

Hadrons in Hot and Dense Matter

Jochen Wambach

TU, Darmstadt and GSI

Workshop on In-Medium Hadron Physics

Giessen, Nov. 11-13, 2004

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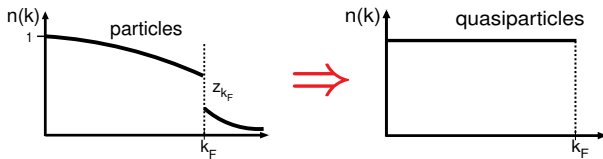
11.11. @ 11.11 am



Medium modifications

L.D Landau, Sov. Phys. JETP, 3, 920 (1956)

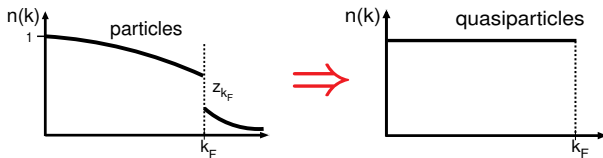
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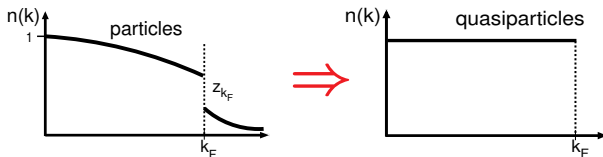


first example of an 'effective field theory'!

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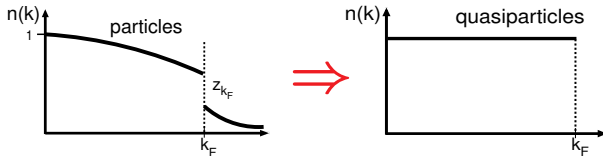
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- nucleon in nuclei (nuclear matter) as a quasiparticle, $M_N \rightarrow M_N^* \dots$

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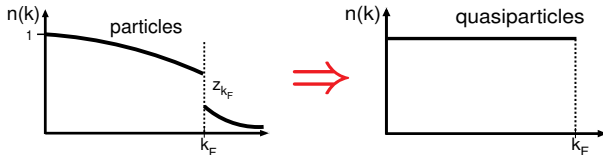
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- pions in nuclei, kaons, eta,
- vector mesons, $\rho, \omega, \phi, J/\psi \dots$
- baryonic resonances,
 $\Delta(1232), \Lambda(1405), N^*(1520), N^*(1535),$ pentaquarks...
- fast partons..

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what do we mean by medium-modifications?

how are they related to changes in the QCD vacuum?

post-Hagedorn

N. Cabbibo and G. Parisi, Phys. Lett. **59 B**, 67 (1975)

'..although the two alternatives (phase transition or limiting temperature) give rise to similar forms of the hadronic spectrum, the equation of state at high densities is radically different..'

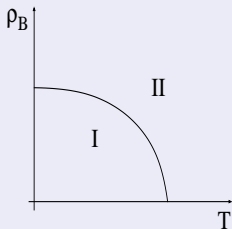
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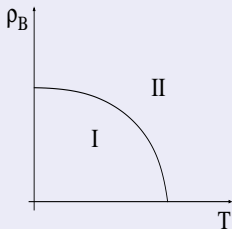
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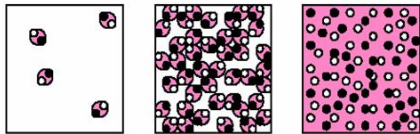
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hadrons with internal structure!

$T \Rightarrow$



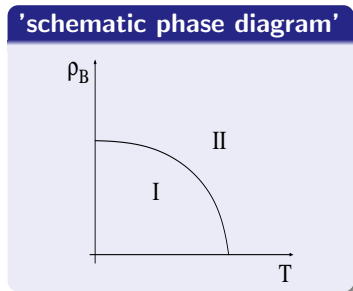
Fischer's droplet model of 2nd order transition

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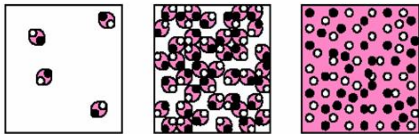
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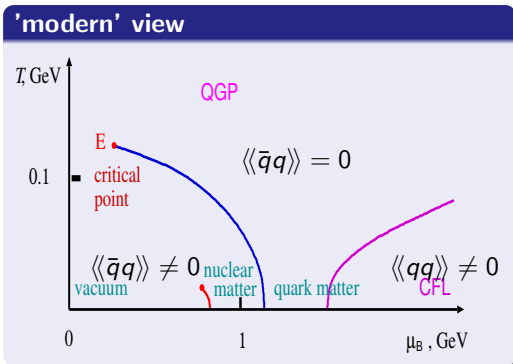
'..The true phase diagram may actually be substantially more complex, due to other kinds of transitions..'

