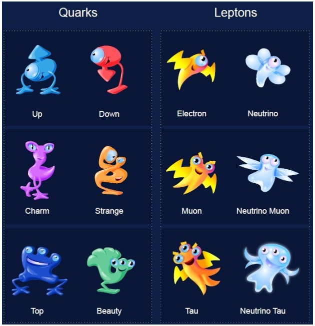




Standard Model of Fundamental Forces

- Standard Model includes members of several classes of elementary particles.

- **Fermions**
- **Gauge Bosons**
- **Higgs Bosons**



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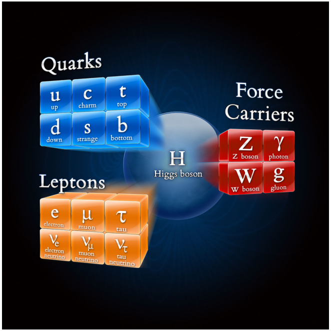

Two unsual properties of QCD

- Confinement
  - Low energy regime $\Rightarrow$ Large distances
  - Linear rising potential $U(r) \propto r$

$$U(r) = -\frac{Q^2}{4\pi}\left[\frac{e^{-m_B r}}{r} - \frac{1}{2} r ln(1 + \kappa_{QCD}^{(d)^2})\right]. \quad (1)$$

- **Garima Punetha and H.C. Chandola: Euro Physics Letter, 116 (2016) 11001**

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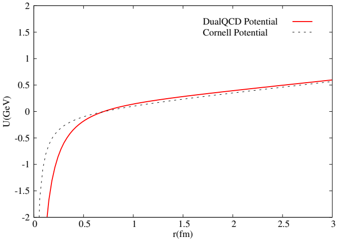

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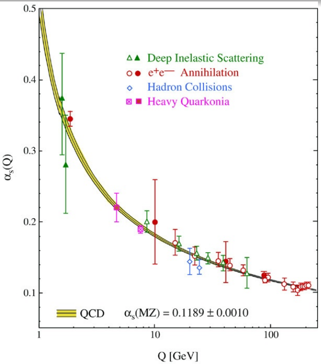
- Running Coupling and Asymptotic Freedom

High energy regime ⇒ Short distances

$$\alpha_s(Q^2) = \frac{4\pi}{(11 - \frac{2}{3}n_F)\ln(\frac{Q^2}{\wedge^2_{QCD}})}, \qquad (2)$$

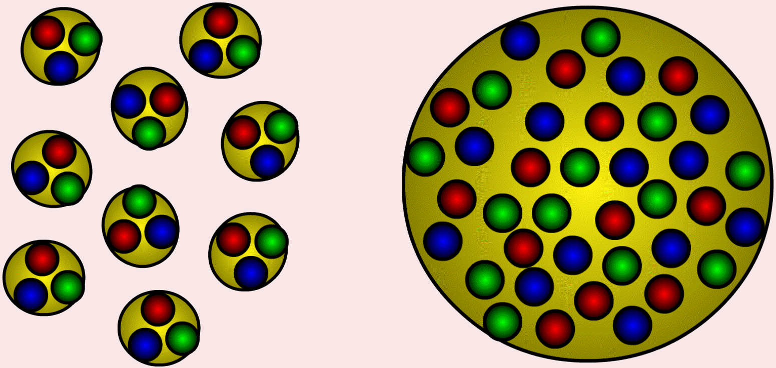
$\wedge_{QCD}$ is the QCD scale parameter.



- D. J. Gross and F. Wilczek, Phys. Rev. Lett. 30 (1973) 1343.
- D. J. Gross and F. Wilczek, Phys. Rev. D8 (1973) 3633.
- H. D. Politzer, Phys. Rep. 14 (1974) 129.

QCD Phase Diagram

In a QCD system at extremely high temperature or very high pressure the nuclear matter is expected to undergo a phase transition to a state called Quark-Gluon Plasma (QGP), identified as the deconfined dense state of matter.



