A model approach to thermodynamics of Strong Interactions

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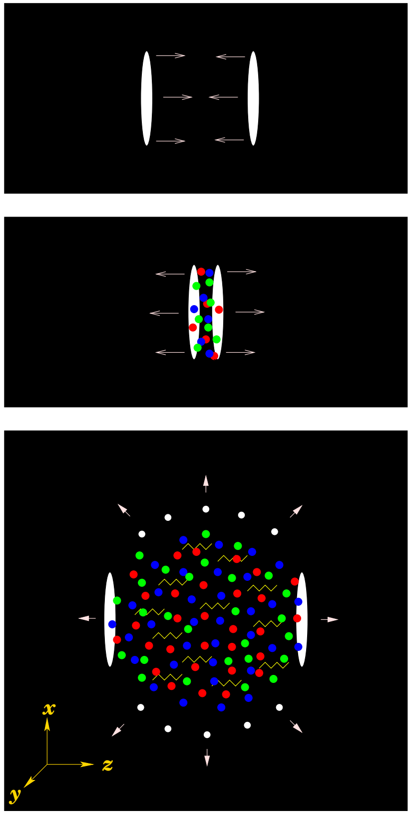
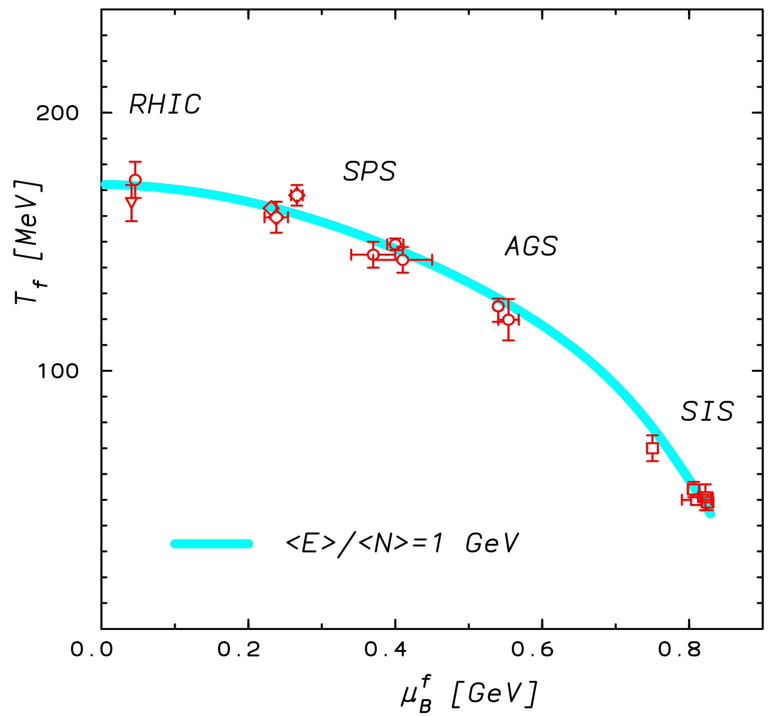
Thermalization in HIC





Thermal model:

$$Z(T,\mu_B,\mu_I,\mu_S) = \sum_i Z_i(T,\mu_B,\mu_I,\mu_S) \;\Rightarrow n_i(T,\mu_B,\mu_I,\mu_S)$$

J. Cleymans and K. Redlich: Phys. Rev. Lett 81 (1998) 5284

P. Braun-Munzinger, K. Redlich and J. Stachel:

Quark Gluon Plasma 3, R.C. Hwa and X.-N. Wang, ed., (World Scientific) (nucl-th/0304013)

QCD

$$\mathcal{L}^E_{QCD} \quad = \quad \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \sum_{f=1}^{N_f} \bar{q}_f \left(\gamma^E_\mu D_\mu + m_f - \mu_f \gamma_0 \right) q_f$$

where,

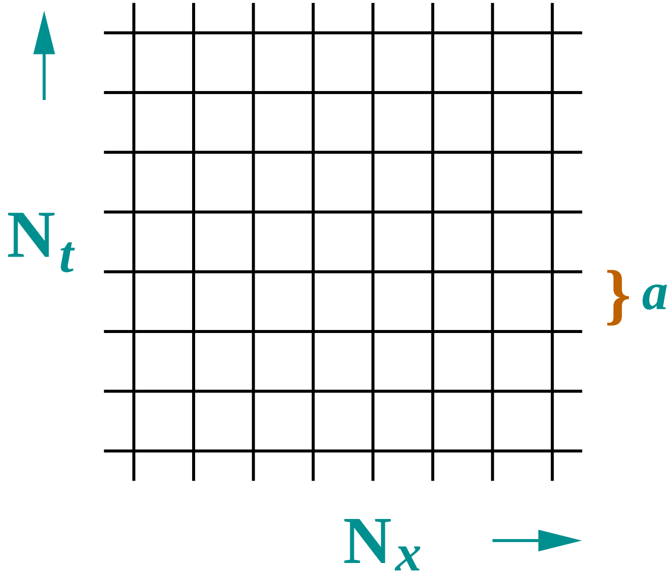
$$F^a_{\mu\nu} \quad = \quad \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g f^{abc} G^b_\mu G^c_\nu$$

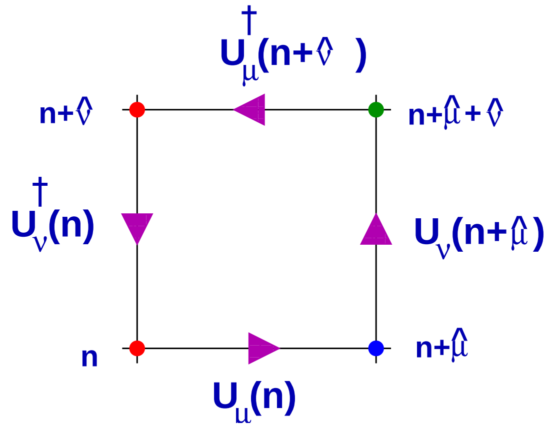
$$D_\mu \quad = \quad \partial_\mu - i g T^a G^a_\mu \qquad\qquad a = 1, 2, ...8.$$

T^a are SU(3) group generators and f^{abc} are SU(3) structure constants
The QCD partition function is,

$$Z = \int DG^a_\nu Dq_f D\bar{q}_f \, \mathrm{e}^{-\int_0^\beta d\tau \int_{-\infty}^{\infty} d^3x \mathcal{L}^E_{QCD}}$$

Non-perturbative QCD





- Quarks sit on the lattice points $q(\mathrm{n})$
- Gluons are on the links $U_\mu(\mathrm{n}) = \mathcal{P}\exp\left[ig\int_{\mathrm{n}}^{\mathrm{n}+\hat{\mu}a} \mathrm{d}y^\sigma\, G^a_\sigma(y)\, T^a\right]$
- $V = a^3(\mathrm{N}_x \times \mathrm{N}_y \times \mathrm{N}_z)$ $\qquad \beta = a\mathrm{N}_t$
- momentum cutoff $\simeq \frac{1}{a}$ $\qquad a \to 0 \Rightarrow$ Continuum physics

Polyakov Nambu Jona-Lasinio Model :

Ratti et.al. PRD 73 014019 '06.

$$\mathcal{L}_{PNJL} = \bar{q}\left(i\gamma^{\mu}D_{\mu} - m_0 + \mu\gamma^0\right)q + \frac{\mathcal{G}}{2}\left[(\bar{q}q)^2 + \left(\bar{q}i\gamma^5\vec{\tau}q\right)^2\right] - \mathcal{U}\left(\bar{\Phi}, \Phi, T\right)$$

where $D_{\mu} = \partial_{\mu} - igG_{\mu}$, and $G_{\mu} = \delta_{\mu 0}G_0$

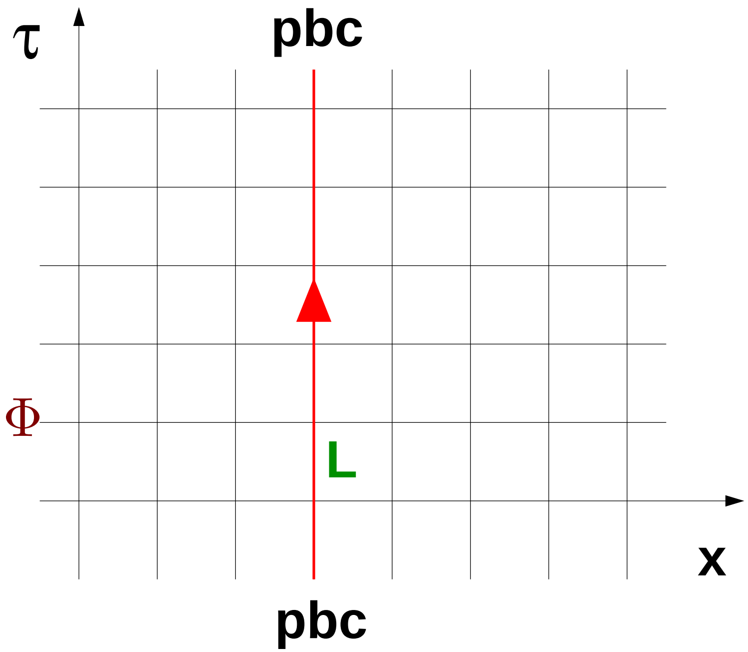
$$\frac{\mathcal{U}\left(\Phi, \bar{\Phi}, T\right)}{T^4} = -\frac{b_2\left(T\right)}{2}\bar{\Phi}\Phi - \frac{b_3}{6}\left(\Phi^3 + \bar{\Phi}^3\right) + \frac{b_4}{4}\left(\bar{\Phi}\Phi\right)^2$$

(De)Confinement at $T \neq 0$

- Finite Temperature
  $\beta = 1/T$
- Free energy of vacuum
  $F_0 = -T \log Z$
- Free energy of a single quark
  $F_q - F_0 = -T \log \langle \mathrm{TrL}(\vec{x})/3 \rangle = -T \log \Phi$

  $\mathrm{L}(\vec{x}) = \mathcal{P}\exp\left[- \int_0^{1/T} \mathrm{d}\tau G_0(\vec{x}, \tau)\right]$

  Wilson Line/Polyakov Loop

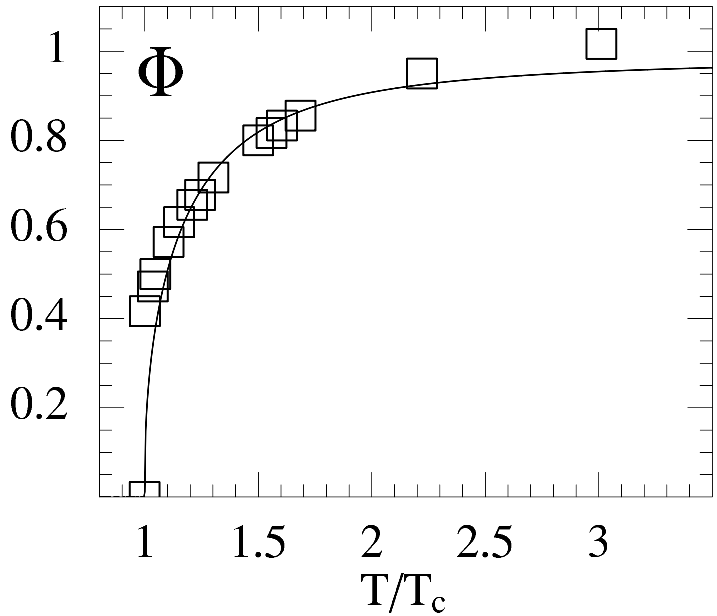


- $\Phi(\vec{x}, \tau) = \begin{cases} \neq 0 \Rightarrow F_q \text{ finite} \Rightarrow \text{deconfined} \\ = 0 \Rightarrow F_q \text{ infinite} \Rightarrow \text{confined} \end{cases}$
- Use Φ as OP for finite temperature phase transition.

