Dileptons and the In-Medium Modification of Hadrons

Jochen Wambach
TU Darmstadt and GSI

GSI Discussion Forum, Feb. 27, 2007

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- the mean free path of photons and dileptons in hot and dense matter is very large ($10^2 - 10^4$ fm)
- good probes on the medium because of weak final-state interaction
  - 'thermometer' for the system
  - quark-hadron phase transition (Feinberg, Shuryak)
  - restoration of chiral symmetry (Brown, Rho, ..)
- can infer the electromagnetic current-current correlation function

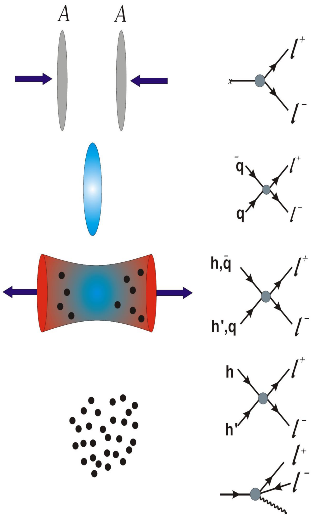
$$\Pi^{\mu\nu}_{elm}(q,\mu,T) = -i\int d^4x\ \Theta(t)e^{iqx}\langle\langle j^{\mu}_{elm}(x)j^{\nu}_{elm}(0)\rangle\rangle$$

$$j^{\mu}_{elm} = \sum_i e_i\bar{q}_i(x)\gamma^{\mu}q_i(x)$$

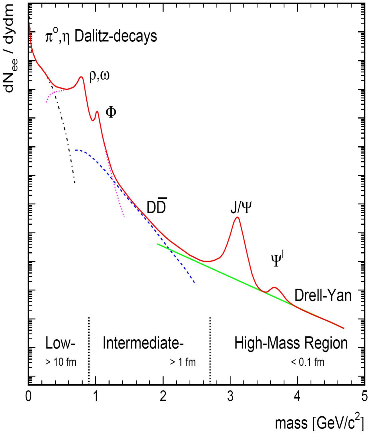
- space-time evolution needed (fireball, hydro, transport)

Dilepton Sources

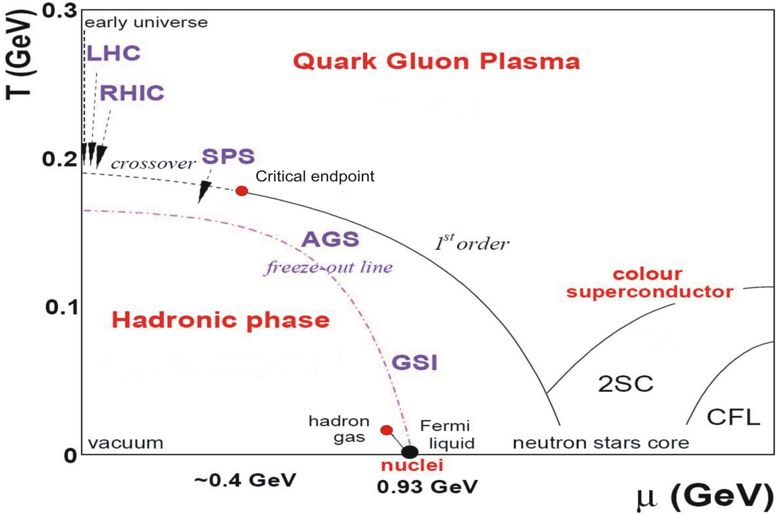
Sources of Dileptons



Dilepton Spectrum (schematic):



Exploring the Phase Diagram



QCD Vacuum

quark content of the current:

$$j^{\mu}_{elm} = \frac{2}{3}\bar{u}\gamma^{\mu}u - \frac{1}{3}\bar{d}\gamma^{\mu}d - \frac{1}{3}\bar{s}\gamma^{\mu}s$$

decomposition into hadrons:

$$j^{\mu}_{elm} = j^{\mu}_{\rho} + j^{\mu}_{\omega} + j^{\mu}_{\phi}$$

$$j^{\mu}_{\rho} = \frac{1}{2}\left(\bar{u}\gamma^{\mu}u - \bar{d}\gamma^{\mu}d\right), \quad j^{\mu}_{\omega} = \frac{1}{6}\left(\bar{u}\gamma^{\mu}u + \bar{d}\gamma^{\mu}d\right), \quad j^{\mu}_{\phi} = -\frac{1}{3}\left(\bar{s}\gamma^{\mu}s\right)$$

