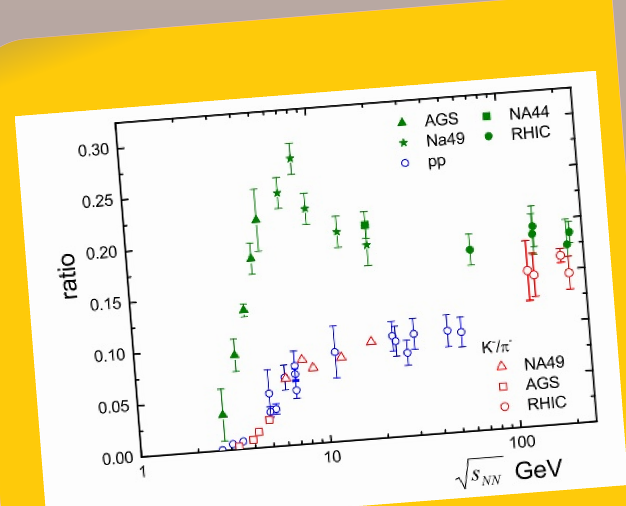
Strange matter in SU(3) PNJL model: kaon-to-pion ratio along PD

A. V. Friesen, Yu. L. Kalinovsky, V. D. Toneev

Joint Institute for Nuclear Research, Dubna, Russia



ABSTRACT

The behaviour of strange matter in the frame of the SU(3) Polyakov-loop extended Nambu-Jona-Lasinio model is considered. We discuss the appearance of a peak in the ratio of the number of strange mesons to non-strange mesons known as the "horn". We showed that the rise in the ratio K^+/π^+ appears in PNJL model when we build the K^+/π^+ ratio along the phase transition diagram. We considered how the matter properties can affect to the behaviour of the kaon-to-pion ratio.

THE 'HORN': THEORY OVERVIEW

- **the statistical model**: hadron resonances + σ - meson (*the hadron phase transition*) $\Rightarrow$ the qualitative reproduction of the peak (A. Andronic, PLB 673, 142 (2009)).
- **the SMES**: a jump in the ratio is a result of the *deconfinement transition*: when deconfinement transition occurs the strangeness yield becomes independent of energy in the QGP ($m_s \to m_{s0}$) (M. Gazdzicki, M.I. Gorenstein, Acta Phys. Pol. B 30, 2705 (1999)).
- **the microscopic transport model + the partial restoration of chiral symmetry** (A. Palmese, et al. PRC 94, 044912 (2016): the quick increase in the K^+/π^+ appears as a result of *the partial chiral symmetry restoration*; the decrease is a result of QGP formation.

The effective potential:

$$\frac{\mathcal{U}(\Phi;T)}{T^4} = -\frac{b_2(T)}{2}\Phi^2 - \frac{b_3}{3}\Phi^3 + \frac{b_4}{4}\Phi^4$$

$$b_2(T) = a_0 + a_1\left(\frac{T_0}{T}\right) + a_2\left(\frac{T_0}{T}\right)^2 + a_3\left(\frac{T_0}{T}\right)^3$$

THE PNJL MODEL

We consider the Polyakov loop extended SU(3) Nambu-Jona-Lasinio model with scalar-pseudoscalar interaction and the t'Hooft interaction which breaks the $U_A(1)$ symmetry [1]:

$$\mathcal{L} = \bar{q}\,(i\gamma^\mu D_\mu - \hat{m} - \gamma_0\mu)\,q + \frac{1}{2}G_s\sum_{a=0}^{8}[(\bar{q}\lambda^a q)^2 + (\bar{q}\,i\gamma_5\lambda^a q)^2] + K\,\{\det[\bar{q}(1+\gamma_5)q] + \det[\bar{q}(1-\gamma_5)q]\} - \mathcal{U}(\Phi,\bar{\Phi};T)$$

$D_\mu = \partial^\mu - iA^\mu$, where A^μ is the gauge field with $A^0 = -iA_4$ and $A^\mu(x) = G_s A^\mu_a \frac{\lambda_a}{2}$.