Phase Diagram

after almost 30 years:

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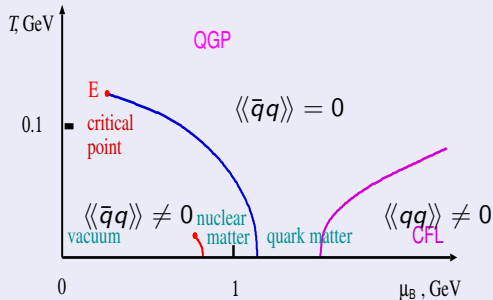


- confinement
- spontaneous chiral symmetry breaking

Phase Diagram

after almost 30 years:

'modern' view



... new questions

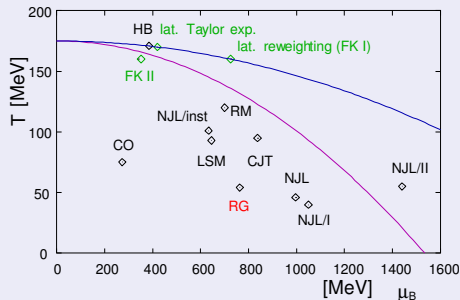
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location of the critical point



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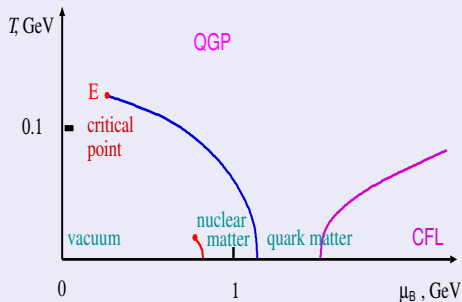
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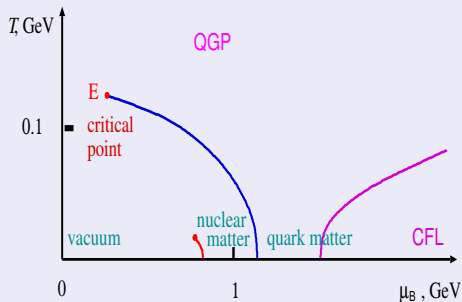
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- hadronic properties near the phase boundary

- confinement
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QCD Thermodynamics

partition function

$$\mathcal{Z}(V, T, \mu) = \text{Tr} \left[\exp \left(-\frac{1}{T} \int_V d^3x (\mathcal{H}_{\text{QCD}} - \mu_q \varrho) \right) \right]$$

equation of state

$$\epsilon \equiv \frac{E}{V} = \frac{T^2}{V} \left(\frac{\partial \ln \mathcal{Z}}{\partial T} \right)_{V, \mu} + \mu \frac{N}{V}; \quad p = T \left(\frac{\partial \ln \mathcal{Z}}{\partial V} \right)_{T, \mu}$$

free energy

$$\Omega(V, T, \mu) = -T \ln \mathcal{Z}(V, T, \mu);$$

thermodynamic limit

$$\lim_{V \rightarrow \infty} \frac{1}{V} \Omega(V, T, \mu) = -p(T, \mu)$$

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QCD condensates

$$\langle\langle \bar{q}q \rangle\rangle = \langle \bar{q}q \rangle + \frac{\partial p}{\partial m_q}; \quad \langle\langle G^2 \rangle\rangle = \langle G^2 \rangle - \frac{32\pi^2}{b} \left(\epsilon - 3p + m_q \frac{\partial p}{\partial m_q} \right)$$

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can be evaluated in lattice QCD at finite T but $\mu = 0$