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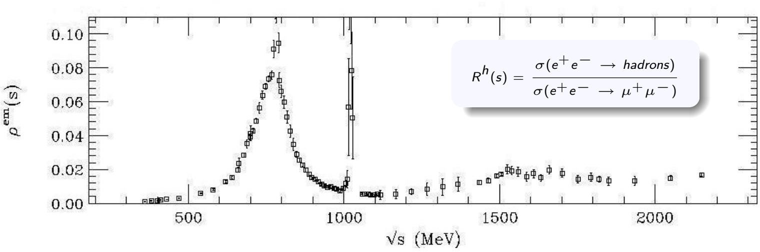
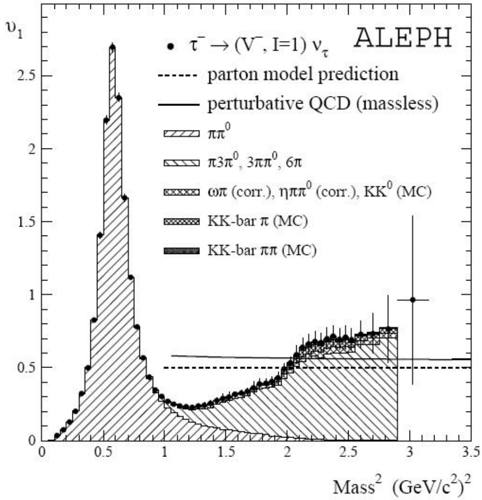


$$\int d\sqrt{s}\; R^{\rho}(s) : \int d\sqrt{s}\; R^{\omega}(s) : \int d\sqrt{s}\; R^{\phi}(s) = 9 : 1 : 4$$

QCD Vacuum

more precise data from the ALEPH collaboration



ρ meson is the 'giant dipole resonance' of the vacuum!

Simple Estimate

dilepton rate:

$$\frac{dN_{l^+l^-}}{d^4q} = \frac{\alpha_e^2}{\pi^2 M^2} \frac{1}{e^{\omega/T} - 1} \rho_{\mathrm{elm}}(\omega, |\vec{q}|)$$

ideal resonance gas:

$$\frac{dR^h}{dM^2} = R^h(M) \frac{\alpha_e}{6\pi^2} MTK_1(M/T)$$

$$R^h(M) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

ideal quark gas:

$$\frac{dR^q}{dM^2} = R^q(M) \frac{\alpha_e}{6\pi^2} MTK_1(M/T)$$

$$R^q(M) = N_c \sum_i e_i^2 = 3\left(\frac{4}{9} + \frac{1}{9} + \frac{1}{9}\right)$$

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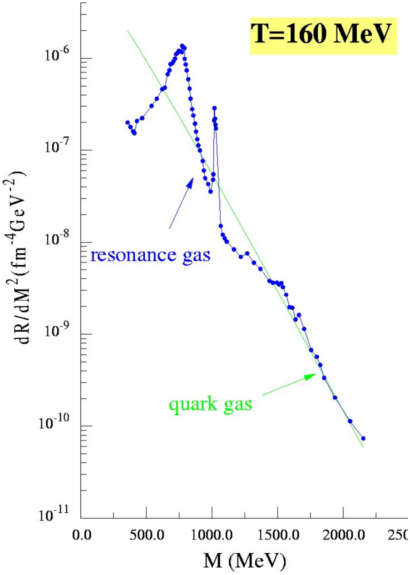


Vector Dominance Model

photons couple to hadrons via vector mesons

(Sakurai 1969):

$$j^{\mu}_{elm} = -\frac{e}{g_\rho} m_\rho^2 \rho^\mu - \frac{e}{g_\omega} m_\omega^2 \omega^\mu - \frac{e}{g_\phi} m_\phi^2 \phi^\mu$$