Global Z(3) symmetry

- The gluons G_μ are bosons and satisfy periodic boundary conditions in the Eucledian time and keep the QCD action invariant
$\Rightarrow G_\mu(\vec{x}, \tau = 0) = G_\mu(\vec{x}, \tau = 1/T)$
- The QCD action is however invariant under a somewhat more general condition
$\Rightarrow G_\mu(\vec{x}, \tau = 0) = z\, G_\mu(\vec{x}, \tau = 1/T)$
with $z \,\epsilon\, Z(3) = exp(i2\pi n/3),\ n = 0, 1, 2$, the center group of SU(3).
- But the Polyakov loop $\Phi(\vec{x}, \tau)$ in not invariant
$\Rightarrow$ There seems to be a connection between deconfinement and spontaneous $Z(3)$ symmetry breaking !!!

Polyakov Loop Model : (De)Confinement



- Choose some $V(\Phi)$ as a polynomial, parametrized using Lattice:

  Lattice EOS: Scavenius et.al. PRC 66 034903 '02.

$$\frac{U\left(\bar{\Phi},\Phi,T\right)}{T^4} = -\frac{b_2\left(T\right)}{2}\bar{\Phi}\Phi - \frac{b_3}{6}\left(\Phi^3+\bar{\Phi}^3\right) + \frac{b_4}{4}\left(\bar{\Phi}\Phi\right)^2$$

where, $\Phi = \langle \mathrm{TrL} \rangle$; $\bar{\Phi} = \langle \mathrm{TrL}^\dagger \rangle$

Global Chiral Symmetry

$$\mathcal{L}_{QCD} = -\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu}_a + \sum_{f=u,d}\left[i\,\bar{q}_f\gamma^\mu D_\mu q_f - m_f\bar{q}_f q_f\right]$$

Symmetries: $SU(3)_c \otimes \underbrace{SU(2)_V \otimes SU(2)_A \otimes U(1)_B \otimes U(1)_A}_{Fermionic}$

- $U(1)_A$ broken by quantum anomalies.
- $SU(2)_V$ broken explicitly when flavour degeneracy is lifted
  e.g. proton and neutron mass splitting.
- $SU(2)_A$ broken explicitly for non-zero quark mass ....
  where are the chiral partners !!
  - $SU(2)_A$ broken spontaneously; pions are the Goldstone Bosons
    $\rightarrow$ Measure is the chiral condensate $\langle\bar{q}q\rangle$.

$$\langle\bar{q}q\rangle = \begin{cases} \neq 0 \Rightarrow \text{symmetry broken} \\ = 0 \Rightarrow \text{symmetry restored} \end{cases}$$

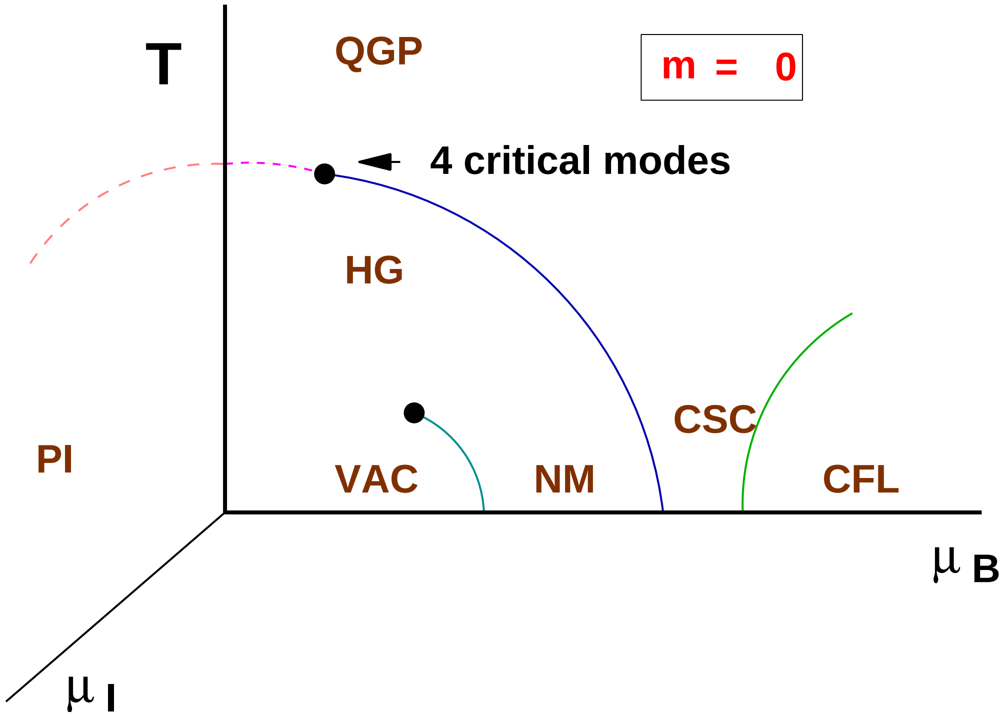
Nambu Jona-Lasinio Model : Chiral aspect

Lagrangian: (1961)

$$\mathcal{L}_{NJL} = \bar{q}\left(i\gamma^\mu\partial_\mu - m_0 + \mu\gamma^0\right)q + \frac{\mathcal{G}}{2}\left[(\bar{q}q)^2 + \left(\bar{q}i\gamma^5\vec{\tau}q\right)^2\right]$$

- Symmetries: $SU(2)_V \otimes SU(2)_A \otimes U(1)_B$.
- Introducing auxillary field variables σ and $\vec{\pi}$ an $\mathcal{L}_{eff}$ is obtained.
- The mean fields $\langle\sigma\rangle = \mathcal{G}\langle\bar{q}q\rangle$ and $\langle\vec{\pi}\rangle = 0$ for $\mu_I < m_\pi$.
- Fit emperical values of m_π, f_π and $g_{\pi NN}$ (RMP 64 649 '92).
  Obtain $m_0 = 5.5\,\mathrm{MeV}$, $\mathcal{G} = 10.08\,\mathrm{GeV}^{-2}$, cutoff $\Lambda = 0.651\,\mathrm{GeV}$.
- Thermodynamic properties studied with the thermodynamic potential $\Omega[\sigma, T, \mu_q, \mu_I]$,
  where $\mu_q = \frac{\mu_u+\mu_d}{2}$; $\mu_I = \frac{\mu_u-\mu_d}{2}$

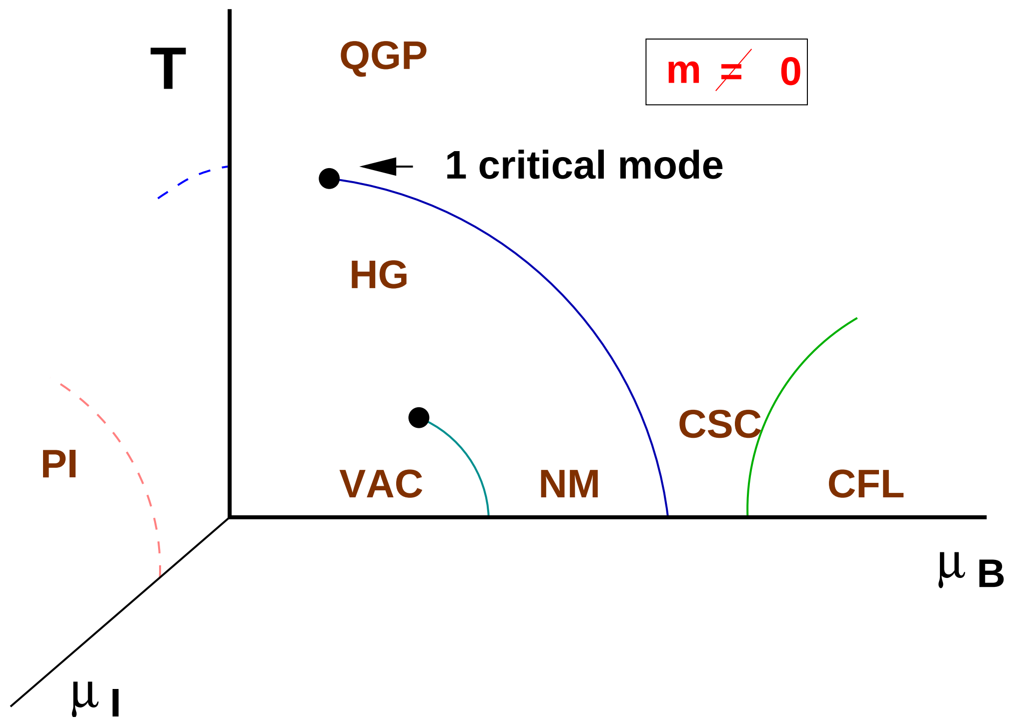
Phase Diagram



$$\mu_B = \frac{1}{3}\left(\frac{\mu_u + \mu_d}{2}\right) \qquad ; \qquad \mu_I = \left(\frac{\mu_u - \mu_d}{2}\right)$$

Rajagopal, Wilczek : The Condensed Matter Physics of QCD
Ch. 35, 'Handbook of QCD', M. Shifman, ed., (World Scientific) (hep-ph/0011333).

Phase Diagram



$$\mu_B = \frac{1}{3}\left(\frac{\mu_u + \mu_d}{2}\right) \qquad ; \qquad \mu_I = \left(\frac{\mu_u - \mu_d}{2}\right)$$

Rajagopal, Wilczek : The Condensed Matter Physics of QCD
Ch. 35, 'Handbook of QCD', M. Shifman, ed., (World Scientific) (hep-ph/0011333).

PNJL Model : Confinement + Chiral aspects

Lagrangian: Ratti et.al. PRD 73 014019 '06.

$$\mathcal{L}_{PNJL} = \bar{q}\left(i\gamma^\mu D_\mu - m_0 + \mu\gamma^0\right) q + \frac{\mathcal{G}}{2}\left[(\bar{q}q)^2 + \left(\bar{q}i\gamma^5\vec{\tau}q\right)^2\right] - U(\bar{\Phi}, \Phi)$$

where $D_\mu = \partial_\mu - igG_\mu$,
and $G_\mu = \delta_{\mu 0} G_0$

- Introducing auxillary field variables σ and $\vec{\pi}$ an $\mathcal{L}_{eff}$ is obtained, with the replacement $\exp\left[-G_0/T\right] \to \Phi$
- The mean fields $\langle\sigma\rangle = \mathcal{G}\langle\bar{q}q\rangle$ and $\langle\vec{\pi}\rangle = 0$ for $\mu_I < m_\pi$.
- Thermodynamic properties studied with $\Phi(T)$ and σ from the thermodynamic potential $\Omega[\bar{\Phi}, \Phi, \sigma, T, \mu_q, \mu_I]$, where $\mu_q = \frac{\mu_u + \mu_d}{2}$; $\mu_I = \frac{\mu_u - \mu_d}{2}$

PNJL Model: 2 flavors

The thermodynamic potential: Ratti et.al. PRD 73 014019 '06.

$$\begin{aligned}
\Omega &= \mathcal{U}\left(\Phi,\bar{\Phi},T\right) + 2G_1(\sigma_u^2+\sigma_d^2) + 4G_2\sigma_u\sigma_d \\
&- \sum_{f=u,d} 2\,T \int \frac{\mathrm{d}^3p}{(2\pi)^3} \left\{ \ln\left[1+3\left(\Phi+\bar{\Phi}\mathrm{e}^{-(E_f-\mu_f)/T}\right)\mathrm{e}^{-(E_f-\mu_f)/T} + \mathrm{e}^{-3(E_f-\mu_f)/T}\right]\right. \\
&+ \left.\ln\left[1+3\left(\bar{\Phi}+\Phi\mathrm{e}^{-(E_f+\mu_f)/T}\right)\mathrm{e}^{-(E_f+\mu_f)/T} + \mathrm{e}^{-3(E_f+\mu_f)/T}\right]\right\} \\
&- \sum_{f=u,d} 6 \int \frac{\mathrm{d}^3p}{(2\pi)^3} E_f \theta\left(\Lambda^2 - \vec{p}^{\,2}\right)
\end{aligned}$$

