Production of hadrons and nuclei as quark clusters at chemical freezeout

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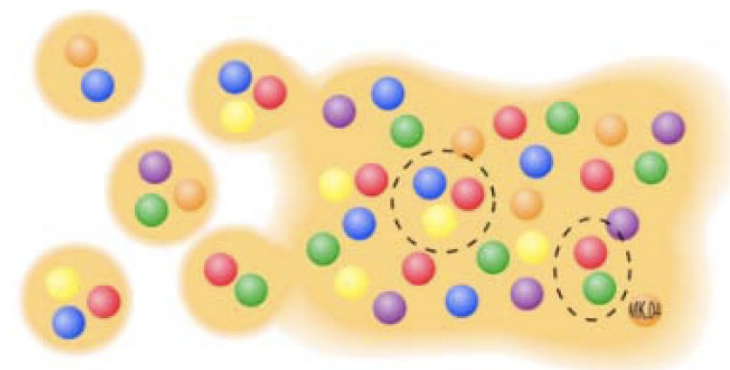
Mott delocalization = dissociation, deconfinement →

Hadrons

Nuclei



Quark-Gluon Plasma

← Mott localization = hadronization, confinement

Light Clusters in Nuclei and Nuclear Matter, ECT* Trento, 05.09.2019

Russian Science Foundation
Grant No. 17-12-01427

Mott-Anderson localization model for chemical freeze-out

DB, J. Berdermann, J. Cleymans, K. Redlich, Phys. Part. Nucl. Lett. 8 (2011) 811

The basic idea: Localization of (certain) multiquark states ("cluster") = hadronization;
Reverse process = delocalization by quark exchange between hadrons

Freeze-out criterion:

$$H_{\exp}(\tau) = \frac{\dot{R}(\tau)}{R(\tau)} = \tau^{-1}_{\mathrm{coll},i}(T,\mu)\ ,$$

$$\tau^{-1}_{\mathrm{coll},i}(T,\mu) = \sum_j \sigma_{ij} v n_j(T,\mu)$$

Povh-Huefner law,
PRC 46 (1992) 990

$$\sigma_{ij} = \lambda \langle r_i^2 \rangle \langle r_j^2 \rangle$$

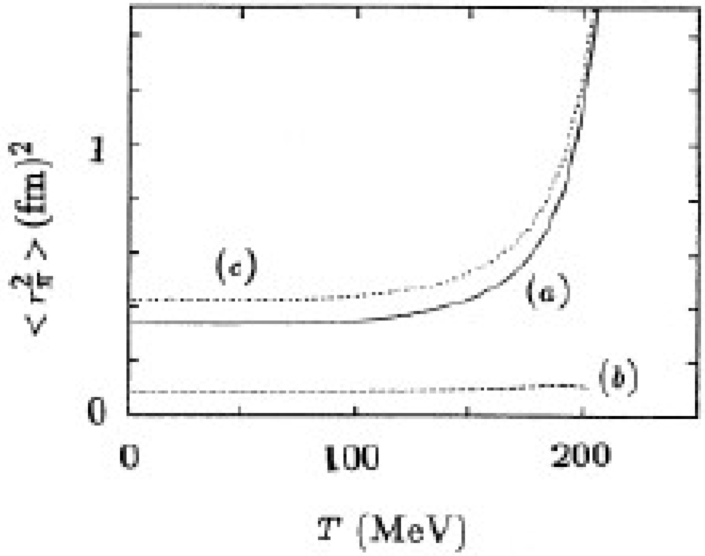
Hippe & Klevansky, PRC 52 (1995) 2172

$$r_\pi^2(T,\mu) = \frac{3}{4\pi^2} f_\pi^{-2}(T,\mu)$$

$$f_\pi^2(T,\mu) = -m_0 \langle \bar{q}q \rangle_{T,\mu} / M_\pi^2$$

$$r_\pi^2(T,\mu) = \frac{3 M_\pi^2}{4\pi^2 m_q} \left| \langle \bar{q}q \rangle_{T,\mu} \right|^{-1}$$

$$\langle \bar{q}q \rangle = \langle \bar{q}q \rangle_{\mathrm{MF}} \left[1 - \frac{T^2}{8 f_\pi^2(T,\mu)} - \frac{\sigma_N n_{s,N}(T,\mu)}{M_\pi^2 f_\pi^2(T,\mu)} \right]$$