Low-energy QCD

in the hadronic phase of QCD eigenstates are (color-singlet) **hadrons**

partition function

$$\mathcal{Z} = \sum_h \langle h | e^{-\beta(E_h - \mu_h N_h)} | h \rangle$$

'resonance gas'

$$p_{\text{rg}}(T, \mu) = T \sum_h \frac{g_h}{2\pi^2} \int_0^\infty dp p^2 \eta_h \ln(1 + \eta_h e^{-\beta(E_h - \mu N_h)})$$

where $E_h = \sqrt{\vec{p}^2 + M_h(m_q)^2}$ and $\eta_h = -1$ for bosons and $+1$ for fermions

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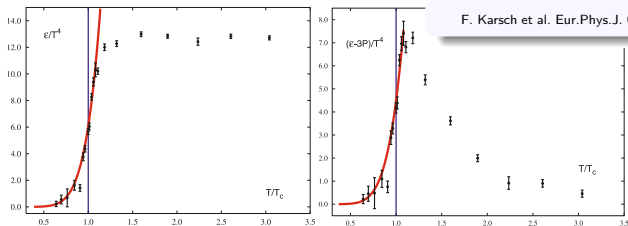
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sum mesonic and baryonic species up to ~ 2 GeV (more than 1000 resonances)



Hadrochemistry

also revealed by 'hadron abundances' in chemical freeze out

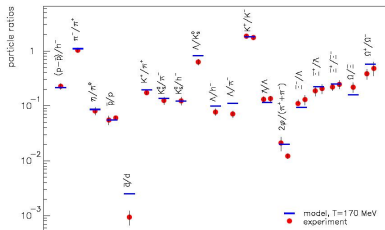
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$$\Omega(T, \mu) = \sum_h \Omega_h(T, \mu) \implies n_h(T, \mu) = \frac{\partial \Omega_h(T, \mu)}{\partial \mu_B}$$

also conserve isospin and strangeness $\rightarrow \mu_1, \mu_S$

particle ratios (Pb-Pb @ 158 GeV/nucleon)



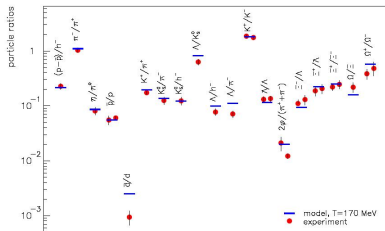
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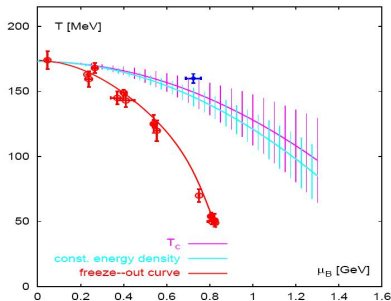
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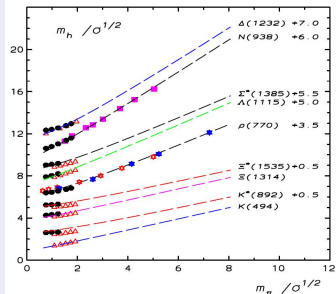
P. Braun-Munzinger et al. arXiv:nucl-th/0304013

universal freeze-out curve



Condensate evolution

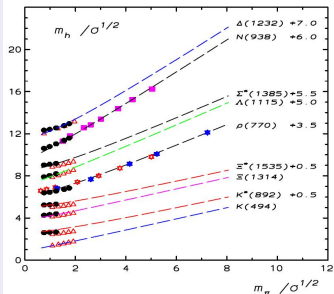
quark mass dependence (lattice fit)



F. Karsch et al. Eur.Phys.J. C29 (2003) 549

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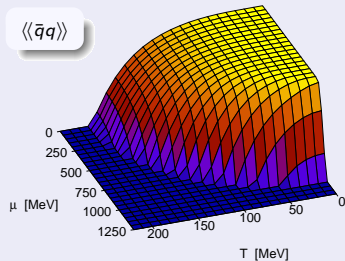
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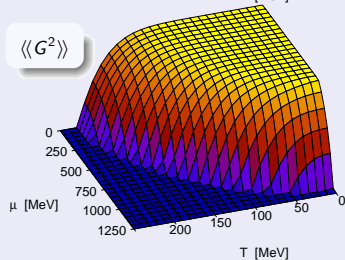
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in-medium condensates

