Equation of state for strongly interacting matter: collective effects, Landau damping and predictions for LHC

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22.01.2008

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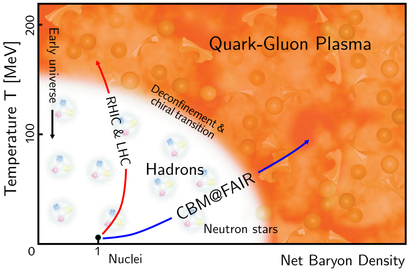
From QCD to thermodynamics

QCD: $\mathcal{L}$
$\longrightarrow$ propagators
$\longrightarrow$ self-energies



thermodyn. potential Ω
$\longrightarrow$ state variables: p, s, n_q, etc.
$\longrightarrow$ EOS $e = e(p)$
$\longrightarrow$ $T^{\mu\nu}$, hydrodynamics

CJT formalism

- effective action

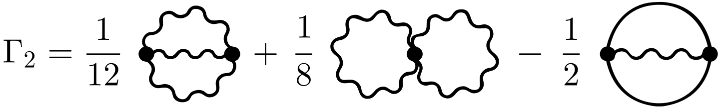
$$\Gamma[D,S] = I - \frac{1}{2}\left\{\mathrm{Tr}\left[\ln D^{-1}\right] + \mathrm{Tr}\left[D_0^{-1}D - 1\right]\right\} + \left\{\mathrm{Tr}\left[\ln S^{-1}\right] + \mathrm{Tr}\left[S_0^{-1}S - 1\right]\right\} + \Gamma_2[D,S]$$

- for translation invariant systems w/o broken symmetries

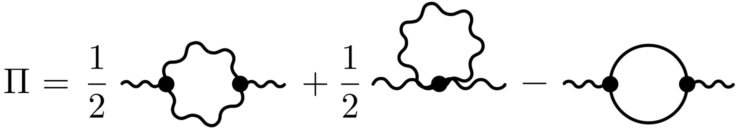
$$\frac{\Omega}{V} = \mathrm{tr}\int\frac{\mathrm{d}^4k}{(2\pi)^4}n_\mathrm{B}(\omega)\,\mathrm{Im}\left(\ln D^{-1} - \Pi D\right) + 2\,\mathrm{tr}\int\frac{\mathrm{d}^4k}{(2\pi)^4}n_\mathrm{F}(\omega)\,\mathrm{Im}\left(\ln S^{-1} - \Sigma S\right) - \frac{T}{V}\Gamma_2$$

2-loop QCD thermodynamics

- truncate Γ_2 at 2-loop order



$\longrightarrow$ self-energies of 1-loop order



- gauge invariance: add. HTL approximation

Effective coupling

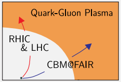
$$g^2(x^2) = \frac{16\pi^2}{\beta_0 \ln(x^2)} \left(1 - \frac{4\beta_1}{\beta_0^2} \frac{\ln[\ln(x^2)]}{\ln(x^2)}\right)$$

- running coupling g^2 $\qquad x = \frac{\bar{\mu}}{\Lambda}$

$$\Big\downarrow \quad T > T_c,\ \mu = 0$$

- effective coupling G^2 $\qquad x = \frac{\lambda}{T_0}(T - T_s)$

Model outline



- $s := -\frac{1}{V}\,\frac{\partial \Omega}{\partial T}\Big|_{\mu} = s_{g,\mathrm{T}} + s_{g,\mathrm{L}} + s_{q,\mathrm{Pt}} + s_{q,\mathrm{Pl}} + s'$ $\qquad s' = 0$

  e.g. gluons:

$$s_{g,\mathrm{T}} \sim \int_{\mathrm{d}^4k} \frac{\partial n_{\mathrm{B}}}{\partial T} \left\{ \underbrace{\pi\varepsilon(\omega)\Theta\left(-\mathrm{Re}D_{\mathrm{T}}^{-1}\right)}_{\text{qp contribution}} + \underbrace{\mathrm{Re}D_{\mathrm{T}}\mathrm{Im}\Pi_{\mathrm{T}} - \arctan\left(\frac{\mathrm{Im}\Pi_{\mathrm{T}}}{\mathrm{Re}D_{\mathrm{T}}^{-1}}\right)}_{\text{damping terms}} \right\}$$