Mott-Anderson localization model for chemical freeze-out

DB, J. Berdermann, J. Cleymans, K. Redlich, Phys. Part. Nucl. Lett. 8 (2011) 811

Povh-Huefner law behaviour for quark exchange between hadrons

PHYSICAL REVIEW C VOLUME 51, NUMBER 5 MAY 1995

Quark exchange model for charmonium dissociation in hot hadronic matter

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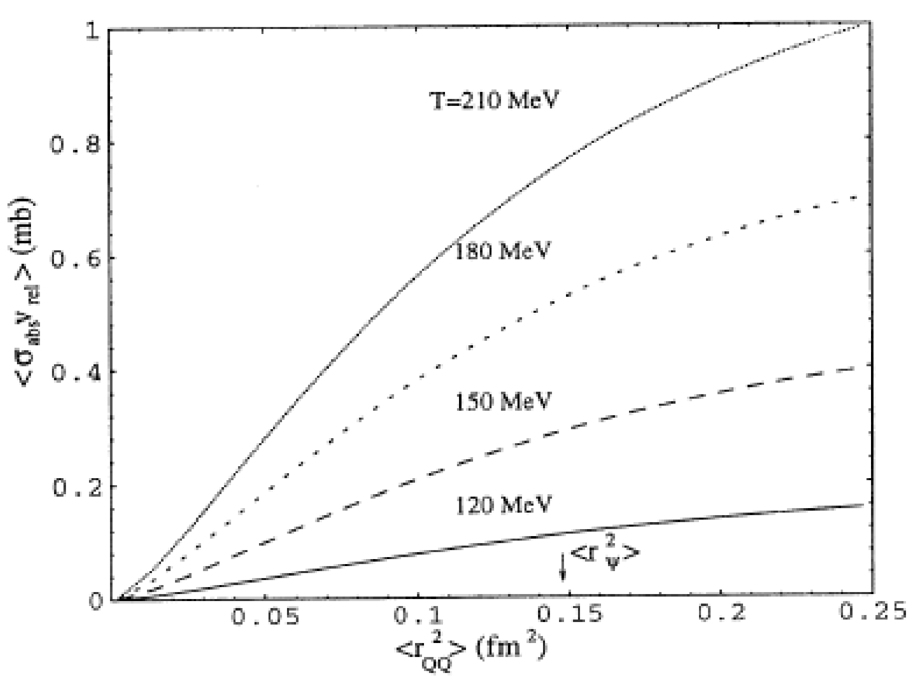
(Received 15 November 1994)



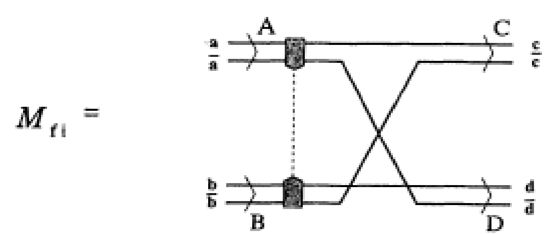
$$\langle \sigma_{\rm abs} v_{\rm rel} \rangle \propto \langle r^2 \rangle_{Q\bar{Q}} \langle r^2 \rangle_{q\bar{q}}$$

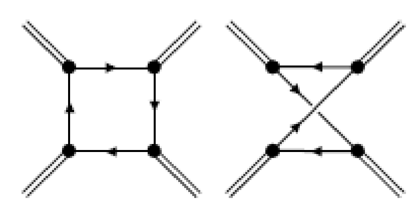
Flavor exchange processes

$$\phi + \pi \to K + \bar{K},$$

$$K^- + p \to \Lambda + X,$$
$$K^+ + p \to \Lambda + X,$$

Nonrelativistic → rel. quark loop integrals





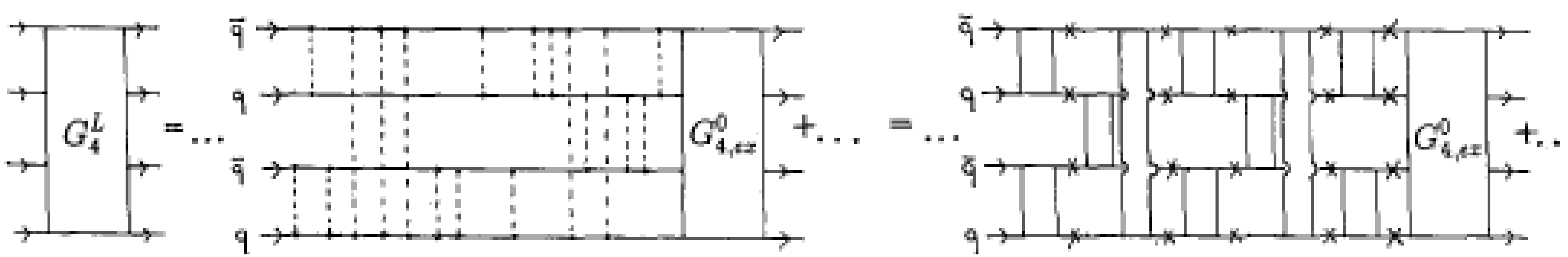
Quark exchange in meson-meson scattering