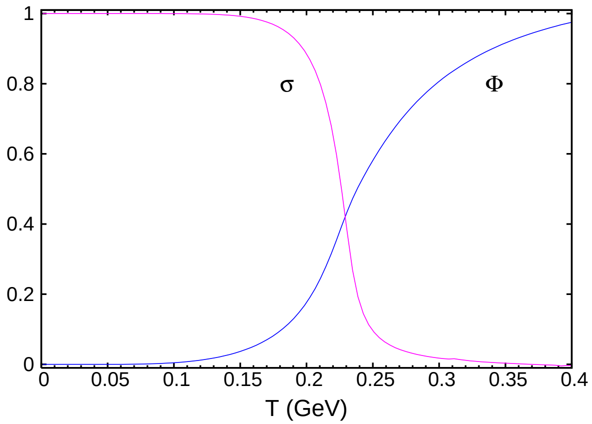
where,

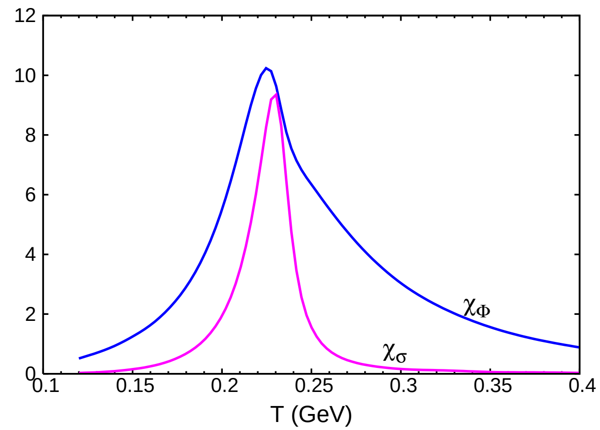
$$\frac{\mathcal{U}\left(\Phi,\bar{\Phi},T\right)}{T^4} = -\frac{b_2\left(T\right)}{2}\bar{\Phi}\Phi - \frac{b_3}{6}\left(\Phi^3+\bar{\Phi}^3\right) + \frac{b_4}{4}\left(\bar{\Phi}\Phi\right)^2$$

Models

- Introduce models incorporating the global symmetries of QCD
  - Aim is to develop physical insights
  - May be too simplified ...
    - Find out problems and keep improving

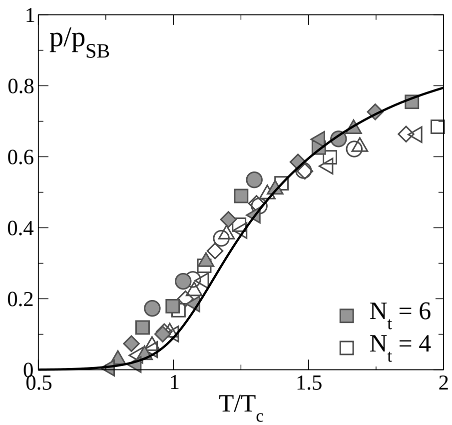
Thermodynamics

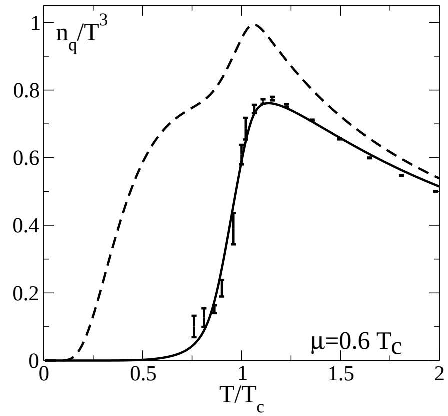




Variation of the OPs

$T_c \sim 230$ MeV (Peak separation $\sim 5\,\mathrm{MeV}$)

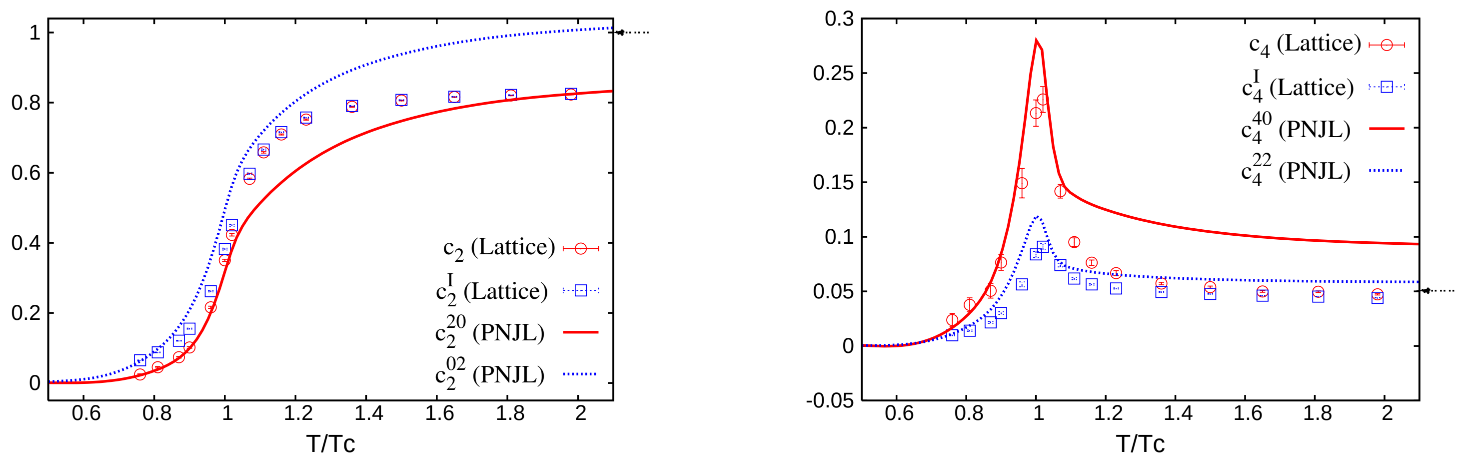




Lattice: CP-PACS PRD 64 074510 ’01.

PNJL model: Ratti et.al. PRD 73 014019 ’06.

Fluctuations



- Lattice: $c_2 \sim c_2^I \sim 80\%$ SB limit ; $c_4 \sim c_4^I \to$ SB limit
- PNJL: $c_2 \neq c_2^I$, $c_4 \neq c_4^I$

  c_2 and c_4 away from SB limit ; c_2^I and $c_4^I \to$ SB limit

Lattice: Bielefeld PRD 71 054508 '05
PNJL model: RR et.al. PRD 73 114007 '06; PRD 77 094015 '07.

PNJL + Van der Monde

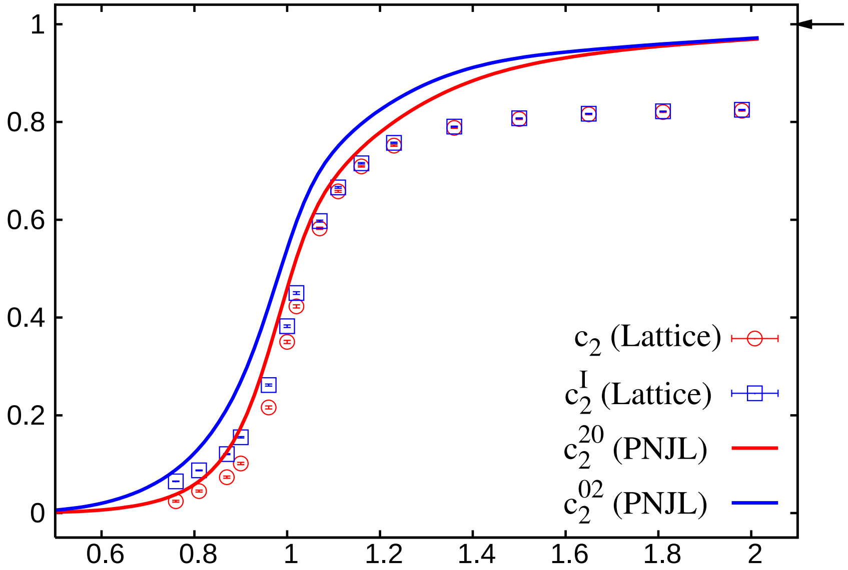
$$\begin{aligned}
\Omega &= \mathcal{U}\left(\Phi,\bar{\Phi},T\right) + 2G_1(\sigma_u^2+\sigma_d^2) + 4G_2\sigma_u\sigma_d \\
&- \sum_{f=u,d} 2\,T\int\frac{\mathrm{d}^3p}{(2\pi)^3}\left\{\ln\left[1+3\left(\Phi+\bar{\Phi}\mathrm{e}^{-(E_f-\mu_f)/T}\right)\mathrm{e}^{-(E_f-\mu_f)/T}+\mathrm{e}^{-3(E_f-\mu_f)/T}\right]\right. \\
&+ \left.\ln\left[1+3\left(\bar{\Phi}+\Phi\mathrm{e}^{-(E_f+\mu_f)/T}\right)\mathrm{e}^{-(E_f+\mu_f)/T}+\mathrm{e}^{-3(E_f+\mu_f)/T}\right]\right\} \\
&- \sum_{f=u,d} 6\int\frac{\mathrm{d}^3p}{(2\pi)^3}E_f\theta\left(\Lambda^2-\vec{p}^{\,2}\right)
\end{aligned}$$

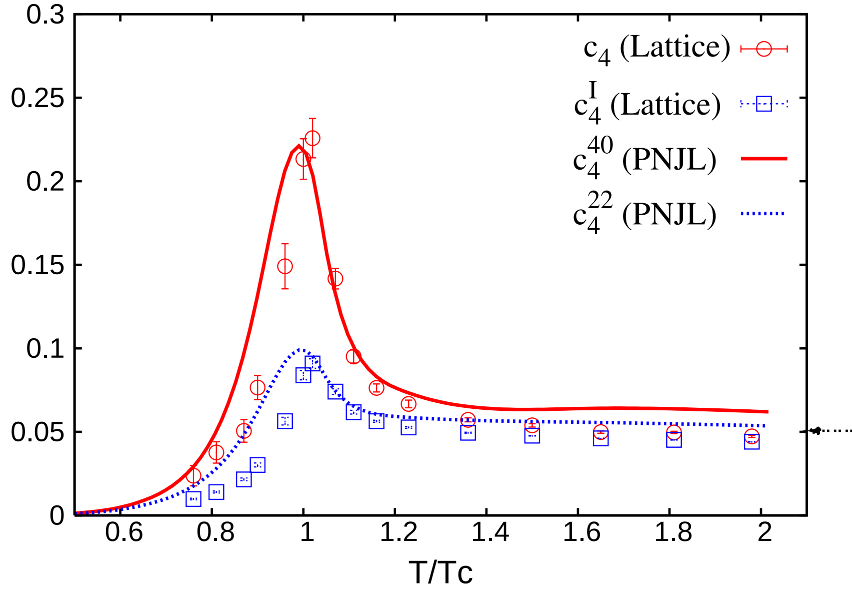
where,

$$\frac{\mathcal{U}\left(\Phi,\bar{\Phi},T\right)}{T^4} = -\frac{b_2\left(T\right)}{2}\bar{\Phi}\Phi - \frac{b_3}{6}\left(\Phi^3+\bar{\Phi}^3\right) + \frac{b_4}{4}\left(\bar{\Phi}\Phi\right)^2$$
$$+\kappa\ln[1-6\,\bar{\Phi}\Phi+4\,\left(\Phi^3+\bar{\Phi}^3\right)-3\,\left(\bar{\Phi}\Phi\right)^2]$$

PNJL model: RR et. al. PRD 77 094024 '08.