- effective QPM: no collective modes, no damping

  Peshier, Kämpfer, Pavlenko, Soff: PLB'94, PRD'96

- adjustment to $s(T, \mu = 0)$ lattice data

  $\rightarrow$ mapping to finite chemical potential

$$\frac{\partial s}{\partial \mu} = \frac{\partial n}{\partial T}$$

Peshier, Kämpfer, Soff: PRC'00, PRD'02

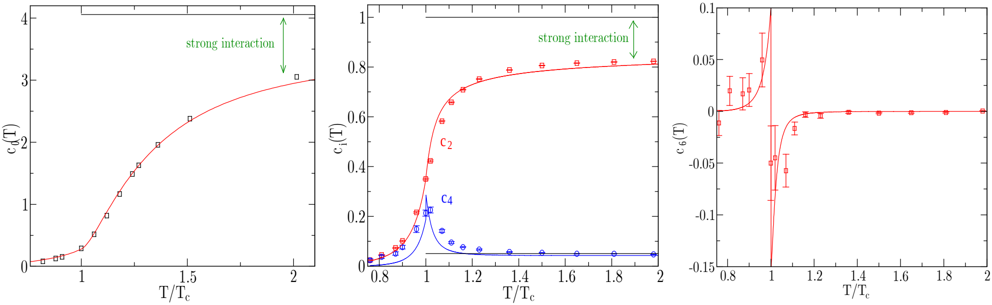
Small chemical potential

- effective QPM: $\boxed{\mathrm{Im}\,\Pi = 0}$

Bluhm, Kämpfer, Soff: PLB'05
Bluhm, Kämpfer, RS, Seipt: EPJC'07

- $p(T, \mu \gtrsim 0)$ lattice data

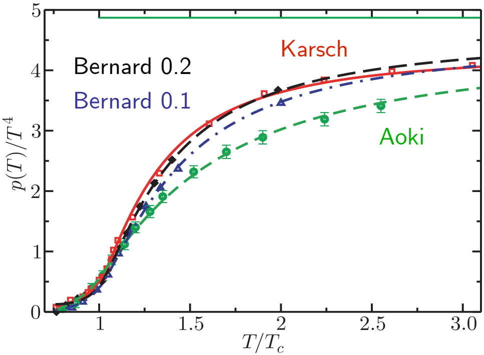
$$p = T^4 \sum_n c_n(T) \left(\frac{\mu}{T}\right)^n \qquad c_n(T) = \frac{1}{n!} \frac{\partial^n (p/T^4)}{\partial(\mu/T)^n}$$

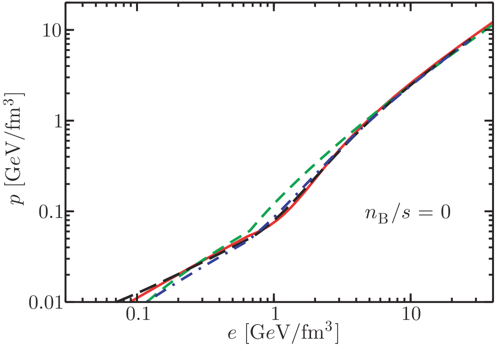


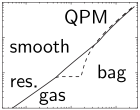
EOS for $N_f = 2+1$

- RHIC, LHC:

$$\mu = 0$$

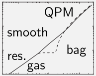




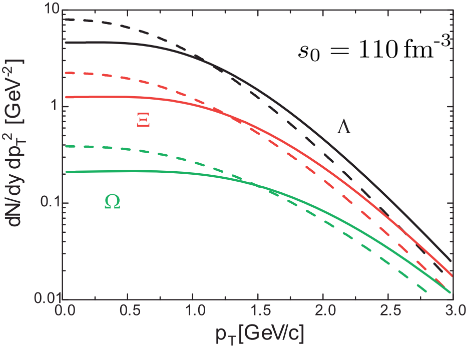


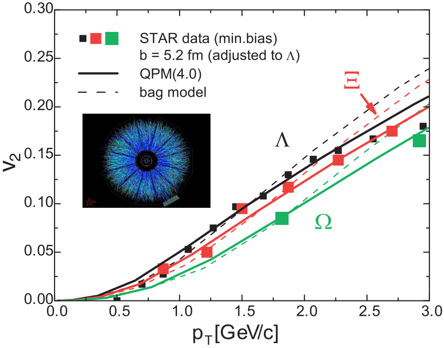
Kämpfer, Bluhm, RS, Seipt, Heinz: NPA'05
Bluhm, Kämpfer, RS, Seipt, Heinz: PRC'07