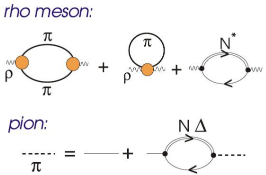
ρ meson:

$$\Pi^{\mu\nu}_{elm} \propto \langle\langle \rho^\mu \rho^\nu \rangle\rangle \to D^{\mu\nu}_\rho$$

$$D^{\mu\nu}_\rho = -\frac{P_L^{\mu\nu}}{q^2 - m_\rho^2 - \Sigma_L} - \frac{P_T^{\mu\nu}}{q^2 - m_\rho^2 - \Sigma_T} - \frac{q^\mu q^\nu}{m_\rho^2 q^2}$$

selfenergy:

$$\Sigma_{L/T} = \Sigma^M_{L/T} + \Sigma^B_{L/T}$$



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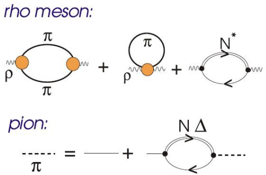
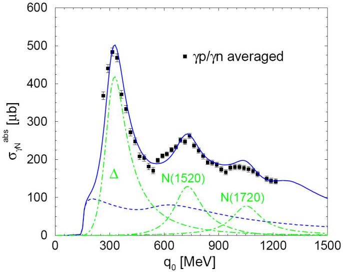
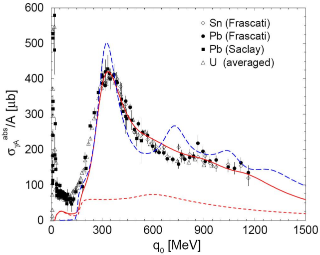


photoabsorption (nucleon)



photoabsorption (nucleus)



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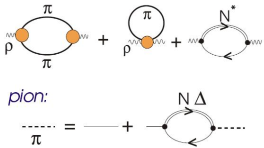
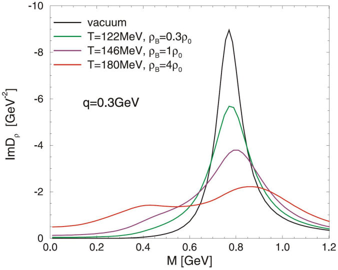
rho meson:

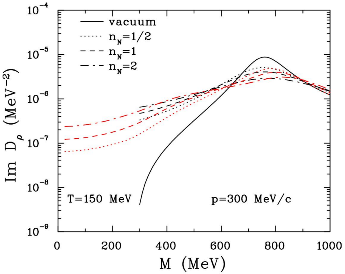
pion:



ρ meson 'melts'



consistent with other approaches



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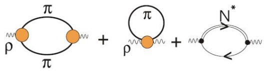

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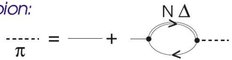
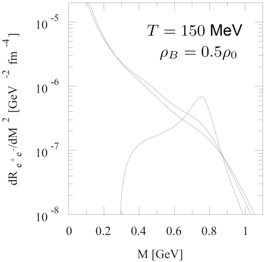
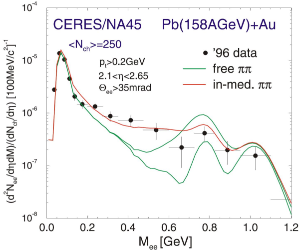


close to QGP rate with HTL



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

comparison to CERES data



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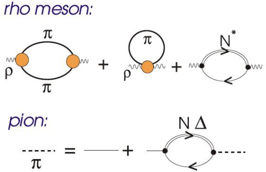
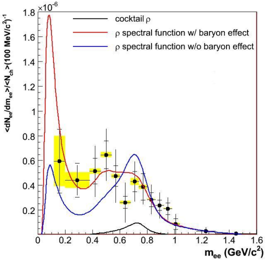
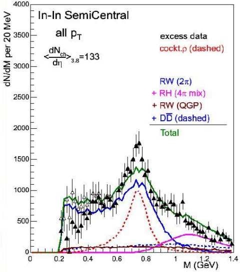