The grand potential density for the PNJL model in the mean-field approximation can be obtained from the Lagrangian density:

$$\Omega = \mathcal{U}(\Phi,\bar{\Phi};T) + G_s\sum_{i=u,d,s}\langle\bar{q}_i q_i\rangle^2 + 4K\langle\bar{q}_u q_u\rangle\langle\bar{q}_d q_d\rangle\langle\bar{q}_s q_s\rangle - 2N_c\sum_{i=u,d,s}\int\frac{d^3p}{(2\pi)^3}E_i - 2T\sum_{i=u,d,s}\int\frac{d^3p}{(2\pi)^3}(N^+_\Phi(E_i) + N^-_\Phi(E_i))$$

with the functions

$$N^+_\Phi(E_i) = \mathrm{Tr}_c\left[\ln(1 + L^\dagger e^{-\beta(E_i-\mu_i)})\right] = \left[1 + 3\left(\Phi + \bar{\Phi}e^{-\beta E_i^+}\right)e^{-\beta E_i^+} + e^{-3\beta E_i^+}\right],\quad N^-_\Phi(E_i) = \mathrm{Tr}_c\left[\ln(1 + Le^{-\beta(E_p+\mu_i)})\right] = \left[1 + 3\left(\bar{\Phi} + \Phi e^{-\beta E_p^-}\right)e^{-\beta E_p^-} + e^{-3\beta E_p^-}\right]$$

where $E_i^\pm = E_i \mp \mu_i$, $\beta = 1/T$, $E_i = \sqrt{\mathbf{p_i}^2 + m_i^2}$ is the energy of quarks and $\langle\bar{q}_i q_i\rangle$ is the quark condensate.

The gap equations:

$$m_i = m_{0i} + 4G < \bar{q}_i q_i > +2K < \bar{q}_j q_j >< \bar{q}_k q_k >$$

The meson masses are defined by the Bethe-Salpeter equation at $\mathbf{P} = 0$:

$$1 - P_{ij}\Pi^P_{ij}(P_0 = M, \mathbf{P} = \mathbf{0}) = 0\,,$$

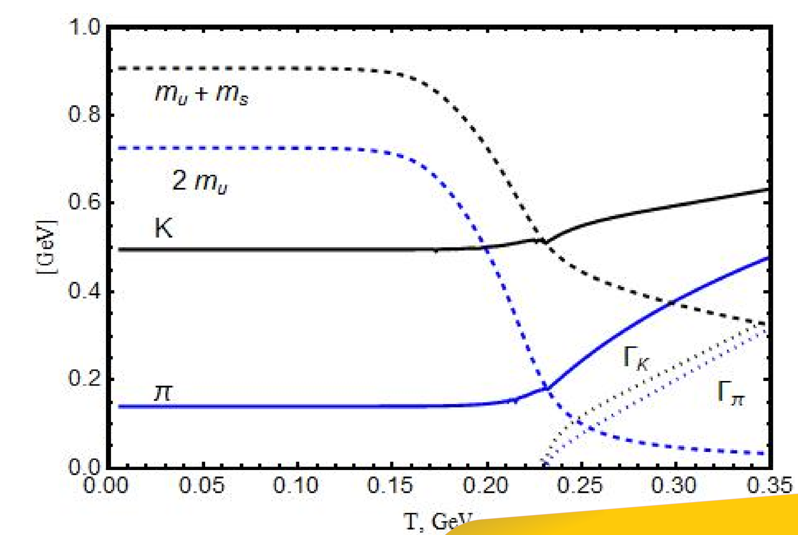
with $P_\pi = G_s + K\langle\bar{q}_s q_s\rangle$, $P_K = G_s + K\langle\bar{q}_u q_u\rangle$ and the polarization operator: $\Pi^P_{ij}(P_0) = 4\left((I^i_1 + I^j_1) - [P_0^2 - (m_i - m_j)^2]\; I^{ij}_2(P_0)\right)$.

The set of parameters: $m_{0u} = m_{0d} = 5.5$ MeV, $m_{0s} = 0.131$ GeV, $\Lambda = 0.652$ GeV, couplings $g_D = 89.9$ GeV^{-2} and $g_S = 4.3$ GeV^{-5}.

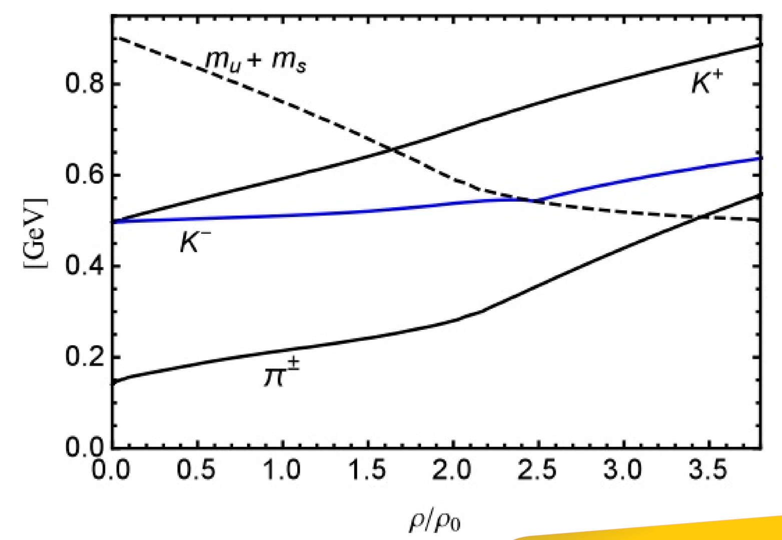
After the Mott temperature $T > T_{Mott}$ the meson mass becomes more than ($P_0 > m_i + m_j$) and the meson from the bound state turns into the resonance state and can dissociate into its constituents, the solution has to be defined in the form $P_0 = M_M - \frac{1}{2}i\Gamma_M$, $T^\pi_{Mott} = 0.232$, $T^K_{Mott} = 0.23$ Gev.