Dual QCD with Magnetic Symmetry

Based on the first principles of QCD a gauge invariant approach has been provided in order to provide a clear picture of QCD vacuum

- The mathematical foundation for the dual gauge theory comes from the observation that the non-Abelian gauge symmetry allow an extra internal symmetry called magnetic symmetry which restricts and reduces the dynamical degrees of the theory .

$$D_\mu \hat{m} = 0, \ i.e. \ (\partial_\mu + g\mathbf{W}_\mu \times) \hat{m} = 0. \tag{3}$$

- The most general gauge potential which satisfies the above constraint is written as,

$$\mathbf{W}_\mu = A_\mu \hat{m} - g^{-1} (\hat{m} \times \partial_\mu \hat{m}), \tag{4}$$

where, A_μ is the Abelian component of $\mathbf{W}_\mu$ along $\hat{m}$ and is unrestricted by the constraint.

- The associated generalized field strength may then be written as,

$$\mathbf{G}_{\mu\nu} = (F_{\mu\nu} + B^{(d)}_{\mu\nu}) \hat{m}, \tag{5}$$

where

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu,$$

$$B^{(d)}_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu = g^{-1} (\hat{m} \times \partial_\mu \hat{m}), \tag{6}$$

- The topological structure may be brought into dynamics in a dual symmetric way by imposing magnetic symmetry and the multiplet $\hat{m}$ may be viewed to define the mapping, $S^2_R \to SU(2)/U(1)$, where S^2_R is the two-dimensional sphere of three dimensional space and S^2 is the group coset space fixed by $\hat{m}$.

- Rotating the magnetic vector $\hat{m}$ to a fix time independent direction by a gauge transformation leads to the value of gauge potential as,

$$\mathbf{W}_\mu \xrightarrow{U} g^{-1}\partial_\mu \beta cos\alpha \hat{\xi}_3, \tag{7}$$

and the associated field strength takes the form as

$$\mathbf{G}_{\mu\nu} \xrightarrow{U} (\, F_{\mu\nu} + B^{(d)}_{\mu\nu}\,)\, \hat{\xi}_3. \tag{8}$$

- The dual QCD Lagrangian associated with the monopoles is expressed in the following form,

$$\mathcal{L} = -\frac{1}{4}F^2_{\mu\nu} - \frac{1}{4}B^2_{\mu\nu} - \frac{1}{2}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}_r\gamma^\mu[i\partial_\mu + \frac{1}{2}g(A^{(d)}_\mu + B_\mu)]\psi_r + \bar{\psi}_b\gamma^\mu[i\partial_\mu + \frac{1}{2}g(A^{(d)}_\mu + B_\mu)]\psi_b + |(\partial_\mu + i\frac{4\pi}{g}(A_\mu + B^{(d)}_\mu))\phi|^2 - m_0(\bar{\psi}_r\psi_r + \bar{\psi}_b\psi_b) - V. \tag{9}$$

- The confinement mechanism of the QCD vacuum can be understood in absence of color electric sources (quarks) and the Lagrangian may be reduced in the following form,

$$\mathcal{L}_d^{(m)} = -\frac{1}{4}B_{\mu\nu}^2 + |(\partial_\mu + i\frac{4\pi}{g}B_\mu^{(d)})\phi|^2 - V(\phi\phi^*), \quad (10)$$

$$V(\phi\phi^*) = 3\lambda\alpha_s^{-2}(\phi^*\phi - \phi_0^2)^2.$$

- Using the cylinderically symmetric form of the potentials,

$$\frac{d}{d\rho}\left[\frac{1}{\rho}\frac{d}{d\rho}\left(\rho B(\rho)\right)\right] - \frac{8\pi}{g}\left(\frac{n}{\rho} + (4\pi\alpha_s^{-1})^{1/2}B(\rho)\right)\chi^2(\rho) = 0,$$

$$\frac{1}{\rho}\frac{d}{d\rho}\left(\rho\frac{d\chi(\rho)}{d\rho}\right) - \left[\left(\frac{n}{\rho} + (4\pi\alpha_s^{-1})^{1/2}B(\rho)\right)^2 + \frac{96\pi^2}{g^4}\lambda\left(\chi^2 - \phi_0^2\right)\right]\chi(\rho) = 0. \quad (11)$$