CERES (no cocktail)



comparison to NA60 data



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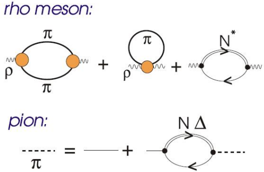
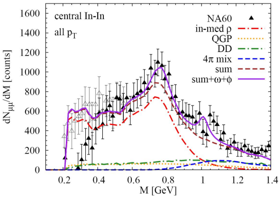
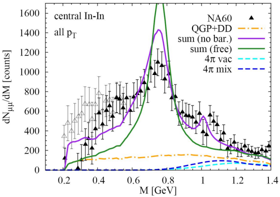


including ω and ϕ contributions



w/o baryonic effects



Chiral Symmetry

the strong interaction is described by QCD

$$\mathcal{L}_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{q}\gamma^\mu (i\partial_\mu - g_s \Lambda_a A^a_\mu) q - m_q \bar{q} q$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_s f_{abc} A^b_\mu A^c_\nu$$

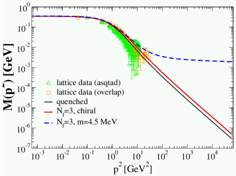
- $\mathcal{L}_{QCD}$ chirally symmetric for $m_q = 0$ $\rightarrow$ left- and right-handed quarks decouple
- chiral symmetry is spontaneously broken in the vacuum

  $\rightarrow$ condensation of quark-antiquark pairs

  $|\langle \bar{q} q \rangle| \sim (240\ \mathrm{MeV})^3 \sim 1.8 \frac{\mathrm{pairs}}{\mathrm{fm}^3}$

  $\leftrightarrow$ generation of mass

  $\Lambda_\chi \sim 1$ GeV



- vacuum no longer invariant under chiral transformations
  - (nearly) massless 'Goldstone bosons'

    $m_\pi \ll \Lambda_\chi$
  - no parity doublets in the hadron spectrum

    $m_{a_1} - m_\rho \sim 490$ MeV

Broken Chiral Symmetry

chiral symmetry breaking in the V-A sector

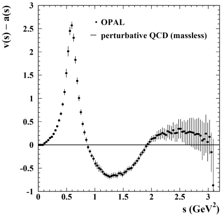
Weinberg sum rule: $(m_\pi = 0)$

$$\int_0^\infty \frac{ds}{s} \; [\rho_V(s) - \rho_A(s)] = F_\pi^2 \propto \langle \bar{q}q \rangle$$

also hold in the nuclear medium! (finite T)

$$\lim_{q \to 0} \int_0^\infty \frac{d\omega}{\omega} \; \left[\rho_V^L(\omega, q) - \rho_A^L(\omega, q)\right] = F_\pi^{*2} \propto \langle\langle \bar{q}q \rangle\rangle$$

$\langle\langle \bar{q}q \rangle\rangle \to 0 \qquad \rho_A^L \to \rho_V^L$



v: $\tau \to \nu_\tau + m\pi$
(m even)

a: $\tau \to \nu_\tau + n\pi$
(n odd)

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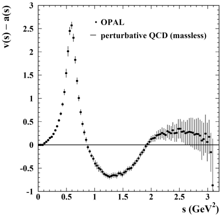
$\langle\langle \bar{q}q \rangle\rangle \to 0 \qquad \rho_A^L \to \rho_V^L$



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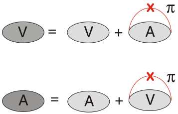
various scenarios as $T \to T_c$:

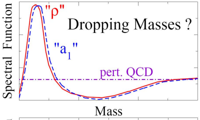


1. spectral densities mix

- Dey-Eletsky-Joffe mixing

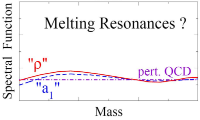
2. ρ and a_1 masses become degenerate

- both go up
- both go down (BR-scaling)
- one goes up one goes down



3. melting

- widths become so large that ρ and a_1 'melt' away



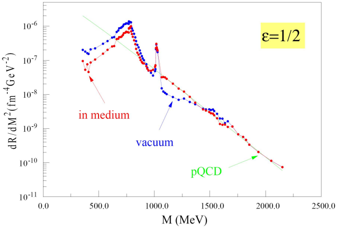
Scenarios

V-A mixing

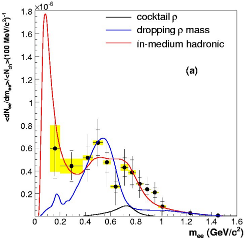
$$\rho_V^{med} = (1-\epsilon)\rho_V^{vac} + \epsilon\rho_A^{vac}$$