We can:

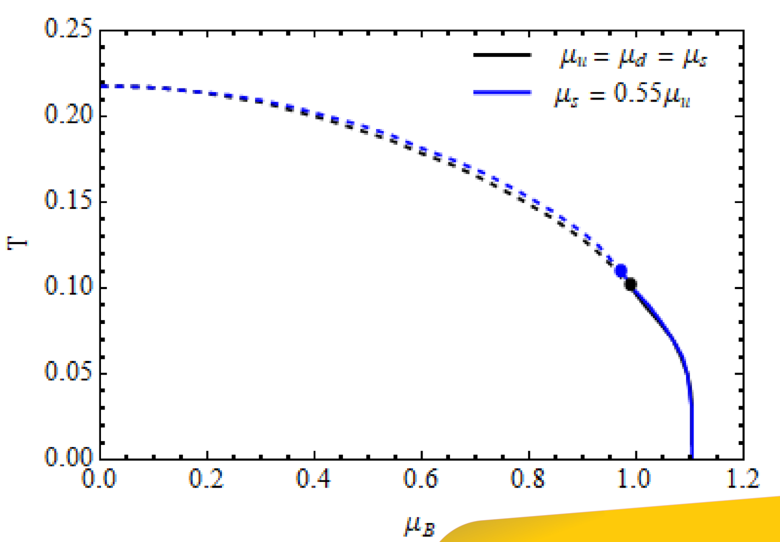
- explain and describe spontaneous chiral symmetry broken as $m_q = m_0 + < \bar{q}q >$;
- simulate the confinement/deconfinement transition
- build the phase diagram with crossover at low chemical potential and 1st order transition at high chemical potential ($m_0 \neq 0$),



Masses at $\mu_B = 0$ and finite T



Masses at $T = 0$ and finite μ_B.



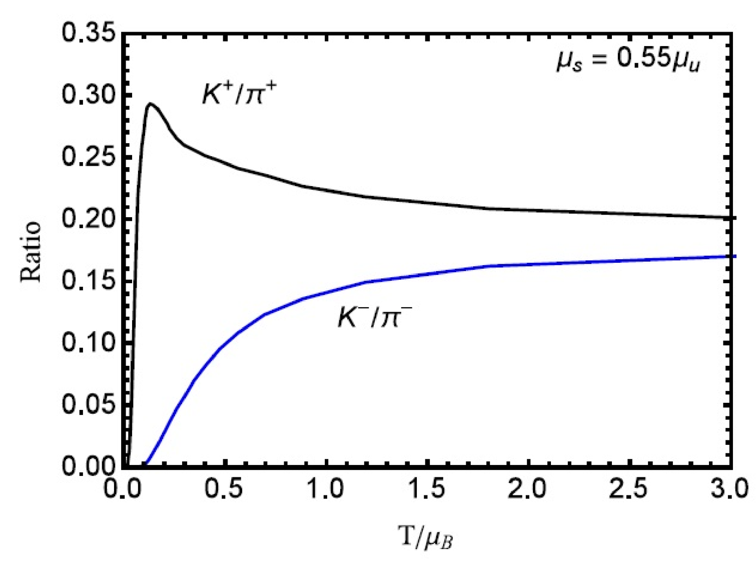
The phase diagram

"HORN" in K/π RATIO

$n_{K^\pm} = \int_0^\infty p^2 dp \frac{1}{e^{(\sqrt{p^2 + m_{K^\pm}} \mp \mu_{K^\pm})/T} - 1}$,

$n_{\pi^\pm} = \int_0^\infty p^2 dp \frac{1}{e^{(\sqrt{p^2 + m_{\pi^\pm}} \mp \mu_{\pi^\pm})/T} - 1}$