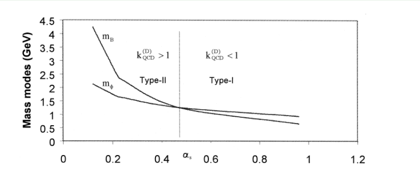
- Utilizing the asymptotic solutions $B(\rho) = -\frac{ng}{4\pi\rho}[1 + F(\rho)]$, the energy per unit length of the resulting flux tube configuration may be derived in the following form,,

$$k = 2\pi \int_0^\infty \rho d\rho \left[\frac{n^2 g^2}{32\pi^2 \rho^2} \left(\frac{dF}{d\rho} \right)^2 + \frac{n^2}{\rho^2} F^2(\rho)\chi^2(\rho) + \left(\frac{d\chi}{d\rho} \right)^2 + 3\lambda\alpha_s^{-2}(\chi^2 - \phi_0^2)^2 \right] \quad (12)$$

where $F(\rho) \stackrel{\rho\to\infty}{\longrightarrow} C\sqrt{\rho} exp\left(-m_B \rho \right)$.

- The numerical results of the vector and scalar glueball masses obtained using the numerical computation are shown in table 1.

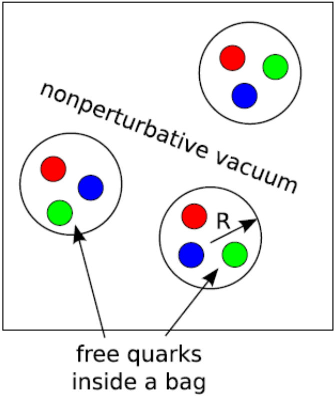
α_s	γ	$\phi_0(GeV)$	$m_B(GeV)$	$m_\phi(GeV)$	$\kappa^{(d)}_{QCD}$
0.12	8.30	0.143	2.11	4.20	2
0.22	6.99	0.156	1.66	2.44	1.5
0.47	5.99	0.170	1.25	1.25	1
0.96	5.05	0.183	0.93	0.65	.7



Equation of state for Quark Gluon Plasma using Dual QCD Bag

- The ground state hadron are spherically symmetric and quarks are confined to a sphere of finite size.
- A model of hadronic bag was identified describing the typical phase structure of QCD.
- The hadron energy in its confined phase is expressed as,

$$E_h = BV + \frac{C}{R_h}. \qquad (13)$$



- **A. Chodos, R.L. Jaffe, K. Johnson, C.B. Thorn, V.F. Weisskopf, Phys. Rev. D 9 (1974) 3471.**

Equation of state for Quark Gluon Plasma using Hadronic Bag

- The dominant part of the energy associated with the confinement regime is identified as temperature dependent bag energy expressed as,

$$B^{1/4} = \left(\frac{12}{\pi}\right)^{1/4} \frac{m_B}{8}. \tag{14}$$

where m_B is the thermal vector glueball mass.

- Inside the bag, positive contribution to energy +B and negative contribution to pressure -B inside the bag.
- Outside, the bag, negative contribution to energy -B and positive contribution to pressure +B outside the bag.

Basic thermodynamic relations.

- Using the grand canonical ensemble formalism partition function for a thermodynamical system in thermal and chemical equilibrium is expressed as,

$$Z(T,V,\mu) = Tre^{-(\hat{H}-\mu\hat{N})/T} = e^{-\Omega(T,V,\mu)/T}.$$

- In presence of non-zero magnetic field the thermodynamical potential is related to the grand canonical partition functions as,

$$\Omega(T,V,\mu) = -TlnZ(T,V,\mu) = F = \epsilon - Ts - eBM.$$

- The thermodynamical variables are related with the grand canonical partition function and expressed as,

$$P = \frac{\partial}{\partial V}(TlnZ), \epsilon = \frac{T^2}{V}\frac{\partial}{\partial T}lnZ + \mu n, s = \frac{1}{V}\frac{\partial}{\partial T}(TlnZ).$$

The grand canonical partition function for the hadron and plasma phase.

$$(TlnZ)_\pi = \frac{V}{30}\pi^2 T^4.$$

$$(TlnZ)_p = V(\frac{2}{9}\pi^2 T^4 + \frac{2}{3}\mu^2 T^2 + \frac{1}{3\pi^2}\mu^4).$$