$\langle\langle \bar{q}q \rangle\rangle$



$\langle\langle G^2 \rangle\rangle$

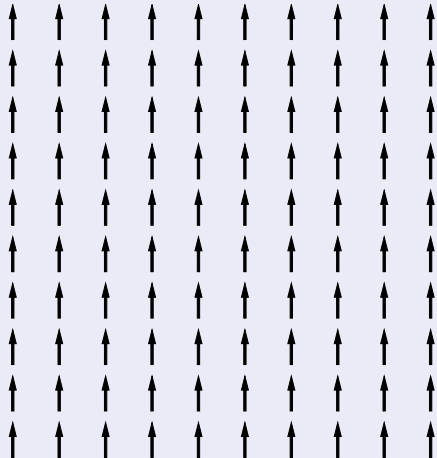


Chiral condensate

$$\frac{\langle\langle \bar{q}q \rangle\rangle}{\langle \bar{q}q \rangle} = 1 - \sum_h \frac{\Sigma_h \varrho_h^s(T, \mu)}{F_\pi^2 M_\pi^2}$$

$$\Sigma_h = m_q \frac{\partial M_h}{\partial m_q}; \quad \varrho_h^s(T, \mu) = -\frac{\partial p(T, \mu)}{\partial M_h}$$

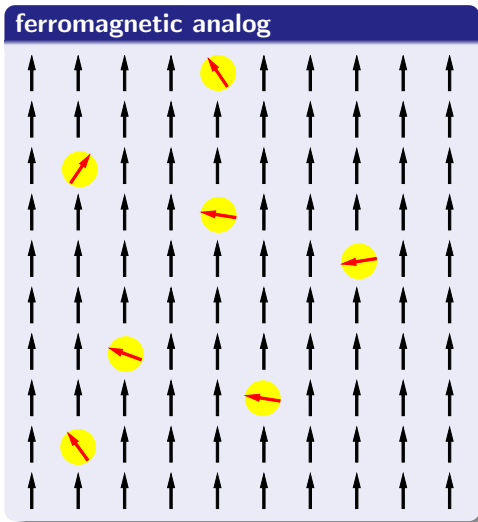
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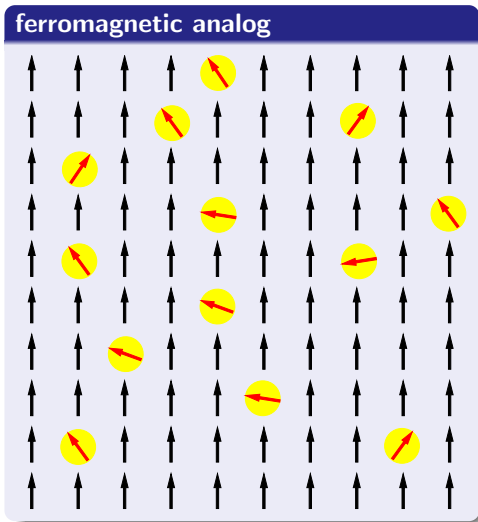
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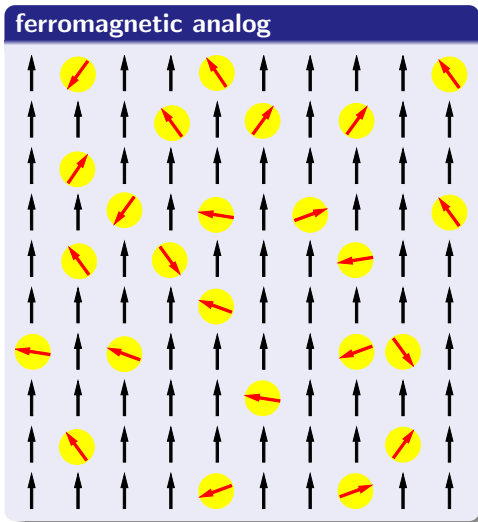
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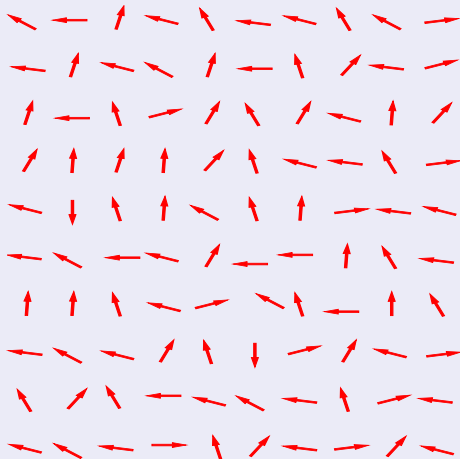