Fluctuations – 2 flavors

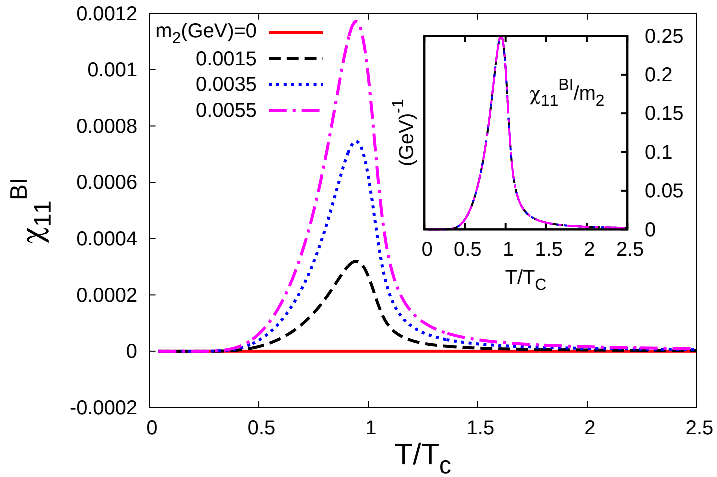




- Lattice: $c_2 \sim c_2^I \sim 80\%$ SB limit ; $c_4 \sim c_4^I \rightarrow$ SB limit
- PNJL: $c_2 \sim c_2^I \rightarrow$ SB limit ; $c_4 \sim c_4^I \rightarrow$ SB limit

Lattice: Bielefeld PRD 71 054508 '05
PNJL model: RR et. al. PRD 77 094024 '08.

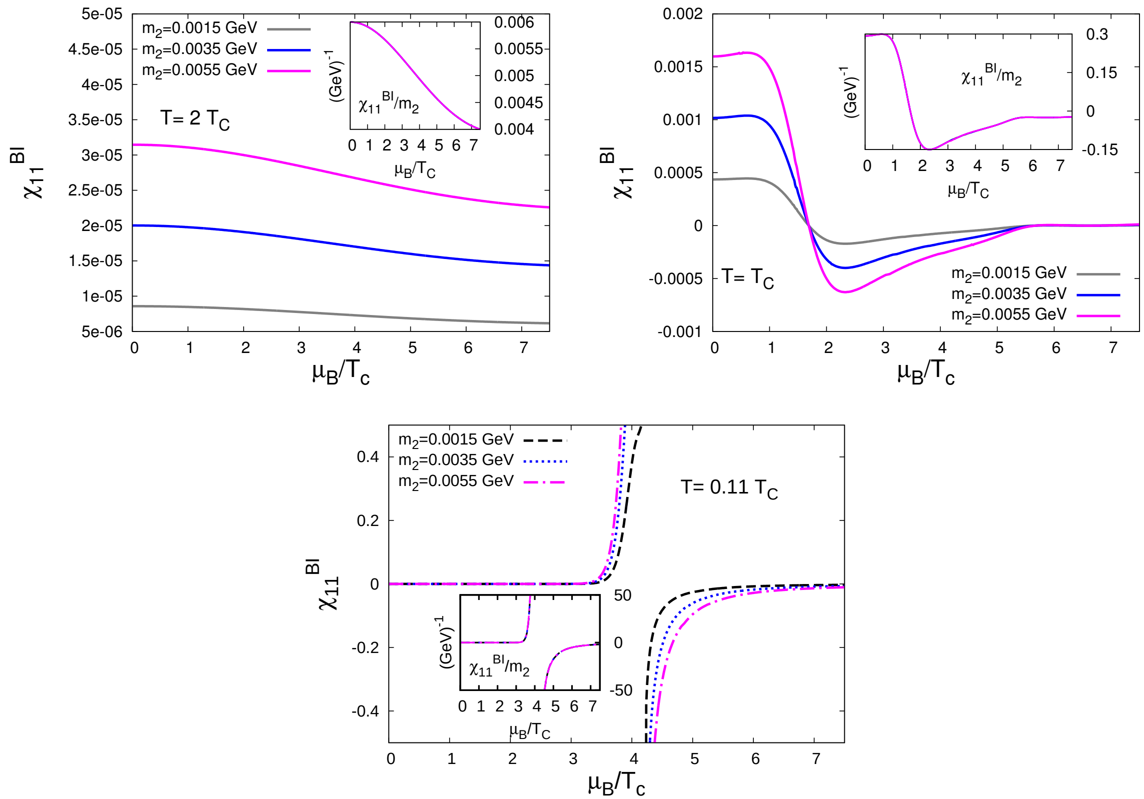
Baryon-Isospin correlation



- We consider the baryon-isospin correlator $\chi^{BI} = \frac{1}{3}(\chi^{uu} - \chi^{dd})$
- Conventional choice is baryon-charge correlator $\chi^{BQ} = \frac{1}{9}(2\chi^{uu} - \chi^{dd} + \chi^{ud})$
  - For isospin symmetric matter, $m_u = m_d$, and $\chi^{BI} = 0 \neq \chi^{BQ}$
  - Thus χ^{BI} would be an excellent signal for $m_u \neq m_d$
    $\rightarrow$ Introduce $m_1 = (m_u + m_d)/2$ and $m_2 = (m_u - m_d)/2$; $m_2 << m_1$.
- At low T, $m_2 << m_1$ and at high T, $m_2 << T$
  - Surprise!! The correlation scales with m_2 !!

PNJL model: RR et. al. PRC 89 064905 '14.

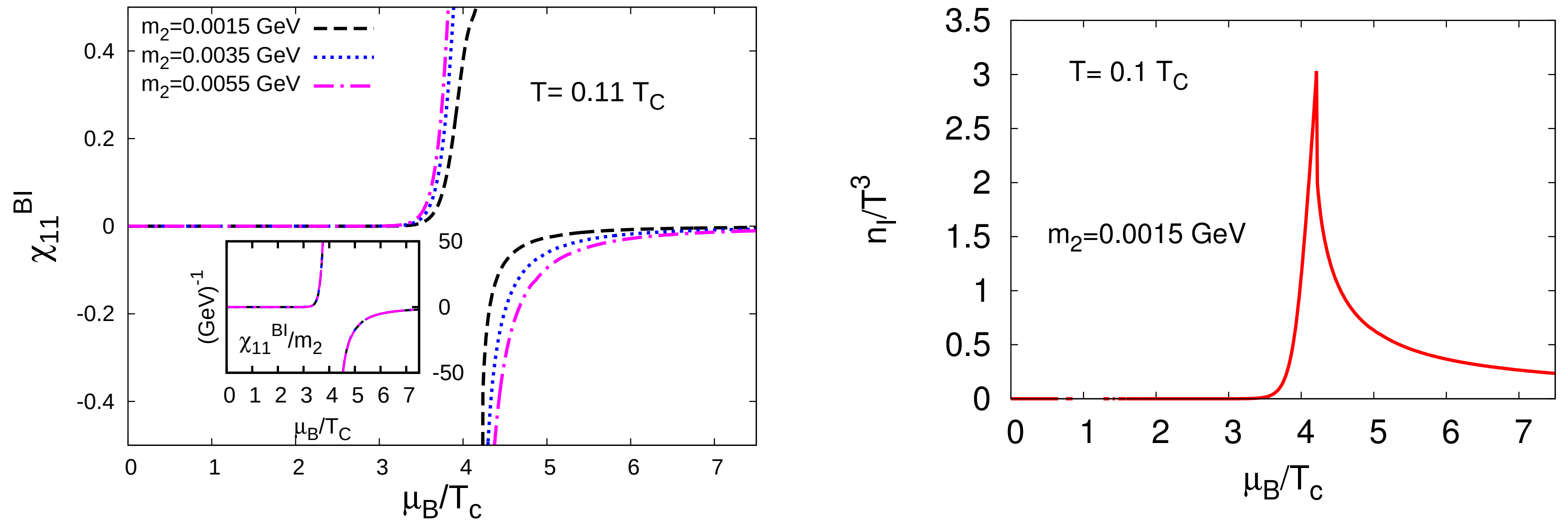
Isospin breaking $T \neq 0$, $\mu_B \neq 0$



- We find m_2 scaling is valid over the whole $T - \mu_B$ plane.
- The scaling is useful to identify m_2 from experiments
- Sign of χ_{11}^{BI} is useful for identifying a first order transition.

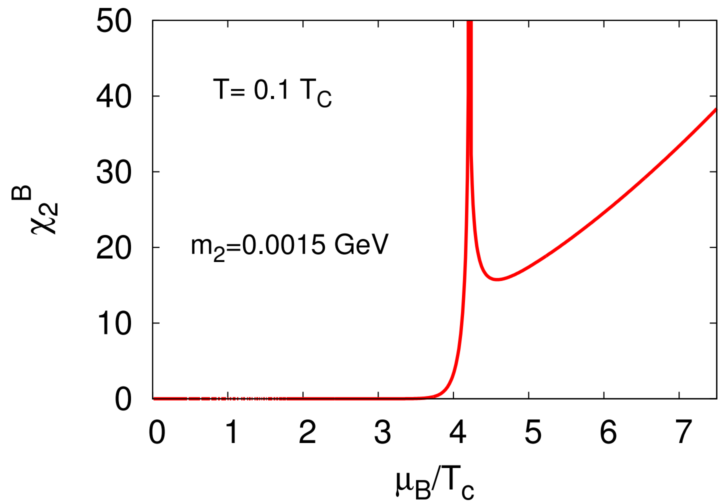
PNJL model: RR et. al. PRC 89 064905 '14.

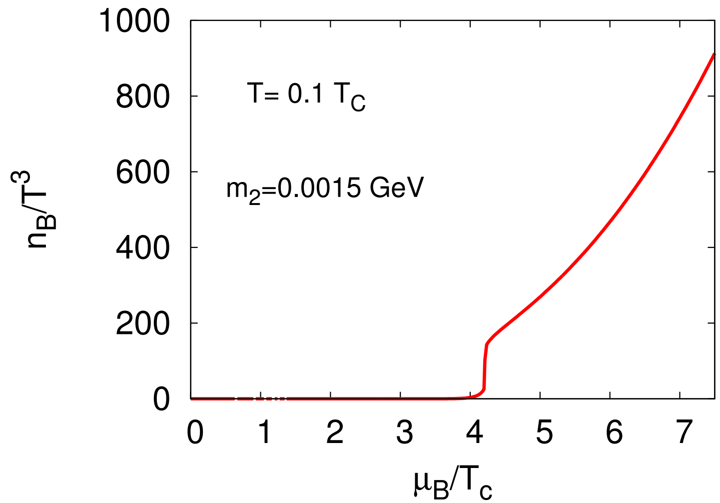
Isospin breaking $T \neq 0$, $\mu_B \neq 0$



- Large discontinuity in $\chi_{11}^{BI}(\mu_B)$ at a first order transition.
- Jump from positive to negative is understood from the relation $\chi_{11}^{BI}(\mu_B) = \partial n_I / \partial \mu_B$
- There is a non-zero isospin number even though no isospin chemical potential.
- Both the isospin number and baryon-isospin correlations seem to be good signal for the first order transition.

Baryon number and fluctuation





- Large fluctuation occurs in $\chi_{20}^B(\mu_B)$ at a first order transition.
- The baryon number shows a jump near the transition and then keeps on increasing.