The pressure, energy density and entropy density for hadron and plasma phase is given as,

$$P_\pi = 3 \times \frac{\pi^2}{90} T^4, \qquad P_p = \frac{2}{9}\pi^2 T^4 + \frac{2}{3} T^2 \mu_q^2 + \frac{\mu_q^4}{3\pi^2} - B.$$

$$\epsilon_\pi = 3 \times \frac{\pi^2}{30} T^4, \qquad \epsilon_p = \frac{2}{3}\pi^2 T^4 + 2T^2 \mu_q^2 + \frac{\mu_q^4}{\pi^2} + B.$$

$$s_\pi = 2 \times \frac{\pi^2}{15} T^4, \qquad s_p = \frac{8}{9}\pi^2 T^3 + \frac{8}{3} T \mu_q^2 + \frac{4}{3}\frac{\mu_q^4}{\pi^2 T}.$$

Dynamics of phase transition is studied by applying Gibbs Criteria given as,

$$P_h = P_p = P_c; \;\; T_h = T_p = T_c; \;\; \mu = 3\mu_q = \mu_c.$$

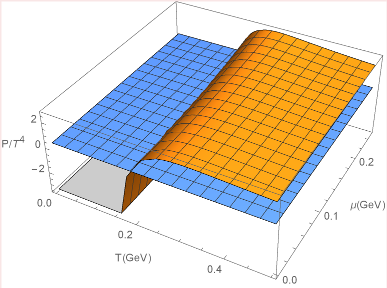
c represent the critical point of QGP-phase transition. The critical temperature of QGP-phase transition is given by,

$$T_c^{QGP} = \frac{90}{17\pi^2}^{1/4} B^{1/4} \approx 0.856 B^{1/4}.$$

Study of strongly interacting Quark-Gluon Plasma

Variation of pressure for hadron and QGP phase.

- The critical temperature of $0.187 GeV$ at $\alpha_s = 0.12$ coupling.
- The critical temperature of $0.140 GeV$ at $\alpha_s = 0.22$ coupling.
- The critical temperature of $0.116 GeV$ at $\alpha_s = 0.47$ coupling.
- The critical temperature of $0.090 GeV$ at $\alpha_s = 0.96$ coupling.



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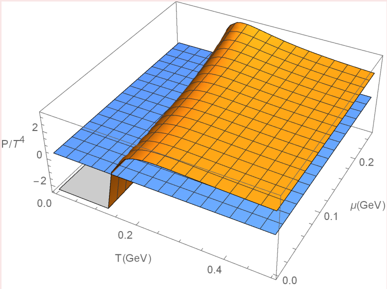

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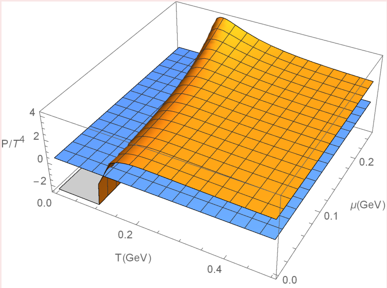

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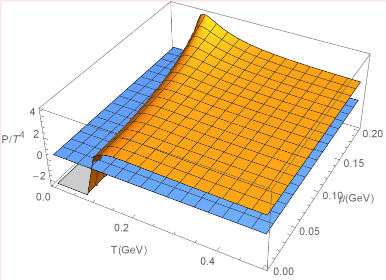

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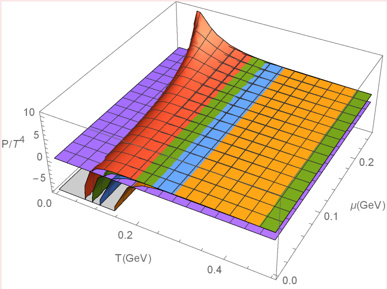

Study of strongly interacting Quark-Gluon Plasma

Variation of energy density for hadron and QGP phase.