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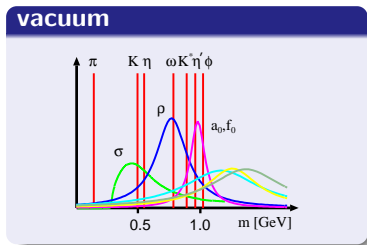
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hadrons as elementary excitations (fluctuations) of the

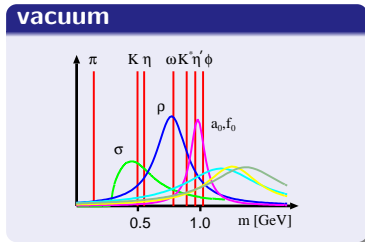


detailed hadron spectroscopy

MAMI, ELSA, TNJAF, COSY, JHF....

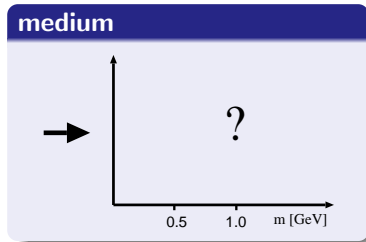
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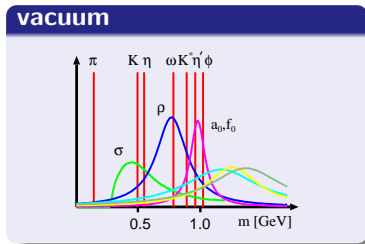


matter under extreme conditions

GSI, CERN SpS, RHIC, LHC

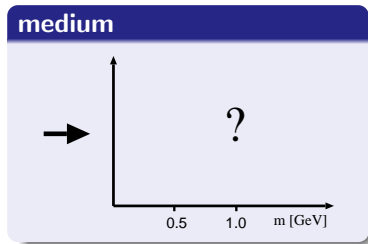
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changes in $\Omega(T, \mu)$ and therefore in the QCD condensates are reflected in measurable hadronic properties!

- identical spectral functions for channels of opposite parity
- if hadrons are made of 'constituent' quarks with $M_h \propto \langle \bar{q}q \rangle$ all masses should drop
- 'melting of $\bar{q}q$ bound state (J/Ψ suppression)
-

Formal connection

hadrons in the medium described by **two-point correlation functions**
thermal averages of composite **current operators**

mesons: $J_i(x) = \bar{q}(x)\Gamma_i q(x), \quad \Gamma_i = 1, \gamma^\mu, \gamma^5, \gamma^\mu \gamma^5 \dots$

baryons: $J_i(x) = \epsilon_{abc} q^a(x) C \gamma_\mu q^b(x) \gamma^5 \gamma^\mu q^c(x) \dots$

act as external sources

$$\mathcal{Z}[\eta] = \text{Tr} \exp \left[-\beta (H_{QCD} - \sum_i \int d^4x \eta_i(x) J_i(x)) \right]$$

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(isothermal) susceptibilities:

$$\chi_{ij}(x, x') = -\frac{\delta^2 \Omega[\eta]}{\delta \eta_i(x) \delta \eta_j(x')} = \beta (\langle \langle J_i(x) J_j(x') \rangle \rangle - \langle \langle J_i(x) \rangle \rangle \langle \langle J_j(x') \rangle \rangle)$$

(retarded) propagator for a particle with quantum numbers i :

$$G_i(q_0, \vec{q}) = i \int d^4x e^{iqx} \theta(x_0) \chi_{ii}(x, 0) = (q_0^2 - \vec{q}^2 - M_i^2 - \Pi_i(q_0, \vec{q}))^{-1}$$

How to 'detect' χ symmetry restoration?

order parameter: $\langle\langle \bar{q}q \rangle\rangle$ chiral symmetry
no order parameter for deconfinement!