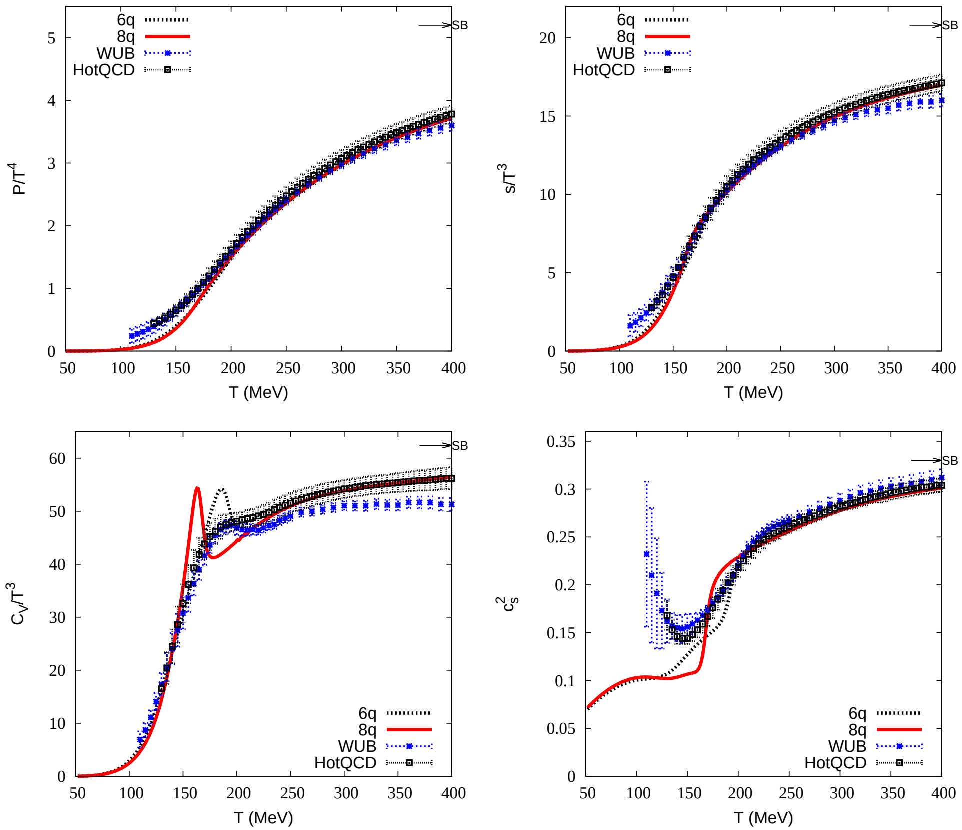
PNJL model: 2+1 flavors

The thermodynamic potential:

$$\Omega = \mathcal{U}'[\Phi, \bar{\Phi}, T] + 2g_S \sum_{f=u,d,s} \sigma_f^2 - \frac{g_D}{2} \sigma_u \sigma_d \sigma_s + 3\frac{g_1}{2} (\sum_{f=u,d,s} {\sigma_f}^2)^2$$
$$+ 3g_2 \sum_{f=u,d,s} \sigma_f^4 - 6 \sum_{f=u,d,s} \int_0^\Lambda \frac{d^3p}{(2\pi)^3} E_f \Theta(\Lambda - |\vec{p}|)$$
$$-2T \sum_{f=u,d,s} \int_0^\infty \frac{d^3p}{(2\pi)^3} \ln \left[1 + 3(\Phi + \bar{\Phi} e^{-\frac{(E_f - \mu)}{T}}) e^{-\frac{(E_f - \mu)}{T}} + e^{-3\frac{(E_f - \mu)}{T}} \right]$$
$$-2T \sum_{f=u,d,s} \int_0^\infty \frac{d^3p}{(2\pi)^3} \ln \left[1 + 3(\bar{\Phi} + \Phi e^{-\frac{(E_f + \mu)}{T}}) e^{-\frac{(E_f + \mu)}{T}} + e^{-3\frac{(E_f + \mu)}{T}} \right]$$

where, g_S is the usual four-fermi interaction, g_D is the coupling for the 't Hooft determinant and g_1 and g_2 are the 8q coupling constants needed to remove an infinite potential well close to the classical vacuum.

PNJL vs Continuum LQCD

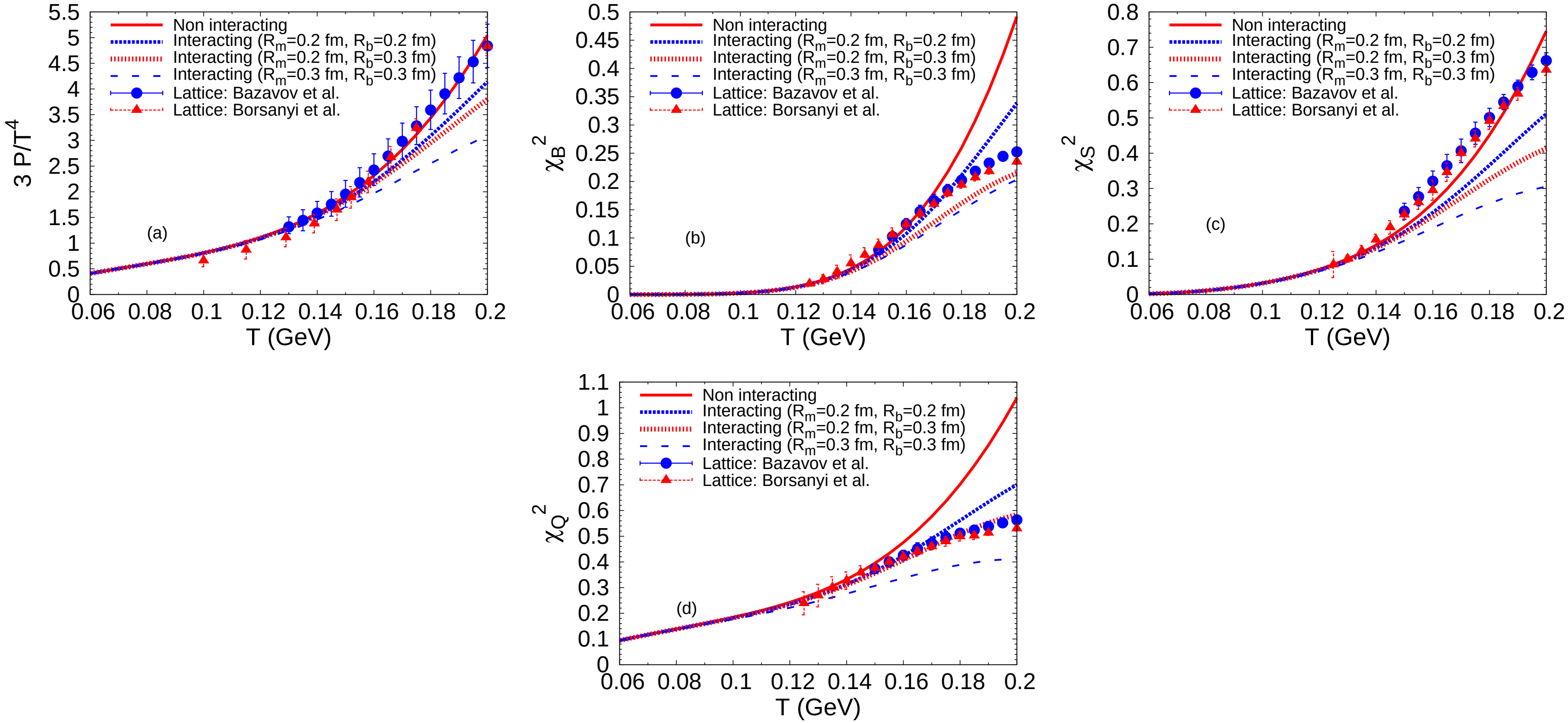


HotQCD: Phys. Rev. D 86, 034509 (2012).

WUB: J. High Energy Phys. 01 138 (2012).

PNJL model: RR et. al. PRD 95 054005 '17.

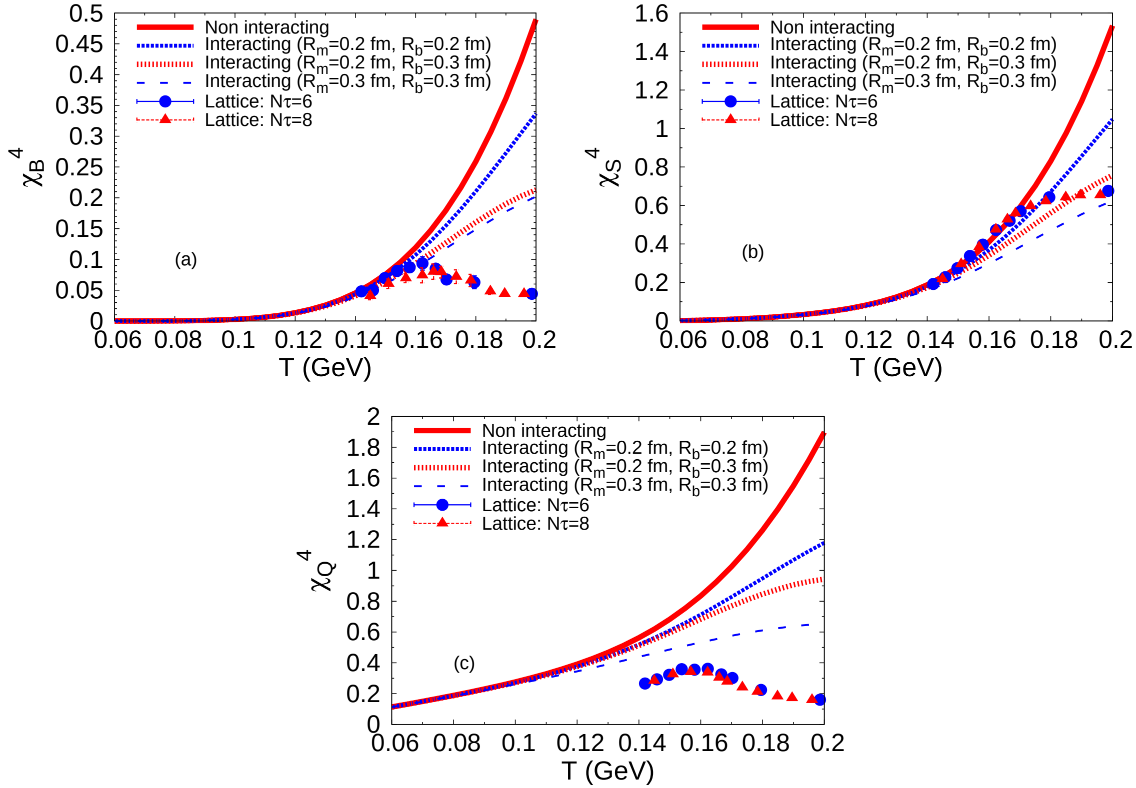
HRG vs LQCD I



RR *et al.*, PRC 90 034909 '14.

- Included hard core repulsion between hadrons to obtain fluctuations
- Reasonable agreement with Lattice QCD data for intermediate T.

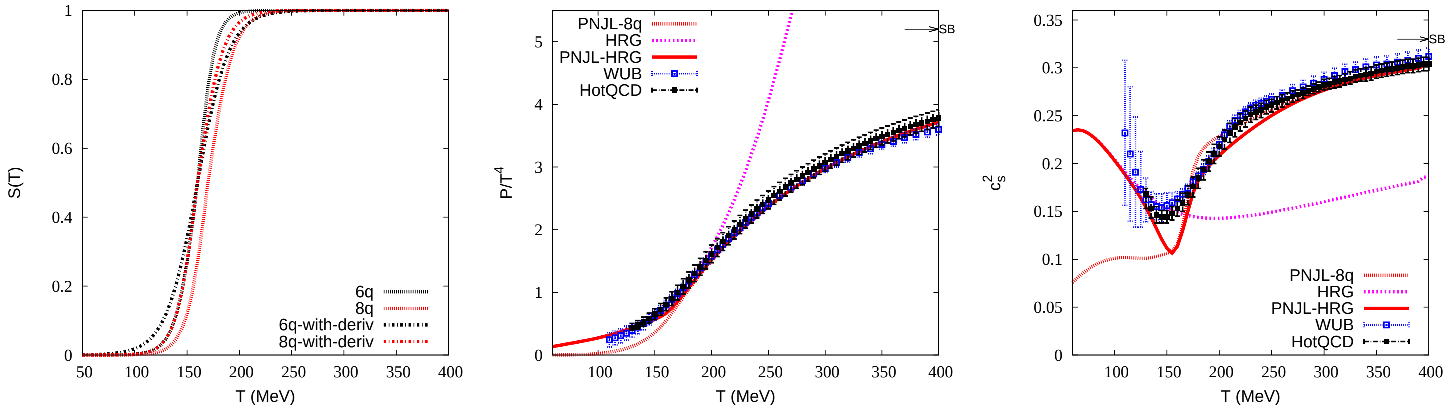
HRG vs LQCD II



RR *et al.*, PRC <u>90</u> 034909 '14.