First test

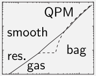


- calculate elliptic flow using relativistic hydro code
- compare with experimental data (RHIC)





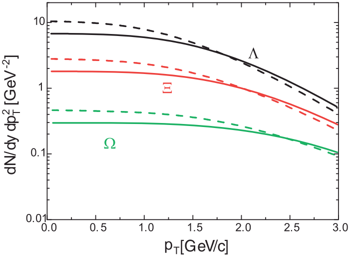
Predictions for LHC

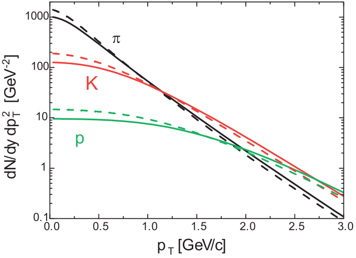


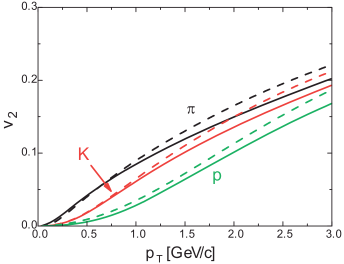
- LHC Pb+Pb collisions - conservative guess:

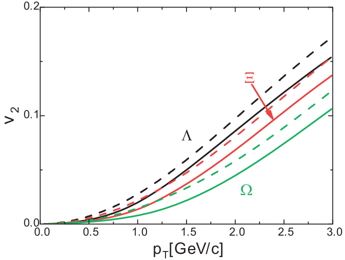
$$s_0 = 330\,\mathrm{fm}^{-3}, \quad \tau_0 = 0.6\,\mathrm{fm}/c$$
$$b = 5.2\,\mathrm{fm} \qquad T_0 = 515\,\mathrm{MeV}$$

- higher initial temperature
  $\rightarrow$ flatter p_T spectra
  $\rightarrow$ smaller v_2





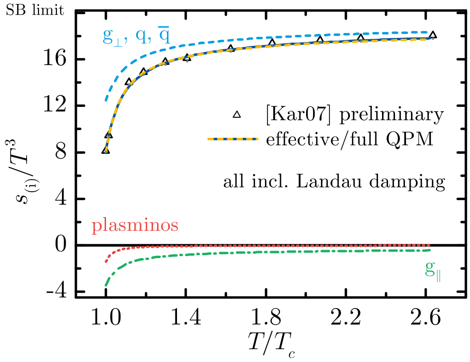


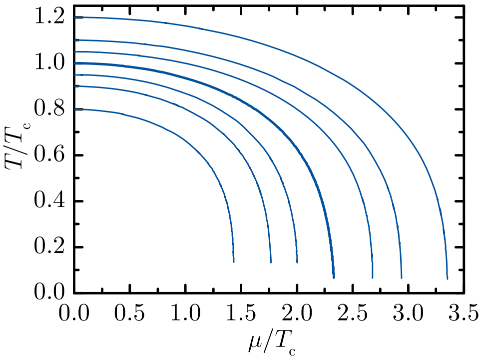


Next step: FAIR, large μ

- effective model: crossing characteristics
- full model: $\boxed{\mathrm{Im}\,\Pi \neq 0}$ + collective excitations