Order parameter fluctuations	Hadronic world
$\langle\langle J_S(x)J_S(0) \rangle\rangle - \langle\langle J_{PS}(x)J_{PS}(0) \rangle\rangle$	$M_{f_0}(600) \rightarrow M_\pi(138)$
$\langle\langle V_\mu^a(x)V_\mu^a(0) \rangle\rangle - \langle\langle A_\mu^a(x)A_\mu^a(0) \rangle\rangle$	$M_{a_1}(1250) \rightarrow M_\rho(770)$
$\langle\langle \Psi_+(x)\Psi_+(0) \rangle\rangle - \langle\langle \Psi_-(x)\Psi_-(0) \rangle\rangle$	$M_{S_{11}}(1535) \rightarrow M_p(938)$

→ 'soft-mode spectroscopy'

transient phenomena in HIC!

Interacting matter

- resonance gas description equivalent to interacting matter with fewer degrees of freedom

$$\rho(E) = (4\pi i)^{-1} \text{Tr} \left[S^\dagger(E) \overleftrightarrow{\frac{\partial}{\partial E}} S(E) \right]_c$$

R. Dashen et al. Phys.Rev. **187** 349 (1969)

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building blocks: Goldstone bosons and (heavy) baryons

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\eta}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta}{\sqrt{6}} \end{pmatrix} \quad \Psi = \begin{pmatrix} \frac{1}{\sqrt{6}}\Lambda + \frac{1}{\sqrt{2}}\Sigma^0 & \Sigma^+ & p \\ \Sigma^- & \frac{1}{\sqrt{6}}\Lambda - \frac{1}{\sqrt{2}}\Sigma^0 & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda \end{pmatrix}$$

Chiral perturbation theory

with:

$$U(x) = \exp(i\lambda^a \phi_a(x)/F_\pi) \in SU(3)$$

effective Lagrangian:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{Gb}}(U, \partial U) + \mathcal{L}_{\text{B}}(\Psi, U, \partial U)$$

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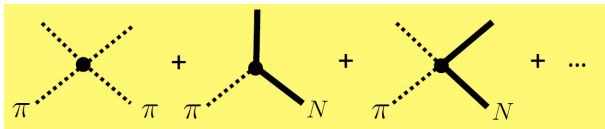
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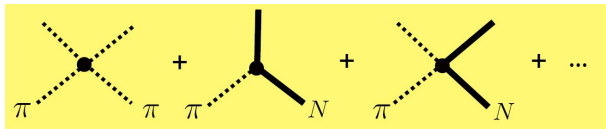
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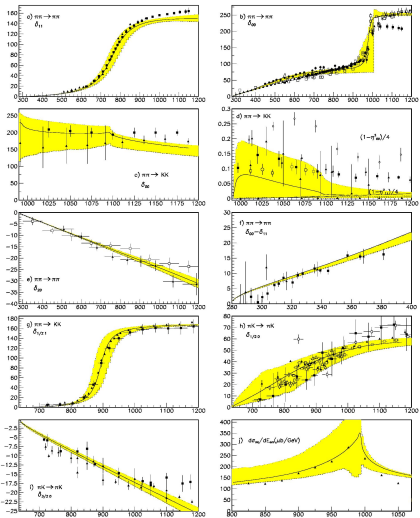
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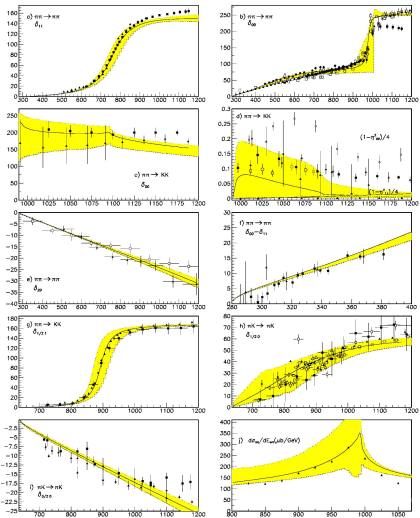
- 'unitarize' to extend to higher energies