- Included hard core repulsion between hadrons to obtain fluctuations
- Reasonable agreement with Lattice QCD data for intermediate T.

PNJL+HRG vs Continuum LQCD



- Total pressure → $P(T) = S(T)P_{PNJL}(T) + (1 - S(T))P_{HRG}(T)$
- The switching function is given as,

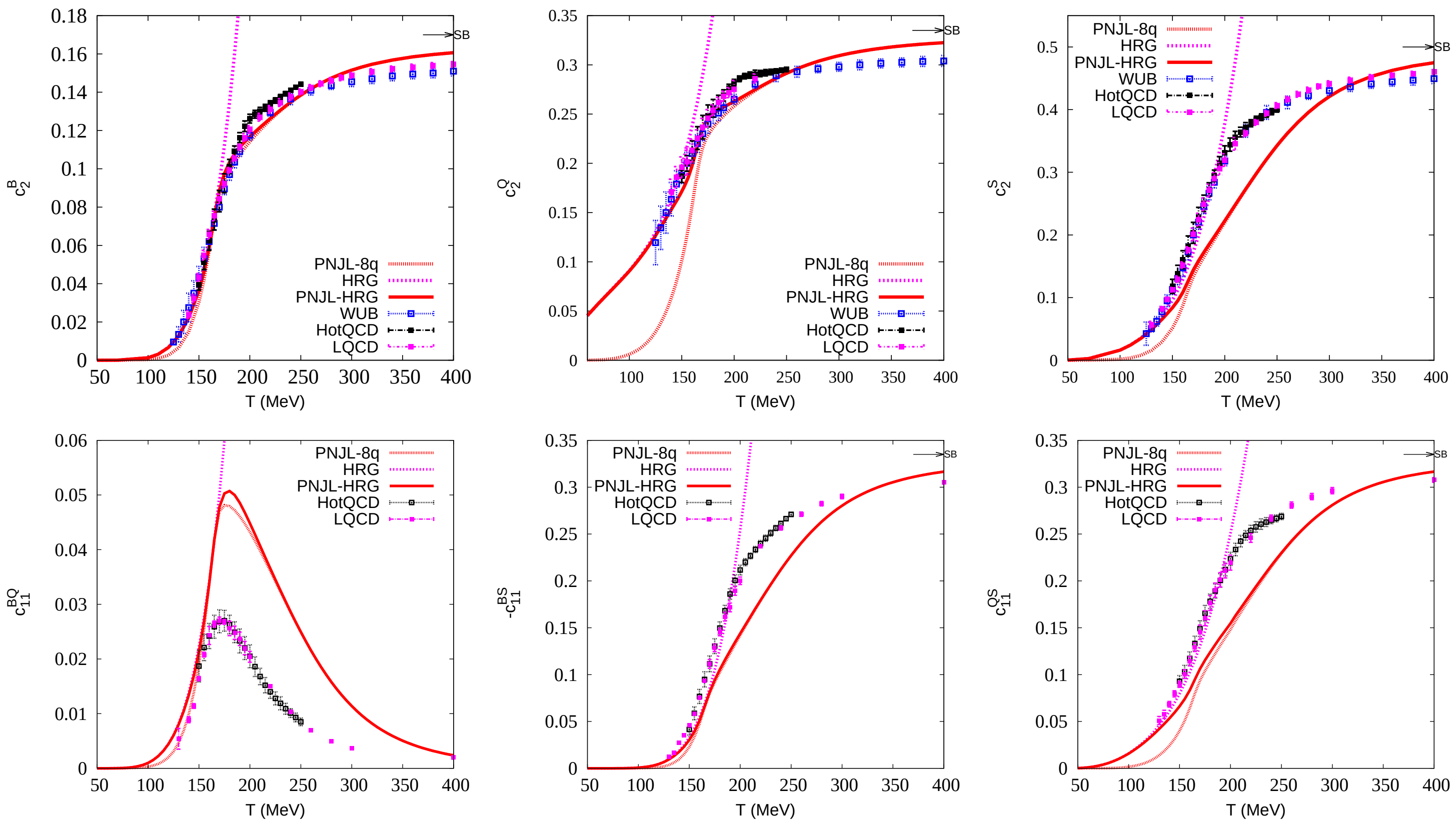
$$S(T) = \left(1 + exp\left[-\frac{T - T_S}{\Delta T_S(T)}\right]\right)^{-1}$$

HotQCD: Phys. Rev. D 86, 034509 (2012).

WUB: J. High Energy Phys. 01 138 (2012).

PNJL + HRG model: RR *et. al*, PRC 99 045207 '19.

PNJL+HRG vs Continuum LQCD



HotQCD: Phys. Rev. D 86, 034509 (2012).

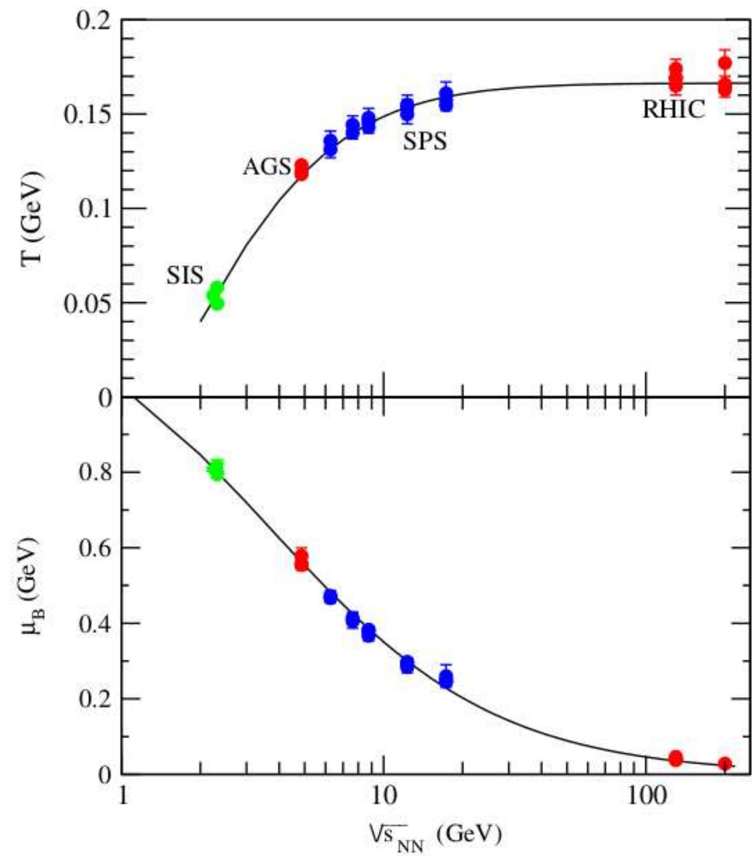
WUB: J. High Energy Phys. 01 138 (2012).

LQCD: Phys. Rev. D 92, 114505 (2015).

PNJL + HRG model: RR *et. al*, PRC 99 045207 '19.

HRG at Freezeout I

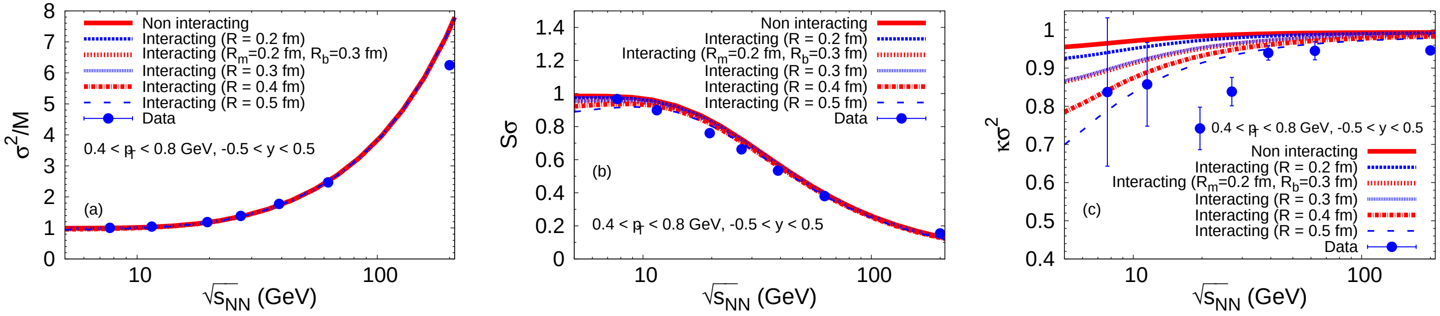
From hadron multiplicity data:



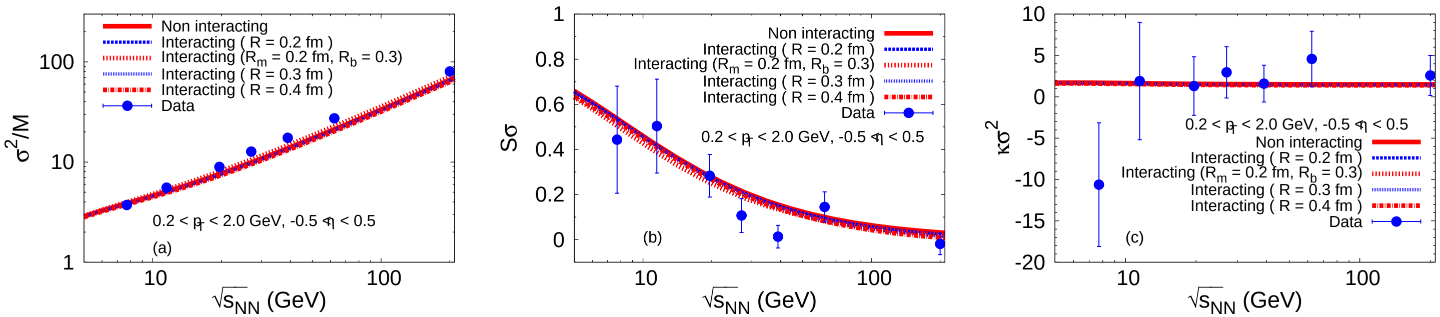
J. Cleymans *et al.*, PRC 73, 034905 (2006)

What happens for ratios of fluctuations with the freezeout data ??

HRG at Freezeout II



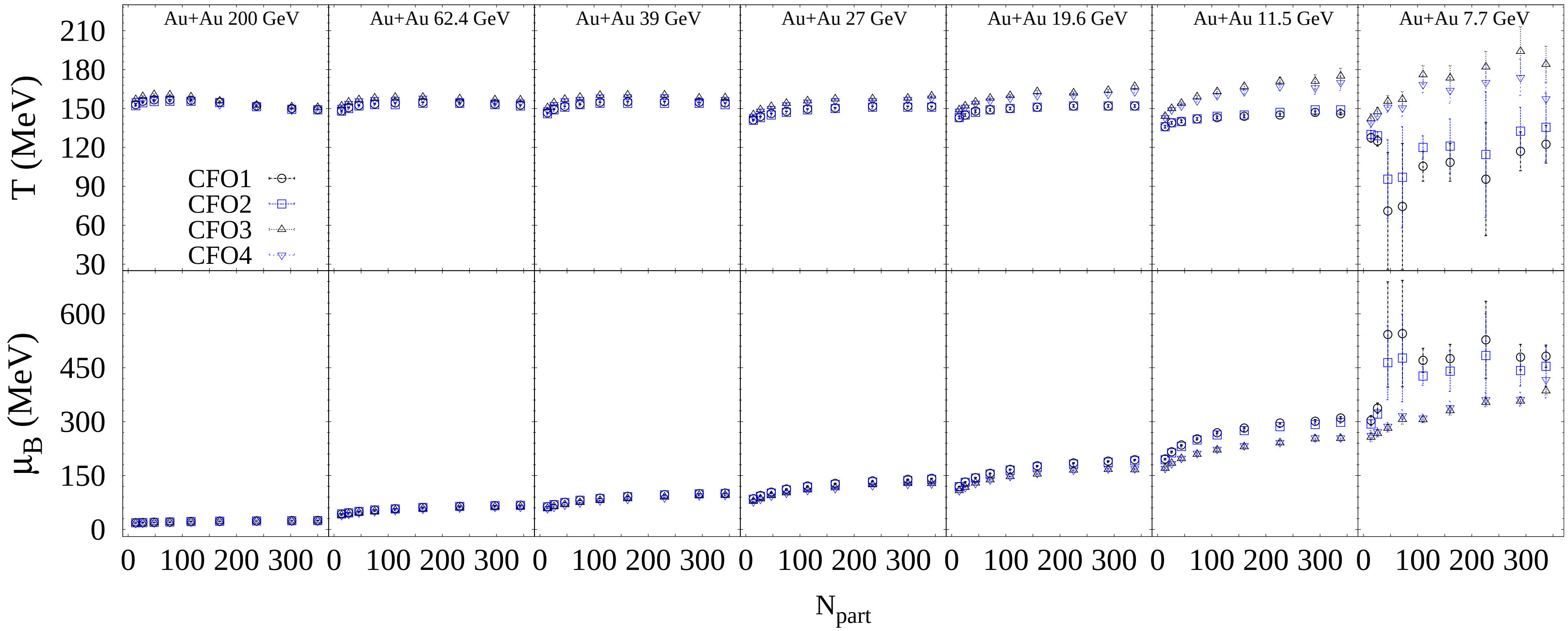
Net-proton data: X. Luo (for the STAR collaboration), Nucl. Phys. A 904-905,911c (2013)



Net-charge data: L. Adamczyk et al. (STAR), Phys. Rev. Lett. 113, 092301 (2014)

- HRG Results: **RR** *et al.*, PRC 90 034909 ’14.