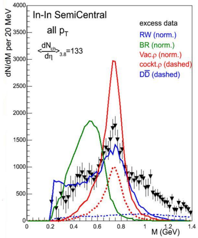
$$\rho_A^{med} = (1-\epsilon)\rho_A^{vac} + \epsilon\rho_V^{vac}$$

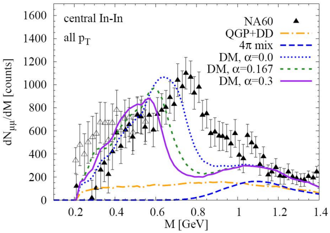
$$\epsilon = \frac{T^2}{6F_\pi^2} \qquad (m_\pi = 0)$$



dropping mass vs melting







dropping mass ruled out by data

Scenarios

'melting' of vector modes also consistent with LQCD data

partition function:

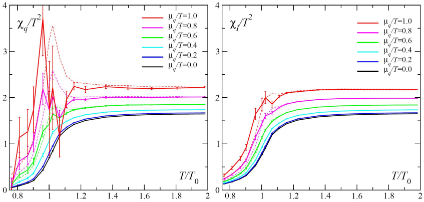
$$\mathcal{Z}(V,T,\mu_i) = \int \mathcal{D}A\mathcal{D}\bar{q}\mathcal{D}q \; \exp\left(-\int_0^{1/T} dx_0 \int_V d^3x \; \left(\mathcal{L}^E_{QCD} - \sum_i \mu_i q_i^\dagger q_i \right) \right)$$

$$\rightarrow \Omega(T,\mu_i) \equiv \ln \mathcal{Z}(V,T,\mu_i)/VT^3$$

number susceptibilites: $(\mu_q = (\mu_u + \mu_d)/2,\; \mu_I = (\mu_u - \mu_d)/2)$

$$\frac{\chi_q}{T^2} = \frac{\partial^2\Omega}{\partial(\mu_q/T)^2} \equiv 2(\chi_{ud} + \chi_{ud}), \qquad \frac{\chi_I}{T^2} = \frac{\partial^2\Omega}{\partial(\mu_I/T)^2} \equiv 2(\chi_{ud} - \chi_{ud})$$

$\propto \Pi_\omega(\omega = 0, q \rightarrow 0)$ $\qquad$ $\propto \Pi_\rho(\omega = 0, q \rightarrow 0)$



(Some) Open Issues

- broadening and chiral symmetry restoration

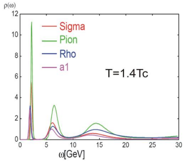
  $\longrightarrow$ consistent treatment $\Pi_V^{\mu\nu}$ and $\Pi_A^{\mu\nu}$

  $\longrightarrow$ detailed understanding of hadronic parity partners

- preformed $\bar{q}q$ and qq pairs above T_c?

  $\longrightarrow$ strongly coupled QGP near phase boundary

  $\longrightarrow$ how do these pairs influence the dilepton emission?



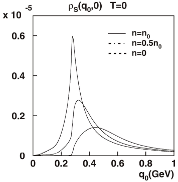
- dilepton spectra near the critical endpoint?

  at the CEP $\chi_q \propto \partial^2\Omega/\partial\mu_q^2$ and $\chi_m \propto \partial^2\Omega/\partial m_q^2$ diverge

  $\chi_m \propto \Pi_\sigma(\omega = 0, q \to 0) \quad \chi_q \propto \Pi_\omega(\omega = 0, q \to 0)$

  $\longrightarrow \rho_\sigma$ and ρ_ω^L mix!

  - longitudinal ω softens?
  - low-mass e^+e^- enhancement?



- dilepton spectra and first-order phase transition

  - large density fluctuations in phase coexistence region
  - 'critical opalescence'?

Charm Spectral Functions above T_c

LQCD results