Meson-Meson scattering

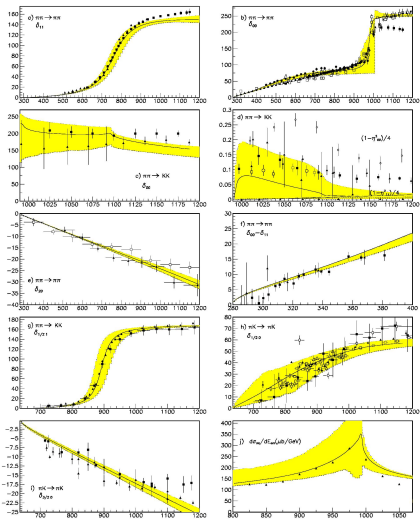


Meson-Meson scattering

→ similar results for baryons



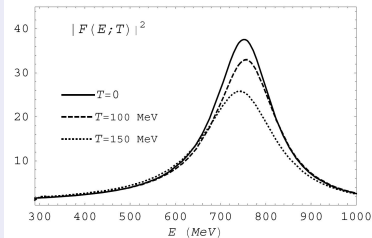
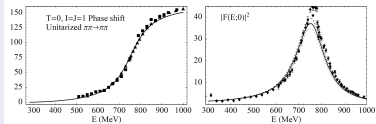
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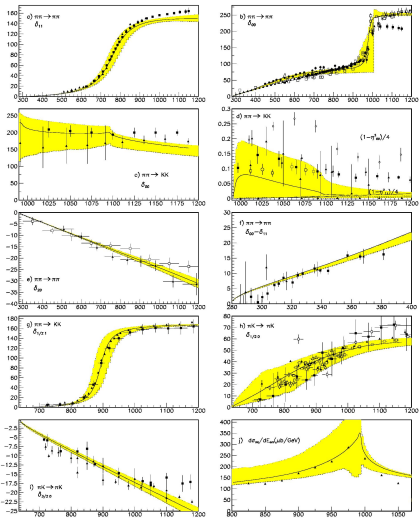
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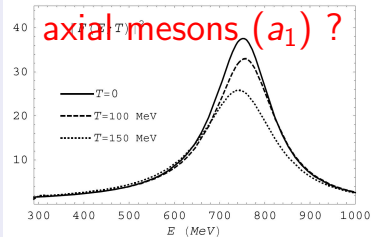
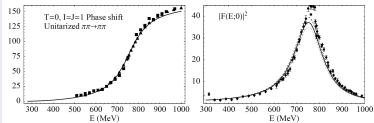
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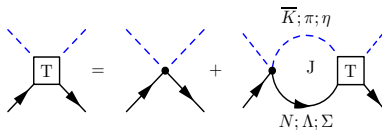
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relevant for kaon production in HIC and the interior of neutron stars

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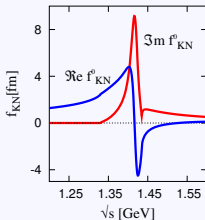
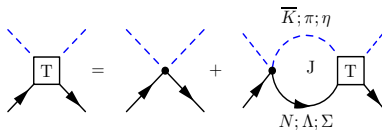
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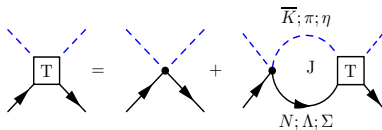


T. Roth et al. to be published

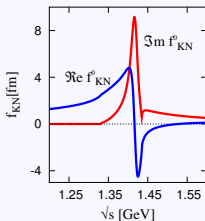
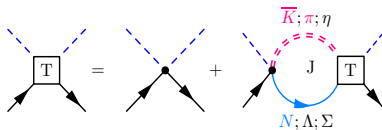
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- 2 in-medium scattering:

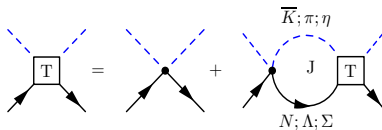


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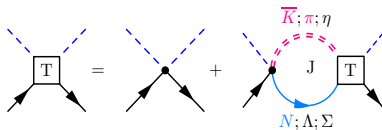
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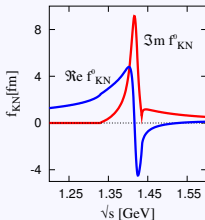
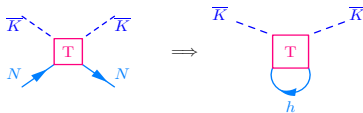
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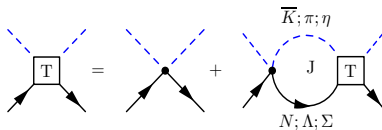