HRG at Freezeout III



Sets of parameters	Experimental data used	Model used
CFO1	$(\sigma^2/M)_{np}, (\sigma^2/M)_{nc}$	HRG
CFO2	$(\sigma^2/M)_{np}, (\sigma^2/M)_{nc}$	EVHRG
CFO3	$(\sigma^2/M)_{nc}, (S\sigma)_{np}, (S\sigma)_{nc}$	HRG
CFO4	$(\sigma^2/M)_{nc}, (S\sigma)_{np}, (S\sigma)_{nc}$	EVHRG

RR *et. al*, PRC 96 014902 '17.

Data from STAR: PRL 112, 032302 (2014); PRL 113, 092301 (2014)

Chemical Freezeout: Alternative approach

- Thermal density of i'th Hadron is given as,

$$\boxed{n_i = \frac{g_i}{(2\pi)^3}\int \frac{d^3p}{\exp[(E_i-\mu_i)/T]\pm 1}.}$$

  - $\mu_i = B_i\mu_B + S_i\mu_S + Q_i\mu_Q$ is total chemical potential, g_i is the degeneracy factor.

- In chemical equilibrium, detected i'th hadron's rapidity density,

$$\boxed{\frac{dN_i}{dy} = \frac{dV}{dy}n_i(T,\mu_Q,\mu_B,\mu_S)} \quad \Rightarrow \quad \boxed{\frac{dN_i/dy}{dN_j/dy} = \frac{n_i}{n_j}}$$

- Add external constraints,

$$\boxed{\frac{\sum_i n_i(T,\mu_B,\mu_S,\mu_Q)Q_i}{\sum_i n_i(T,\mu_B,\mu_S,\mu_Q)B_i} = r}$$

$$\boxed{\sum_i n_i(T,\mu_B,\mu_S,\mu_Q)S_i = 0}$$

Chemical Freezeout: Alternative approach

- Thermal density of i'th Hadron is given as,

$$n_i = \frac{g_i}{(2\pi)^3} \int \frac{d^3p}{\exp[(E_i - \mu_i)/T] \pm 1}.$$

• $\mu_i = B_i\mu_B + S_i\mu_S + Q_i\mu_Q$ is total chemical potential, g_i is the degeneracy factor.

- In chemical equilibrium,

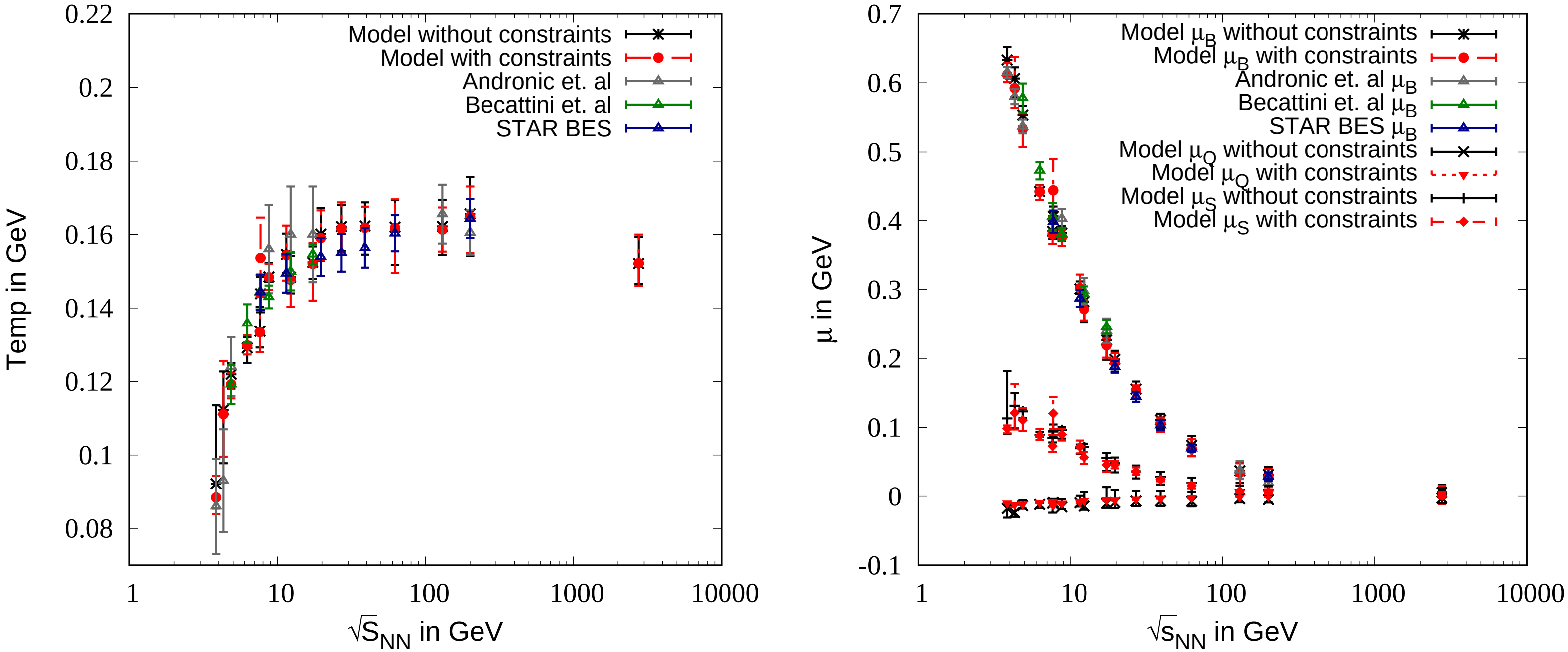
$$\text{Minimize } \chi^2 \text{ w.r.t. T and } \mu_\mathrm{B} \text{ constructed from } \left(\frac{\mathrm{dN_i/dy}}{\mathrm{dN_j/dy}} - \frac{\mathrm{n_i}}{\mathrm{n_j}}\right)$$

- Add external constraints,

$$\frac{\sum_i n_i(T,\mu_B,\mu_S,\mu_Q)Q_i}{\sum_i n_i(T,\mu_B,\mu_S,\mu_Q)B_i} = r$$

$$\sum_i n_i(T,\mu_B,\mu_S,\mu_Q)S_i = 0$$

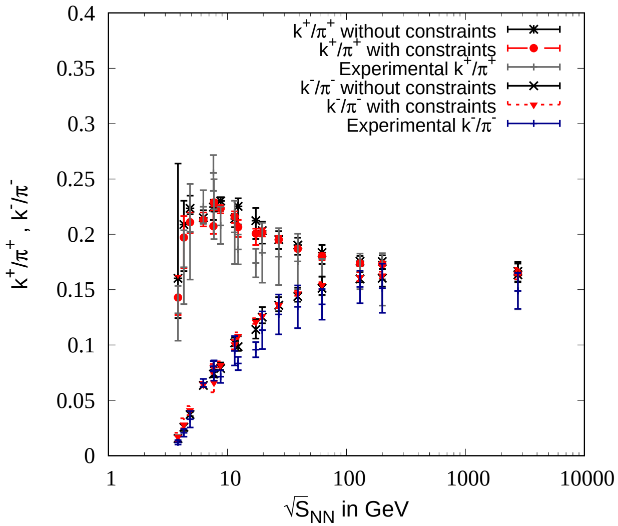
Chemical Freezeout: Alternative approach

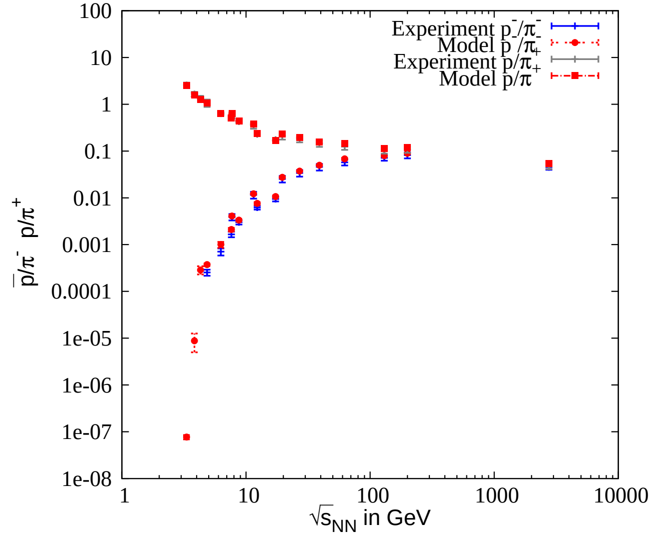


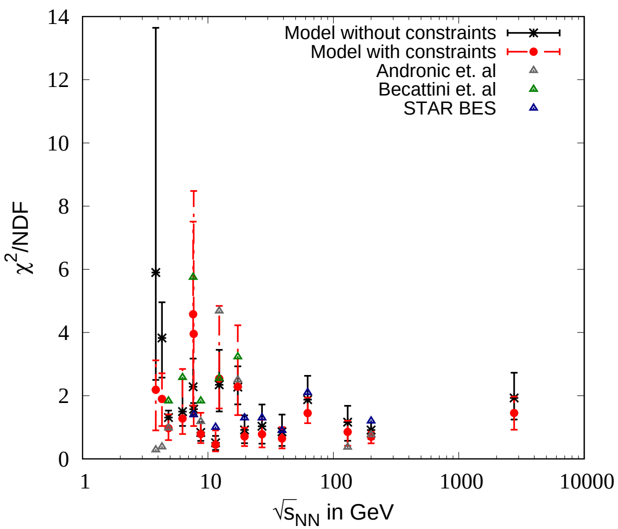
- AGS, SPS, RHIC and LHC (2.76 TeV) data have been used.
- Study has been performed for mid-rapidity data of most central collision of these $\sqrt{s}$.
- Yield of ($\pi^{\pm}, k^{\pm}$ and $p, \bar{p}, \Lambda, \bar{\Lambda}, \Xi^{\pm}$) were used for fitting.
- We have not used $\Omega^{\pm}$ yield as it is not available for most of the $\sqrt{s}$.