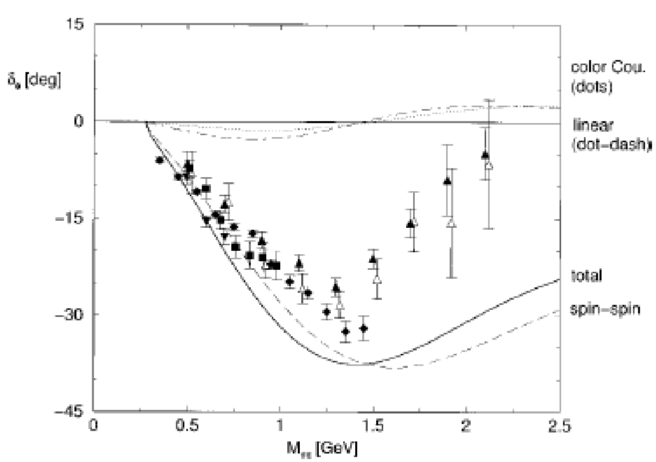
DB, G. Roepke, Phys. Lett. B 299 (1993) 332; T. Barnes et al., PRC 63 (2001) 025204

Povh-Huefner law behaviour for quark exchange between hadrons ?

$$\sigma_{ij} = \lambda \langle r_i^2 \rangle \langle r_j^2 \rangle \qquad r_\pi^2(T,\mu) = \frac{3 M_\pi^2}{4\pi^2 m_q} \left| \langle \bar{q} q \rangle_{T,\mu} \right|^{-1}$$

$$\mathcal{V}^{ss}(12, 1'2') = \frac{16}{3\sqrt{3}} C_{SFC}(12, 1'2') \frac{(2\pi)^3}{\Omega_0} \frac{\alpha_s}{3\pi^2 m_q^2} \exp\left(-\frac{1}{4b^2} \left(k'^2 + \tfrac{1}{3} k^2\right) \right) \delta_{K,K'}$$

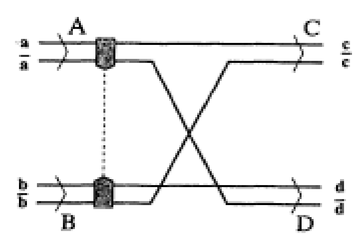


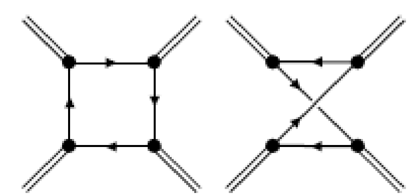


Quark exchange process in M-M scattering

Nonrelativistic → rel. quark loop integrals

M_{fi} =





Mott-Anderson localization model for chemical freeze-out

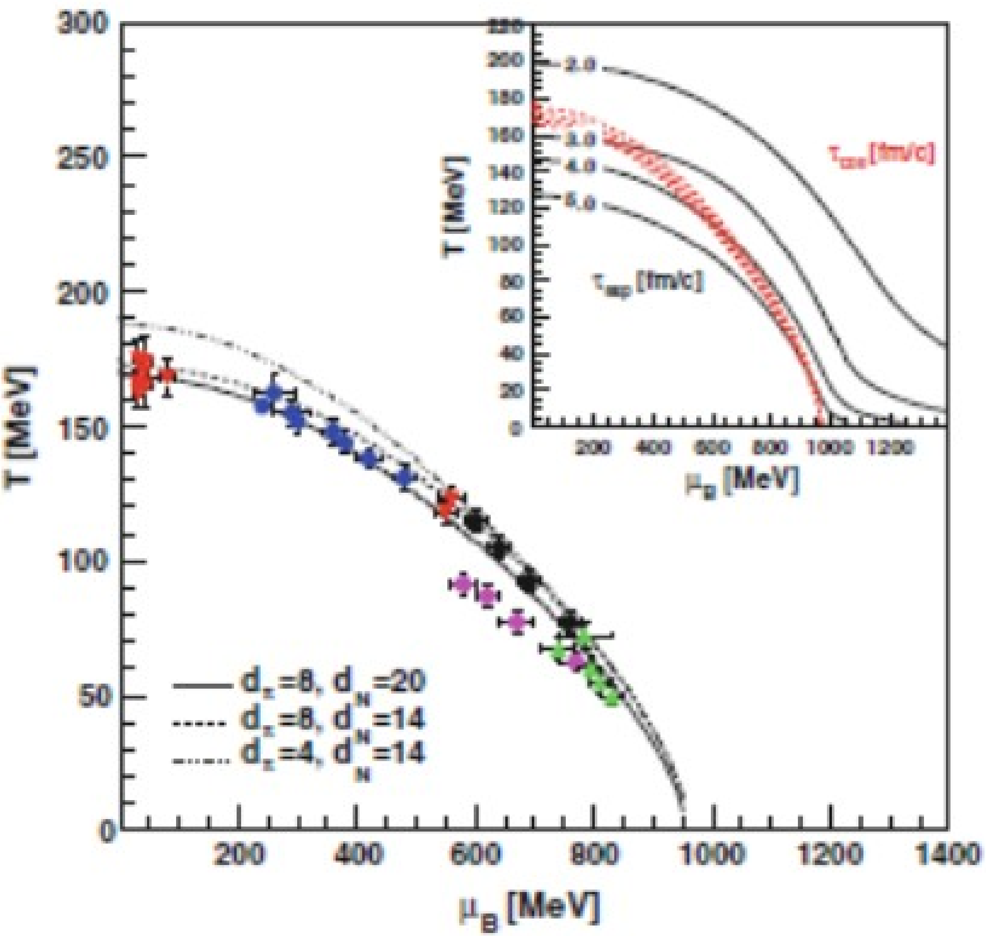
DB, J. Berdermann, J. Cleymans, K. Redlich, Phys. Part. Nucl. Lett. 8 (2011) 811