- The normalized value of $\Delta\epsilon$ at T_c is found to be $1.19 GeV/fm^3$ at $\alpha_s = 0.12$ coupling.
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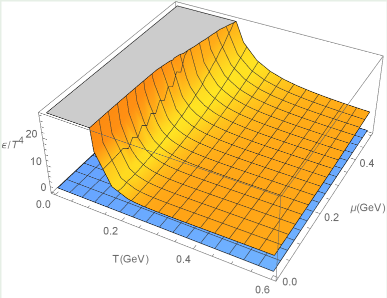
$$\Delta\epsilon = \epsilon_p(T_c) - \epsilon_\pi(T_c)$$



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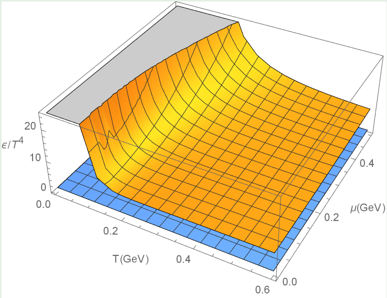

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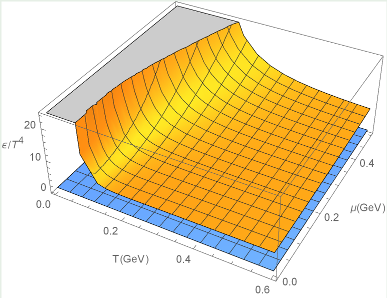

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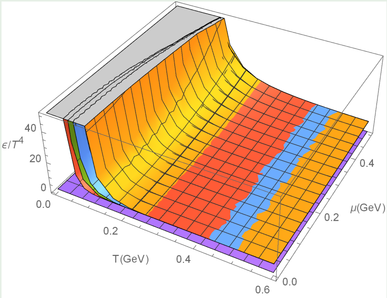

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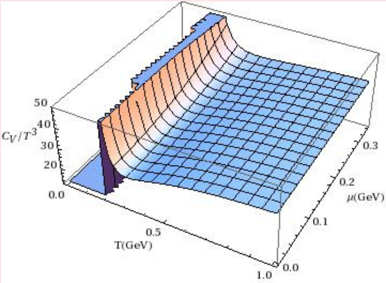
Variation of specific heat for QGP.

- The variation of normalized specific heat for QGP in the infrared sector of QCD for α_s= 0.12, 0.22, 0.47 and 0.96 respectively.



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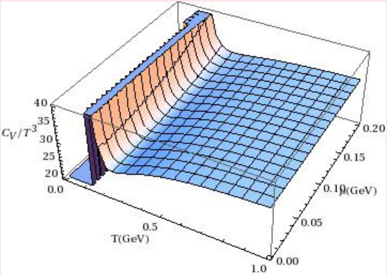

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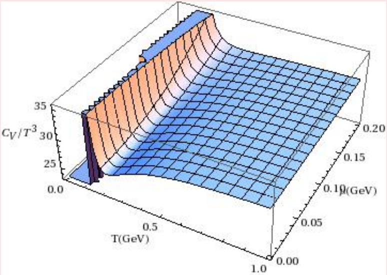

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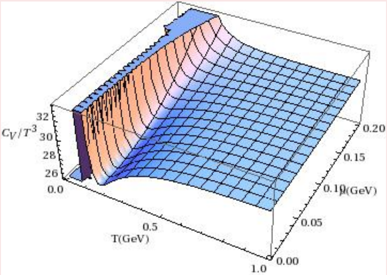

Study of strongly interacting Quark-Gluon Plasma

Variation of speed of sound for QGP phase

- In QGP phase at the critical temperature the speed of sound drops to its minimum and with the increase in temperature its approaches to the value $c_s^2 = 0.33$.
- $\alpha_s = 0.12$
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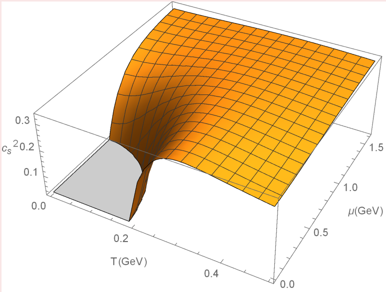
$$c_s^2 = \frac{dP_p}{d\epsilon_p}$$