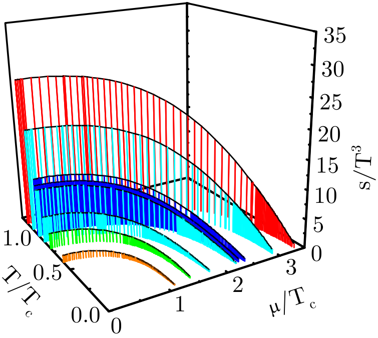
RS, Bluhm, Kämpfer: EPJ ST'08

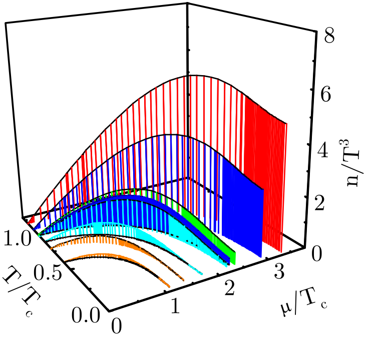




Towards an EOS

- entropy and Baryon density accessible





- next step: pressure, energy density, EOS

Summary & Outlook

- 2-loop Γ_2 + eff. coupling $G^2 \rightarrow$ QPM
- Im $\Pi = 0$: $c_i(T)$, EOS(T, $\mu > 0$)
  $\rightarrow$ agreement w/ RHIC; LHC predictions
- Im $\Pi \neq 0$: Landau damping + collective modes
  $\rightarrow$ vanishing crossings, large μ accessible
- outlook: EOS for cold and dense matter (FAIR, neutron/quark/strange stars); transport coefficients, critical endpoint

More LHC predictions

- initial parameters translate to

$$e_0 = 127\,\mathrm{GeV},\ p_0 = 42\,\frac{\mathrm{GeV}}{\mathrm{fm}^3},\ T_0 = 515\,\mathrm{MeV}$$

- LHC: higher initial temperature $\rightarrow$ longer fireball lifetime $\rightarrow$ stronger radial flow $\rightarrow$ p_T spectra flat

More full HTL quasiparticle model

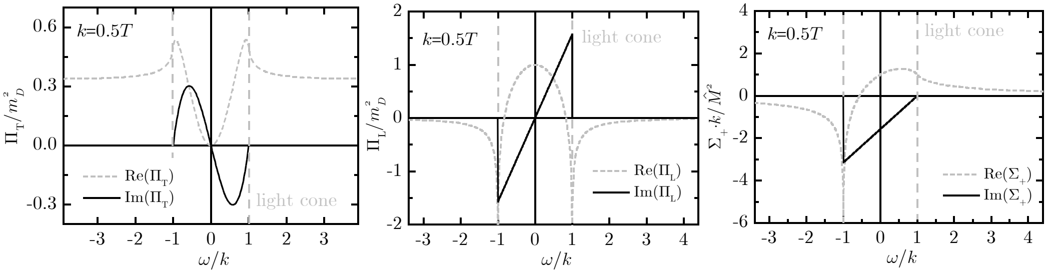
- now: $\boxed{\mathrm{Im}\,\Pi \neq 0}$ + collective excitations

$$s = s_{qp} + s_{damp} = s_{qp} + (\tilde{s} - s_{qp})$$

$$\tilde{s} = \int d\omega \underbrace{\int dk\, \sigma(\omega, k)}_{\hat{=} s_{qp}(\omega)} \cdot F(\mathrm{Im}\Pi(\omega, k))$$

$$\xi := \frac{\mathrm{Im}\Pi}{\mathrm{Re}D^{-1}}$$

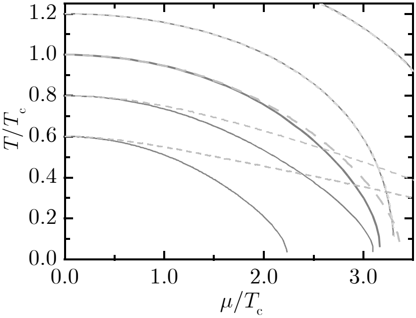
$$F := -\frac{1}{\pi}\left(\frac{\xi^2(\omega)}{(1+\xi^2(\omega))^2} + \frac{\xi^2(-\omega)}{(1+\xi^2(-\omega))^2}\right)\frac{\partial \xi}{\partial \omega}$$



→ Landau damping

More effects of collective excitations

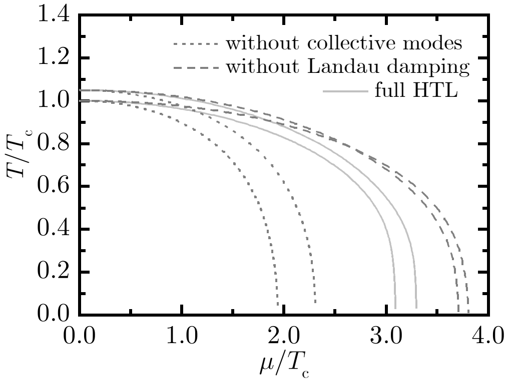
- collective modes
  $\longrightarrow$ neg. entropy contrib.