<u>Model results:</u>

$$\tau_{\rm exp}(T,\mu) = \tau_{\rm coll}(T,\mu)$$

Collision time strongly T, mu dependent !

Schematic resonance gas: dπ pions, dN nucleons

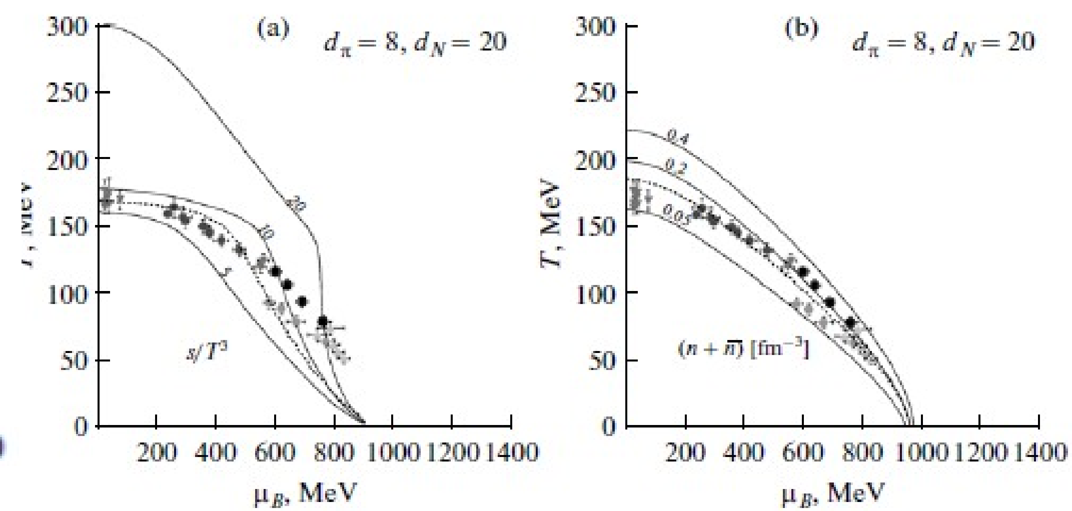


Expansion time scale from entropy conservation:

$$s(T,\mu)\,V(\tau_{\rm exp}) = {\rm const}$$

$$\tau_{\rm exp}(T,\mu) = a s^{-1/3}(T,\mu),$$

Thermodynamics consistent with phenomenological Freeze-out rules:



Mott-Anderson localization model for chemical freeze-out

DB, J. Berdermann, J. Cleymans, K. Redlich, Few Body Syst. 53 (2012) 99

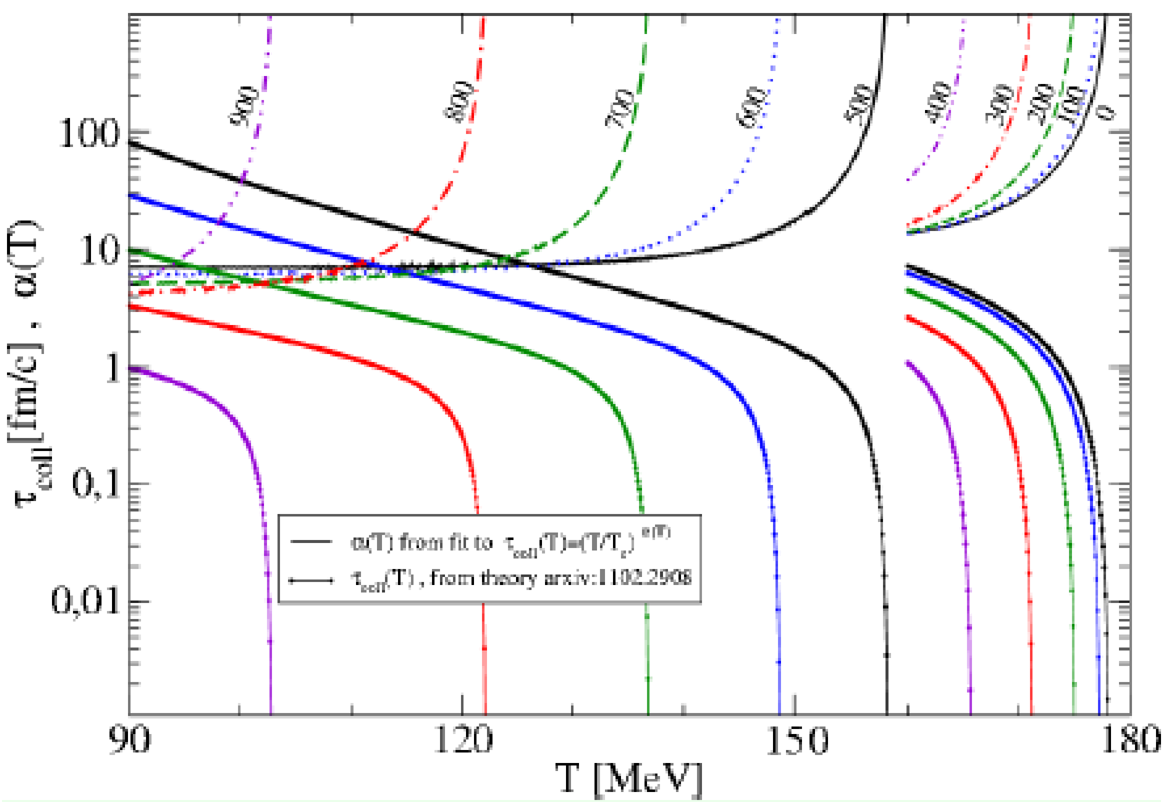
<u>Model results:</u>
Full hadron resonance gas model

$$\sigma_{ij} = \lambda \langle r_i^2 \rangle \langle r_j^2 \rangle \;;$$

$$r_\pi^2(T,\mu) = \frac{3 M_\pi^2}{4\pi^2 m_q} \left|\langle \bar{q} q \rangle_{T,\mu}\right|^{-1}$$

$$r_N^2(T,\mu) = r_0^2 + r_\pi^2(T,\mu)$$

$$\frac{\langle \bar{q}q\rangle}{\langle \bar{q}q\rangle_{\rm vac}} = 1 - \frac{m_0}{F_\pi^2 m_\pi^2}\Bigg[4N_c \int \frac{dp\, p^2}{2\pi^2}\frac{m}{\varepsilon_p}\left[f_\Phi^+ + f_\Phi^-\right]$$
$$+ \sum_{M=f_0,\omega,\ldots} d_M(2-N_s)\int \frac{dp\, p^2}{2\pi^2}\frac{m_M}{E_M(p)} f_M(E_M(p))$$
$$+ \sum_{B=N,\Lambda,\ldots} d_B(3-N_s)\int \frac{dp\, p^2}{2\pi^2}\frac{m_B}{E_B(p)}\left[f_B^+(E_B(p)) + f_B^-(E_B(p))\right]\Bigg]$$
$$- \sum_{G=\pi,K,\eta,\eta'} \frac{d_G r_G}{4\pi^2 F_G^2}\int dp\, \frac{p^2}{E_G(p)} f_G(E_G(p)).$$



Collision time follows a power law
τ_coll ~ (T/Tc)^α
with a large exponent α ~ 20