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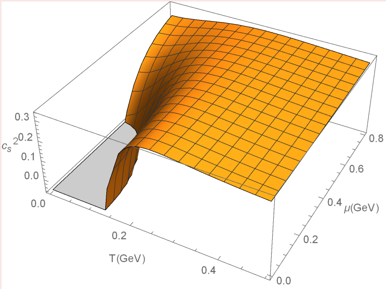

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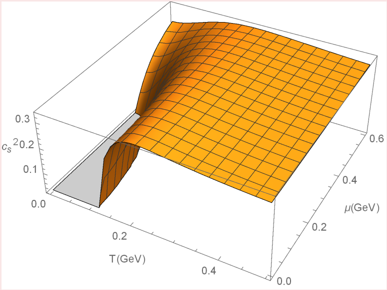

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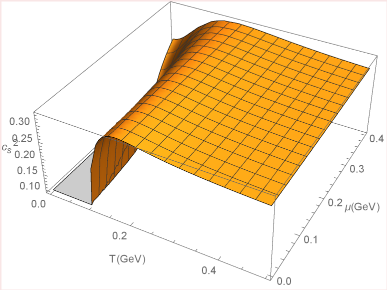
- $\alpha_s = 0.12$
- $\alpha_s = 0.22$
- $\alpha_s = 0.47$
- $\alpha_s = 0.96$

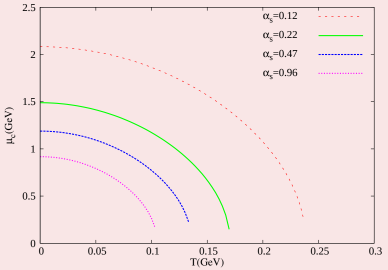
$$c_s^2 = \frac{dP_p}{d\epsilon_p}$$



Study of strongly interacting Quark-Gluon Plasma

Variation of chemical potential with temperature

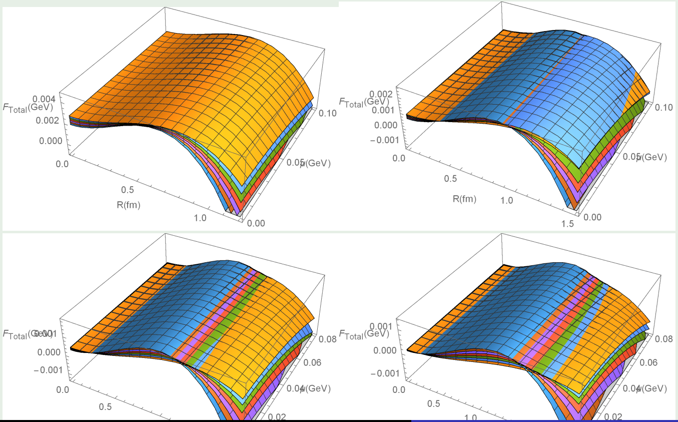
- The first-order phase transition line ends at a QCD critical end point (CEP) beyond which a transitional crossover region exists and for $\alpha_s = 0.12$ and $\alpha_s = 0.22$ the coordinates of such CEP are $(T_E, \mu_E) = (0.184,$ $0.311)$ GeV and $(0.138,$ $0.215)$GeV respectively.



Study of strongly interacting Quark-Gluon Plasma

Free energy change for quark-hadron phase transition

$$\Delta F(R) = -\Delta P \frac{4\pi R^3}{3} + \sigma 4\pi R^2,$$



Study of strongly interacting Quark-Gluon Plasma

α_s	$T_c(GeV)$	$R_c(fm)$	$F_{Total}(GeV)$	$\sigma^{1/3}(GeV)$
0.12	0.172	0.7052	0.004565	0.04223
	0.177	0.7246	0.004637	0.04283
	0.182	0.7450	0.004709	0.04341
	0.187	0.7052	0.004781	0.04397
	0.192	0.6868	0.004493	0.04451
	0.197	0.6694	0.004422	0.04505
	0.202	0.6528	0.004353	0.04556
0.22	0.125	1.0549	0.002426	0.02722
	0.130	1.0143	0.002442	0.02801
	0.135	0.9768	0.002457	0.02878
	0.140	0.9419	0.002472	0.02955
	0.145	0.9094	0.002487	0.03031
	0.150	0.8791	0.002503	0.03107
	0.155	0.8508	0.002518	0.03182