RR et. al. arXiv: 1911.04828

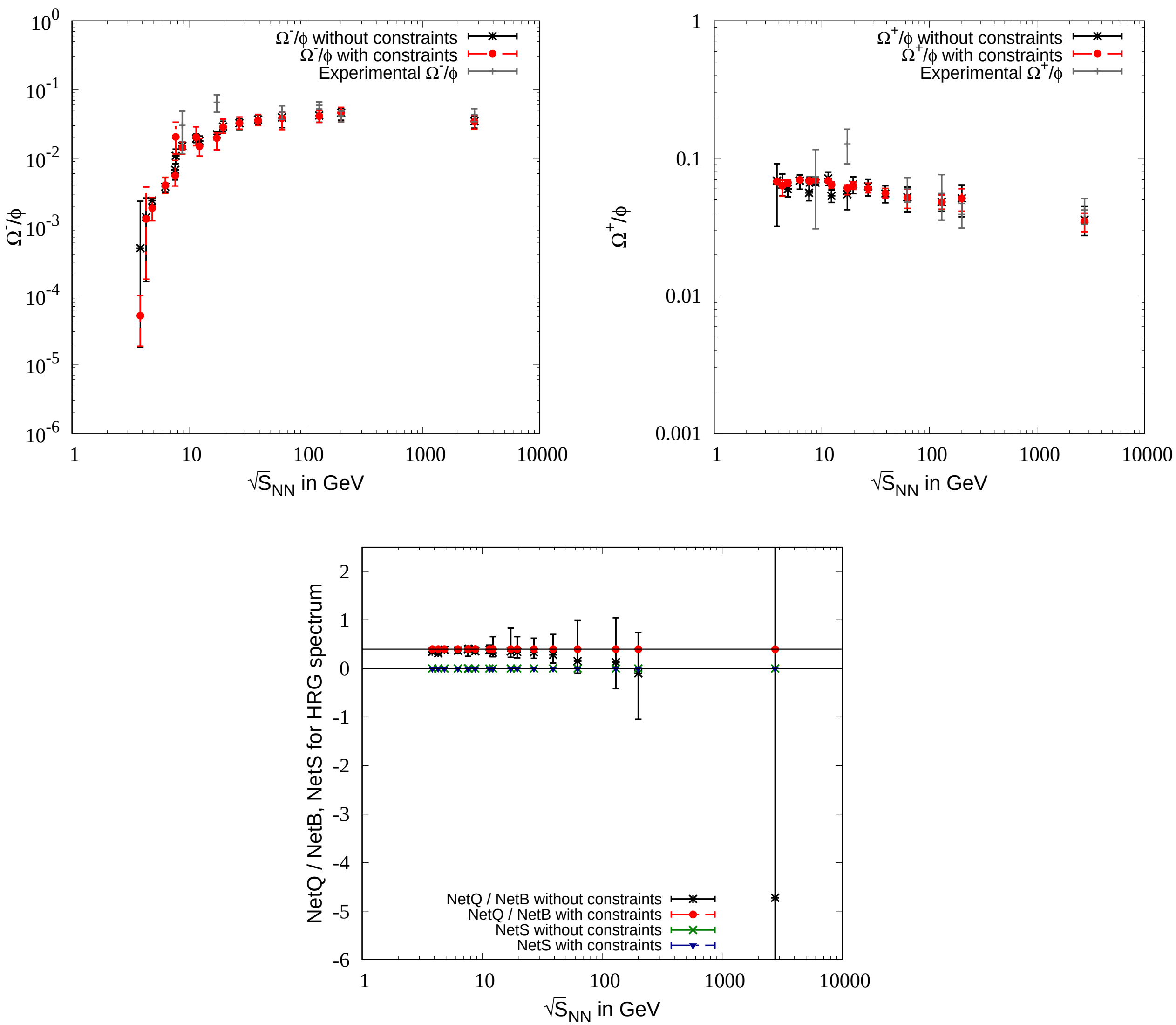
Chemical Freezeout: Alternative approach



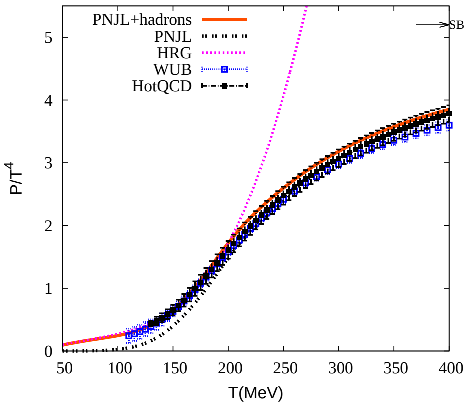


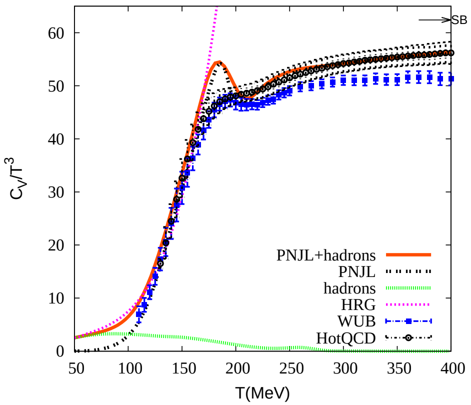


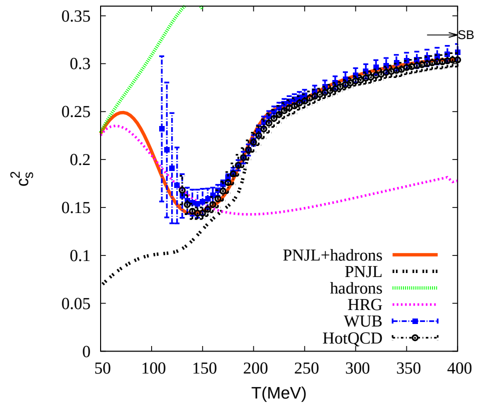
Chemical Freezeout: Alternative approach

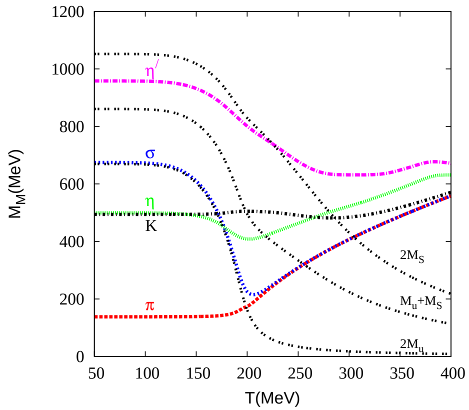


PNJL beyond Mean Field vs Continuum LQCD



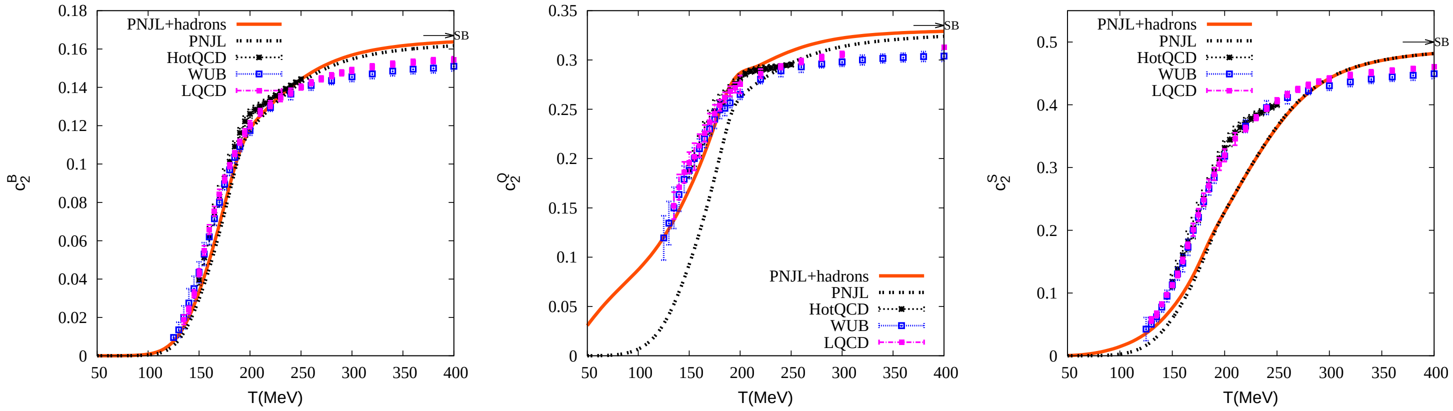






- Total pressure $\rightarrow \quad P(T,\mu) = P_{PNJLMeanfield}(T,\mu) + P_{PNJLHadrons}(T,\mu)$
- The increasing hadron masses provide automatic switch

PNJL beyond Mean Field vs Continuum LQCD



- Total pressure $\rightarrow \quad P(T,\mu) = P_{PNJLMeanfield}(T,\mu) + P_{PNJLHadrons}(T,\mu)$
- The increasing hadron masses provide automatic switch
- Though hadronic region is satisfactory but significant difference in partonic sector

PNJL beyond mean field: RR et. al. Under progress

HotQCD: Phys. Rev. D 86, 034509 (2012).

WUB: J. High Energy Phys. 01 138 (2012).

Gluons + Glueballs ??

- Consider adjoint Polyakov Loop

$$L_A = \text{diag}(1, 1, e^{i(\phi_1-\phi_2)}, e^{-i(\phi_1-\phi_2)} e^{i(2\phi_1+\phi_2)}, e^{-i(2\phi_1+\phi_2)} e^{i(\phi_1+2\phi_2)} e^{-i(\phi_1+2\phi_2)})$$

- The partition function

$$\mathcal{Z} = \int \mathcal{D}\Phi\mathcal{D}\bar{\Phi} H \exp\left(-2V \int \frac{d^3p}{(2\pi)^3} ln\left[1 + \Sigma_{n=1}^{8} C_n e^{(-nE_g/T)}\right]\right)$$

where, H is the Haar measure is given by,

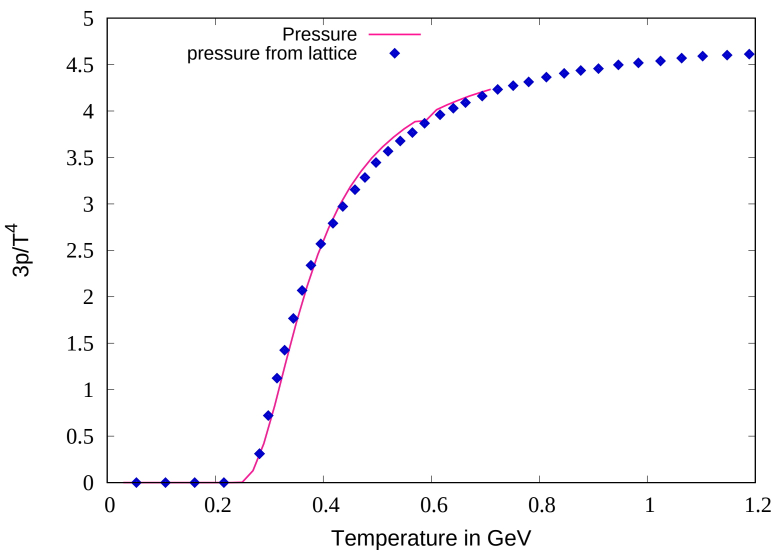
$$H = \frac{8}{9\pi^2}[1 - 6\bar{\Phi}\Phi + 4(\bar{\Phi}^3 + \Phi^3) - 3(\bar{\Phi}\Phi)^2]$$

and the coefficient C_n is given by,

$$\begin{aligned}
C_8 &= 1; C_1 = C_7 = 1 - 9\bar{\Phi}\Phi \\
C_2 &= C_6 = 1 - 27\bar{\Phi}\Phi \\
C_3 &= C_5 = -2 + 27\bar{\Phi}\Phi - 81(\bar{\Phi}\Phi)^2 \\
C_4 &= 2[-1 + 9\bar{\Phi}\Phi - 27(\bar{\Phi}^3 + \Phi^3) + 81(\bar{\Phi}\Phi)^2]
\end{aligned}$$

Gluons + Glueballs ??

- A saddle point analysis yields negative pressure for $T < T_c$
  RR et.al. J. Phys. G, 41 (2014) 025001
- Integrate over all possible constant field configurations



RR et. al. Under progress

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