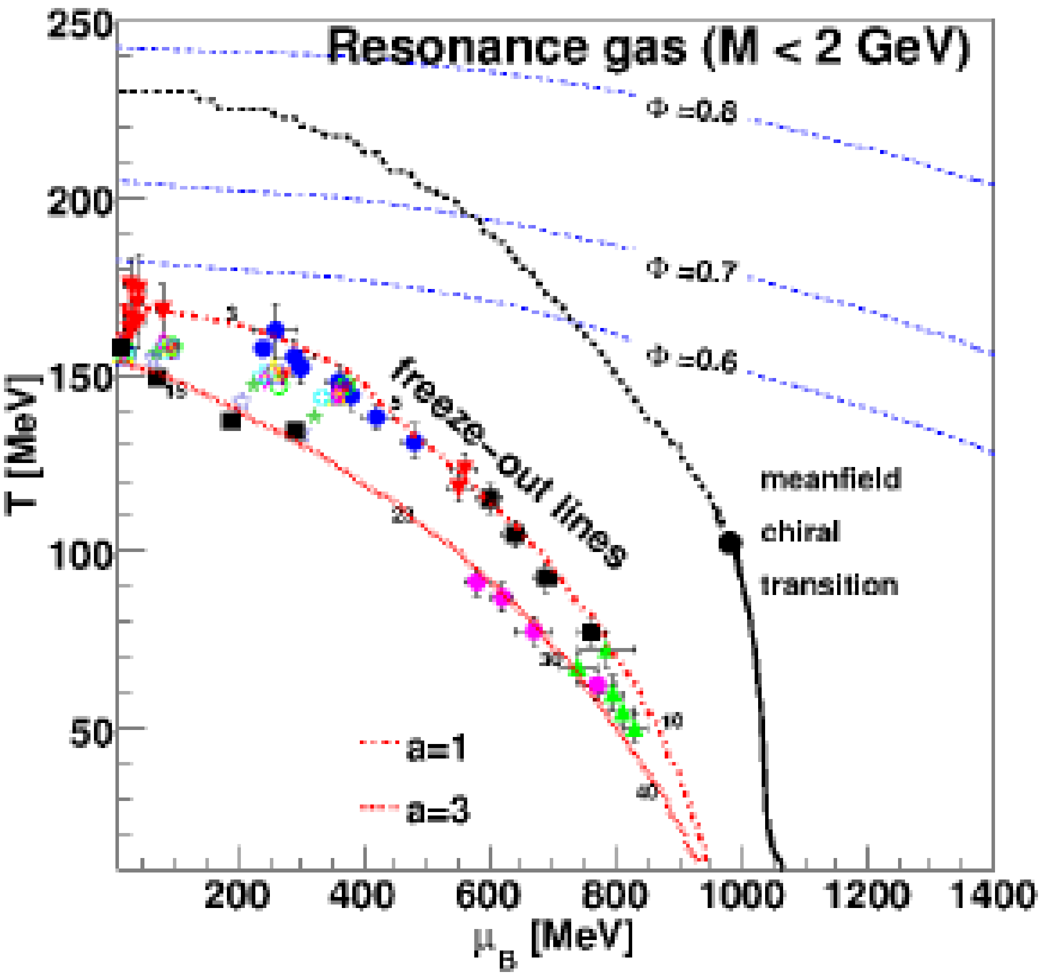
See also: P. Braun-Munzinger, J. Stachel, C. Wetterich, PLB (2004)

1. Mott-Anderson localization model for chemical freeze-out

DB, J. Berdermann, J. Cleymans, K. Redlich, Few Body Syst. 53 (2012) 99

Model results:
Full hadron resonance gas model

See also: S. Leupold, J. Phys. G (2006)



$$\frac{\langle\bar{q}q\rangle}{\langle\bar{q}q\rangle_{\rm vac}} = 1 - \frac{m_0}{F_\pi^2 m_\pi^2}\Big\{4N_c\int\frac{dp\,p^2}{2\pi^2}\frac{m}{\varepsilon_p}[f_\Phi^+ + f_\Phi^-] + \sum_{M=f_0,\omega,\ldots} d_M(2-N_s)\int\frac{dp\,p^2}{2\pi^2}\frac{m_M}{E_M(p)}f_M(E_M(p)) + \sum_{B=N,\Lambda,\ldots} d_B(3-N_s)\int\frac{dp\,p^2}{2\pi^2}\frac{m_B}{E_B(p)}[f_B^+(E_B(p)) + f_B^-(E_B(p))]\Big\} - \sum_{G=\pi,K,\eta,\eta'}\frac{d_G r_G}{4\pi^2 F_G^2}\int dp\,\frac{p^2}{E_G(p)}f_G(E_G(p)).$$

$$\sigma_{ij} = \lambda\,\langle r_i^2\rangle\langle r_j^2\rangle \quad ; \quad r_N^2(T,\mu) = r_0^2 + r_\pi^2(T,\mu)$$

$$r_\pi^2(T,\mu) = \frac{3M_\pi^2}{4\pi^2 m_q}\left|\langle\bar{q}q\rangle_{T,\mu}\right|^{-1}$$

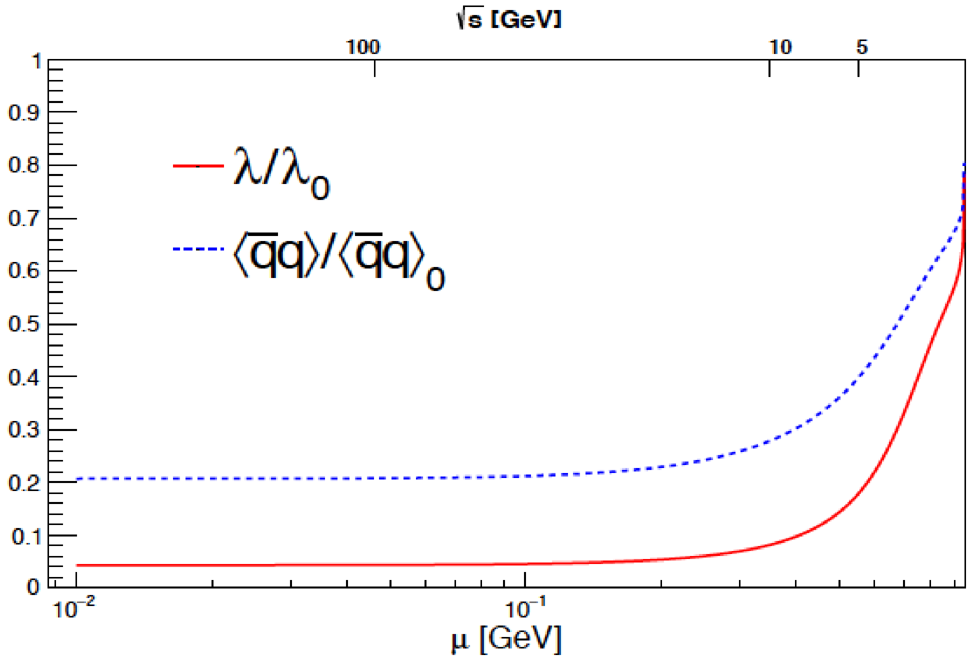
The factor a stands for the inverse system size in the formula