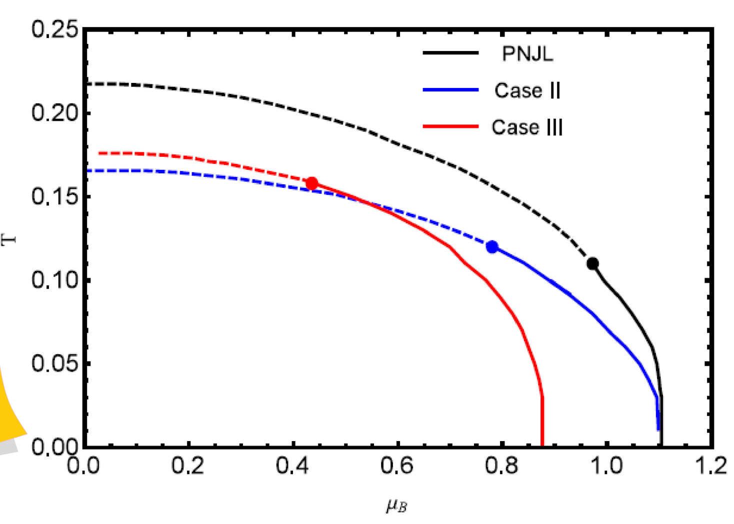
with parameter $\mu_\pi = 0.135$ [2] and $\mu_K = \mu_u - \mu_s$ (see for example [3]

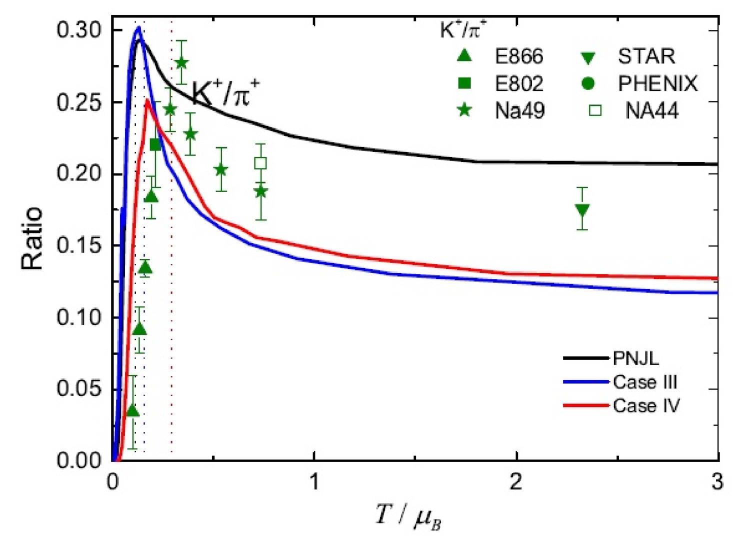


THE MODEL IMPROVEMENTS

- **Case I:** introduce a phenomenological dependence of $G_s(\Phi)$ [4] $\tilde{G}_s(\Phi) = G_s[1 - \alpha_1\Phi\bar{\Phi} - \alpha_2(\Phi^3 + \bar{\Phi}^3)]$ with $\alpha_1 = \alpha_2 = 0.2$.
- **Case II:** Case I + the effect of axial symmetry and dependence of the coupling $K = K_0\exp(-(\rho/\rho_0)^2)$ on the dense states [5]

As in an effective model the energy of collision $\sqrt{s_{NN}}$ does not appear in the natural way, we introduced a new variable T/μ_B, where both T and μ_B were chosen along the phase transition line.





CONCLUSION AND OUTLOOKS:

- splitting of kaons masses at high densities $\Rightarrow$ the difference in the behavior of the K/π at low energies.
- the hight of the peak in the model depends on the properties of the matter (strange chemical potential, T and μ_B) - it looks like we need more realistic description of the media. F.e. strangeness neutrality in PNJL model can be introduced by additional condition $n_s = \frac{\partial\Omega}{\partial\mu_B}$.
- the position of the peak pretends to be depend on curvature of phase diagram/CEP position.
- it is interestig to consider baryon-to-pion ratio in the PNJL model

The work of Yu. K. and A.F. was supported by the RFBR grant no. 18-02-40137.

BIBLIOGRAPHY

[1] P. Costa et al. PRD79, 116003 (2009); E. Blanquier J. Phys. G: NPP 38, 105003 (2011), A. Friesen et al. Phys.-Usp 59, 367 (2017)

[2] M. Kataja, P.V. Ruuskanen PLB 243, 181 (1990).

[3] A. Lavagno and D. Pigato, EPJ Web of Conferences **37**, 09022 (2012))

[4] Y. Sakai et al PRD 82, 076003 (2010), P. de Forcrand, O. Philipsen NPB 642, 290(2002), A. Friesen et al. IJMPA30, 1550089 (2015).

[5] K. Fukushima PR77, 114028 (2008); P. Costa, Yu. Kalinovsky et al AIP Conf.Proc. 775 (2005) 173; arXiv::0503258

[6] A. V. Friesen, Yu. L. Kalinovsky, V. D. Toneev Phys.Rev. C99 (2019) no.4, 045201

LaTeX TikZposter