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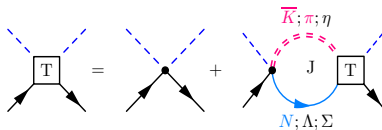
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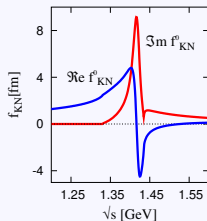
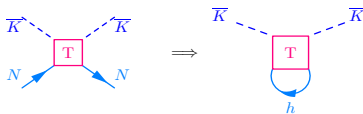
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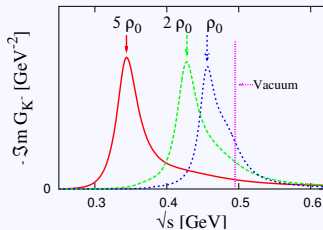
- ② in-medium scattering:



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kaon condensation unlikely in neutron stars!

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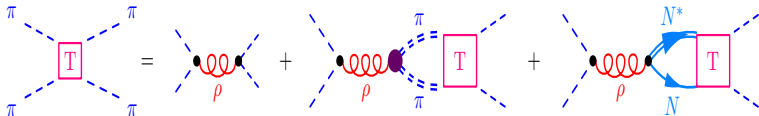
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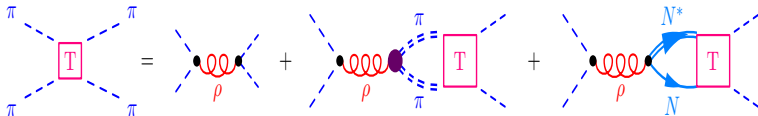
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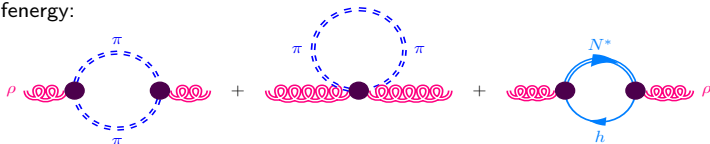
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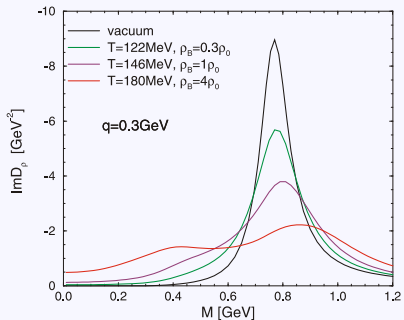
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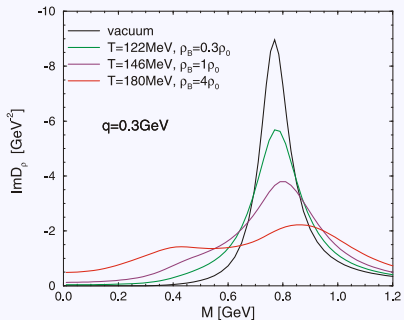
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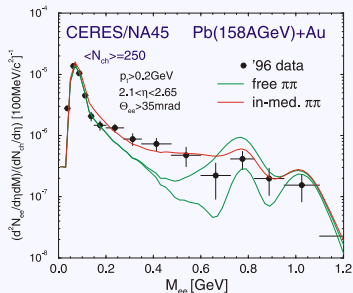
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Rho mesons in matter



M. Urban et al. NPA 673 (2000) 357



R.Rapp, J.W. Adv.Nucl.Phys. 25 (2000) 1

baryons are most important!

Summary

- hot and dense hadronic matter behaves like a 'resonance gas'
- changes of the vacuum structure \longrightarrow 'defects'
how do hadron masses depend on the light quark masses?
- how to construct the phase transitions?
- hadrons as 'elementary excitations'
- resonance gas \iff interacting system with fewer degrees of freedom
- 'unitarized ChPT' \rightarrow dynamical resonances
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