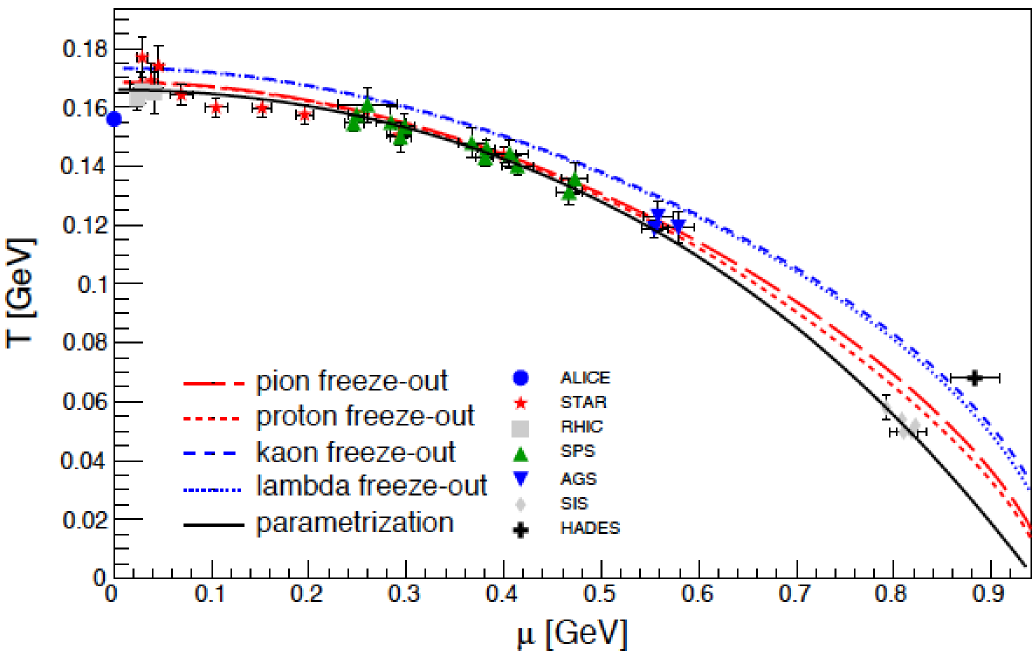
$$\tau_{\rm exp}(T,\mu) = \tau_{\rm coll}(T,\mu)$$

for the 3D expansion time scale assuming entropy conservation

Mott-Anderson localization model for K+/π+ “horn”

DB, J. Jankowski, M. Naskret, arxiv:1705.00169; arxiv:1501.01599





Full HRG model condensate;
J. Jankowski et al., Phys. Rev. D (2013)

$$\langle \bar{q}q\rangle_{T,\mu} = \langle \bar{q}q\rangle^{MF}_{T,\mu} + \sum_{h=M,B} \frac{\sigma_q^h}{m_q} n_h(T,\mu) \ ,$$

$$n_h(T,\mu) = \frac{d_h}{2\pi^2}\int_0^\infty dk k^2 \frac{m_h}{E_h}\frac{1}{e^{(E_h-\mu_h)/T} \mp 1} \ .$$

$$\tau^{-1}_{\mathrm{coll},i}(T,\mu) = \sum_j \sigma_{ij} v n_j(T,\mu) \ ; \ \ \sigma_{ij} = \lambda \langle r_i^2\rangle \langle r_j^2\rangle$$

$$\langle r_\pi^2\rangle_{T,\mu} \simeq \frac{3}{4\pi^2} f_\pi^{-2}(T,\mu) = \frac{3M_\pi^2}{4\pi^2 m_q}\left|\langle \bar{q}q\rangle_{T,\mu}\right|^{-1}$$

$$\langle r_K^2\rangle_{T,\mu} \simeq \frac{3M_K^2}{\pi^2(m_q+m_s)}\left|\langle \bar{q}q\rangle_{T,\mu} + \langle \bar{s}s\rangle_{T,\mu}\right|^{-1}$$