Study of strongly interacting Quark-Gluon Plasma

α_s	$T_c(GeV)$	$R_c(fm)$	$F_{Total}(GeV)$	$\sigma^{1/3}(GeV)$
0.47	0.101	1.3056	0.001643	0.02074
	0.106	1.2441	0.001684	0.02160
	0.111	1.1880	0.001724	0.02245
	0.116	1.1368	0.001764	0.02329
	0.121	1.0898	0.001803	0.02413
	0.126	1.0466	0.001843	0.02498
	0.131	1.0066	0.001882	0.02582
0.96	0.075	1.7582	0.001076	0.01477
	0.080	1.6483	0.001128	0.01567
	0.085	1.5514	0.001181	0.01656
	0.090	1.4652	0.001233	0.01746
	0.095	1.3881	0.001286	0.01835
	0.100	1.3186	0.001338	0.01924
	0.105	1.2559	0.001390	0.02013

Study of strongly interacting Quark-Gluon Plasma

Variation of trace anomaly and conformal measure for QGP

$$\Delta(T) = \frac{\epsilon_p - 3P_p}{T^4} = \frac{4B(T)}{T^4}$$

$$\mathcal{C} = \frac{\epsilon_p - 3P_p}{\epsilon_p} = \frac{4B(T)}{\epsilon_p}$$

- $\alpha_s = 0.12$
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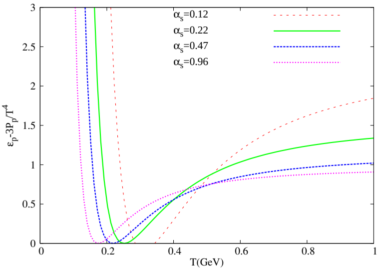

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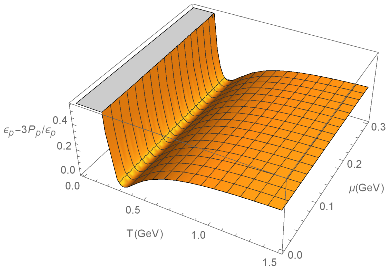

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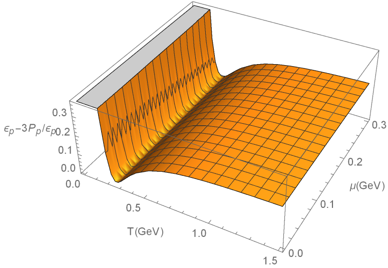

Study of strongly interacting Quark-Gluon Plasma

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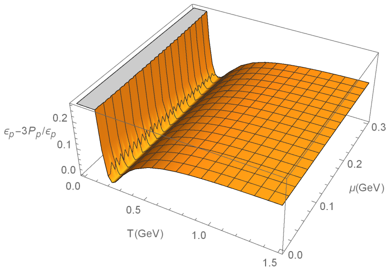

Study of strongly interacting Quark-Gluon Plasma

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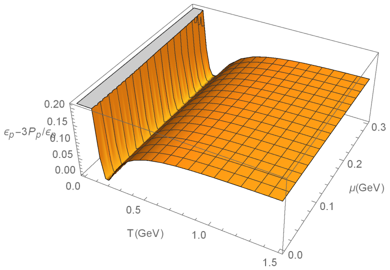

Conclusion

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- Based on the topological structure of non-abelian gauge theories, a dual QCD gauge formulation has been developed in terms of magnetic symmetry, which manifest the topological structure of the symmetry group in a non-trivial way.
- The dynamical breaking of the magnetic symmetry has been shown to impart the dual superconducting properties to the magnetically condensed QCD vacuum which ultimately leads to a unique flux tube configuration in QCD vacuum responsible for enforcing the color confinement.
- Utilizing the dual QCD model in terms of the magnetic symmetry structure of non-Abelian gauge theories, the dual QCD hadronic bag has been constructed which mainly satisfy the main qualitative feature observed for a strongly interacting QGP.

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THANK YOU