situation improves

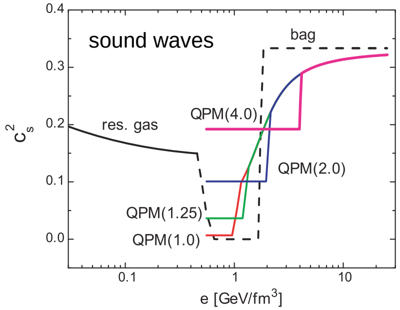
More effects of Landau damping

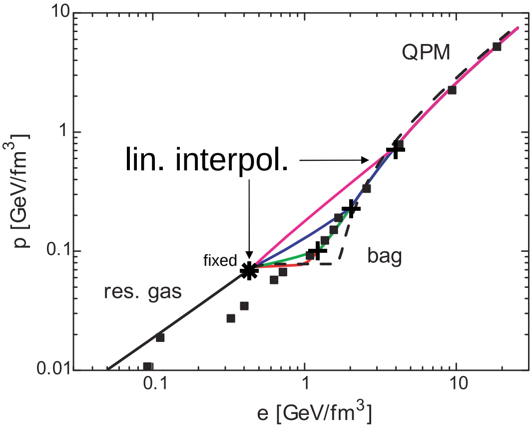
- only minor contribution at $\mu = 0$
- essential for $\mu > 0$



A family of EOS's $\mu_B \ll T$

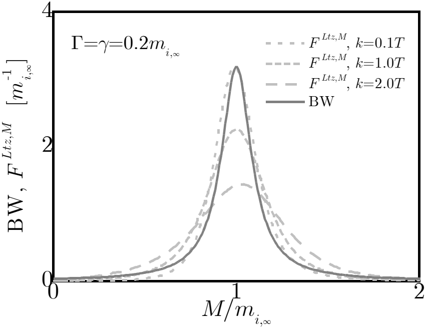
- interpolate between hadron gas and QPM description





Backup: Inclusion of widths

- Peshier: $\mathrm{Im}\,\Pi = 2\gamma\omega$

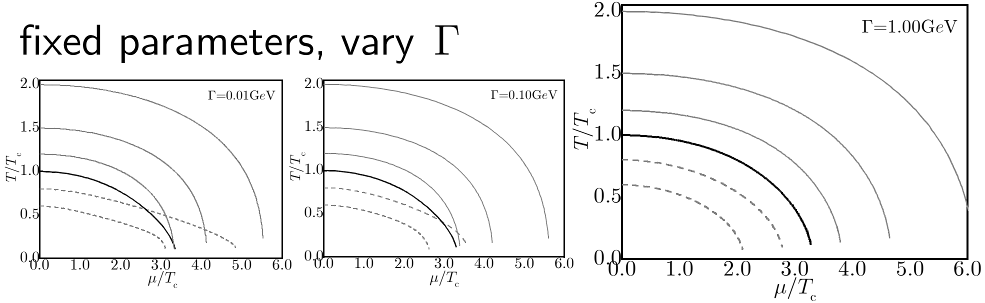


- ansatz $F(\omega,k) \rightarrow \mathrm{BW}(m)$

$$s(T) = \int \mathrm{d}M\, s_{qp}(T,M)\mathrm{BW}(m,M,\Gamma)$$

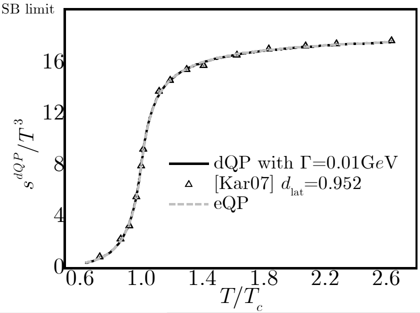
Backup: Distributed quasiparticle model

- fixed parameters, vary Γ



- adjustment to lattice

$$\Gamma = 0.01\,\mathrm{GeV}$$



Backup: Distributed quasiparticle model II

- bias adjustment $\Gamma \overset{!}{=} 1\,\mathrm{G}e\mathrm{V}$