The factor a stands for the inverse system size in the formula

$$\tau_{\exp}(T,\mu) = \tau_{\mathrm{coll}}(T,\mu)$$

for the 3D expansion time scale assuming entropy conservation

PHYSICAL REVIEW C VOLUME 44, NUMBER 6 DECEMBER 1991

Nuclear to quark-matter transition in the string-flip model

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(Received 20 May 1991)

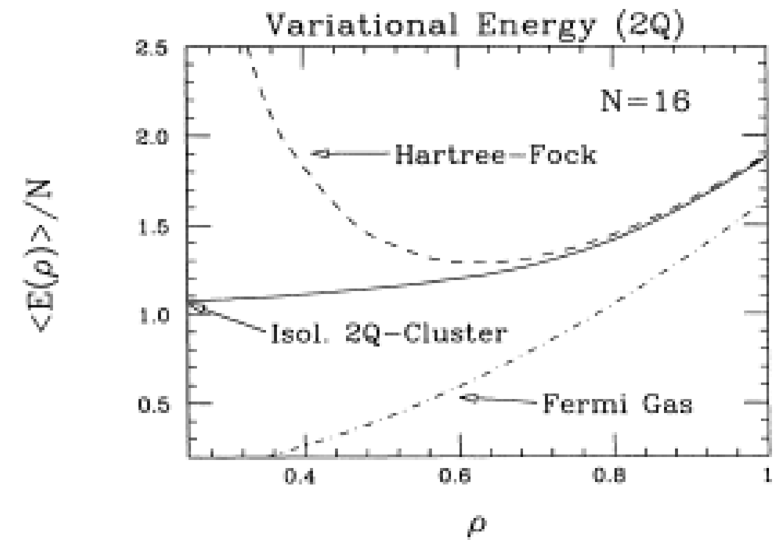
$$H = \tfrac{1}{2}P_1^2 + \tfrac{1}{2}P_2^2 + \tfrac{1}{2}P_3^2 + v(x_{12}) + v(x_{23}) + v(x_{31})$$
$$= -\tfrac{1}{2}\partial_1^2 - \tfrac{1}{2}\partial_2^2 - \tfrac{1}{2}\partial_3^2 + \tfrac{1}{2}(x_1 - x_2)^2 + \tfrac{1}{2}(x_2 - x_3)^2$$
$$+ \tfrac{1}{2}(x_3 - x_1)^2 \ . \qquad (3.1)$$

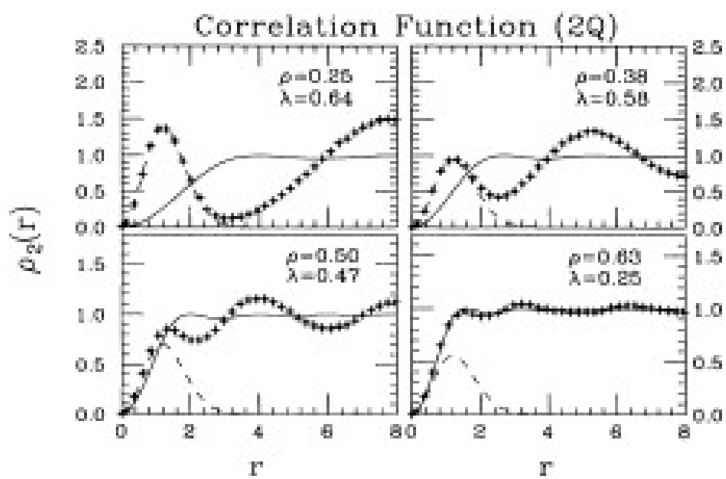
$$\psi_0(x_1, x_2, x_3) = x_{12}x_{23}x_{31}e^{-\lambda_0(x_{12}^2 + x_{23}^2 + x_{31}^2)/2} \ , \qquad (3.2)$$

$$v(x_{p_i^1 p_i^2 p_i^3}) = \tfrac{1}{2}(x_{p_i^1} - x_{p_i^2})^2 + \tfrac{1}{2}(x_{p_i^2} - x_{p_i^3})^2 + \tfrac{1}{2}(x_{p_i^3} - x_{p_i^1})^2 \ .$$

$$V(x) = \min_{[P]} V_P(x) \ . \qquad V_P(x) \equiv \sum_{i=1}^{A} v(x_{p_i^1 p_i^2 p_i^3}) \ .$$

$$E_{\rm HF}(\rho) = T_{\rm FG}(\rho) + V_{\rm HF}(\rho) \simeq \frac{\pi^2\rho^2}{6} + \frac{1}{4\rho^2} \ . \qquad (4.1)$$





Transition from ideal gas of isolated hadrons to
A Fermi gas of quarks = quark matter