

Meson Propagation in Nuclear Matter

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ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS



I) Strong-Interaction Matter

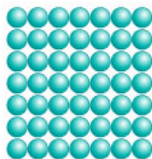
- ▶ Thermodynamics
- ▶ Phase Transitions
- ▶ Quantum-Chromodynamics
- ▶ The QCD Phase Diagram
- ▶ The Functional Renormalization Group

II) Hadrons in QCD Matter

- ▶ The Role of Photons
- ▶ Dileptons in Heavy-Ion Collisions
- ▶ Spectral Functions from the FRG

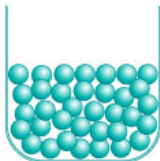
States of Matter

Physical states



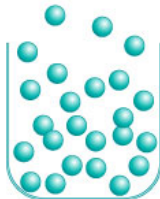
Solid

The molecules that make up a solid are arranged in regular, repeating patterns. They are held firmly in place but can vibrate within a limited area.



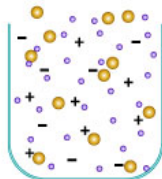
Liquid

The molecules that make up a liquid flow easily around one another. They are kept from flying apart by attractive forces between them. Liquids assume the shape of their containers.



Gas

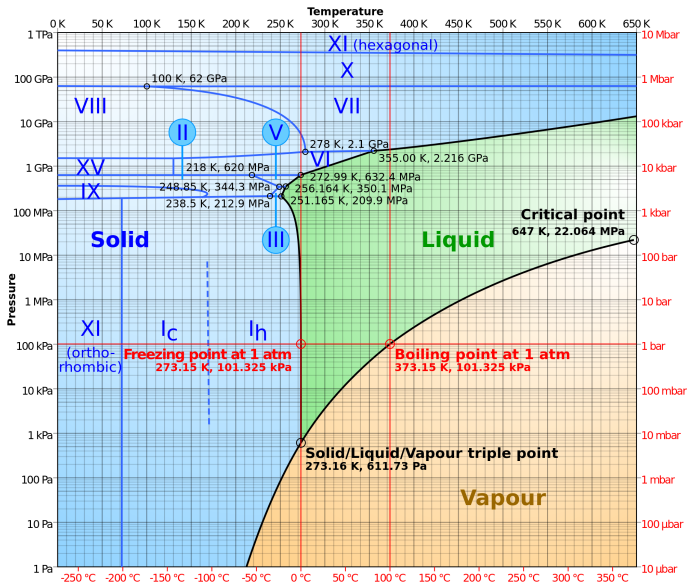
The molecules that make up a gas fly in all directions at great speeds. They are so far apart that the attractive forces between them are insignificant.



Plasma

At the very high temperatures of stars, atoms lose their electrons. The mixture of electrons and nuclei that results is the plasma state of matter.

Phase Diagram of H₂O



Landau Functions

\mathcal{L}_{eff}

Spin system in $d = 3$

Fig. 6.3(a)

Second order,

$$\frac{a}{2}\sigma^2 + \frac{b}{4}\sigma^4 - h\sigma,$$

controlled by (a, h)

Ising model

$$\begin{cases} \sigma \sim M \\ (a, h) \leftrightarrow (T, H) \end{cases}$$

Fig. 6.3(b)

First order,

$$\frac{a}{2}\sigma^2 - \frac{c}{3}\sigma^3 + \frac{b}{4}\sigma^4 - h\sigma,$$

controlled by (a, h)

Z(3) Potts model

$$\begin{cases} \sigma \sim M \\ (a, h) \leftrightarrow (T, H) \end{cases}$$

Fig. 6.5

Tricritical behavior,

$$\frac{a}{2}\sigma^2 + \frac{b}{4}\sigma^4 + \frac{c}{6}\sigma^6 - h\sigma,$$

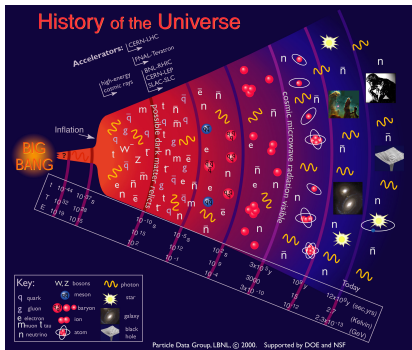
controlled by (a, b, h)

model for metamagnet

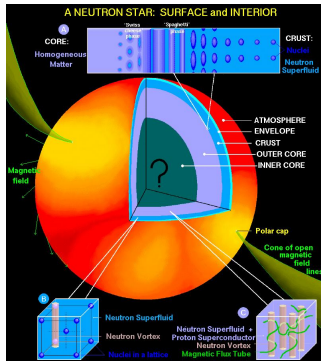
$$\begin{cases} \sigma \sim \tilde{M} \\ (a, b, h) \leftrightarrow (T, H, \tilde{H}) \end{cases}$$

Matter under Extreme Conditions

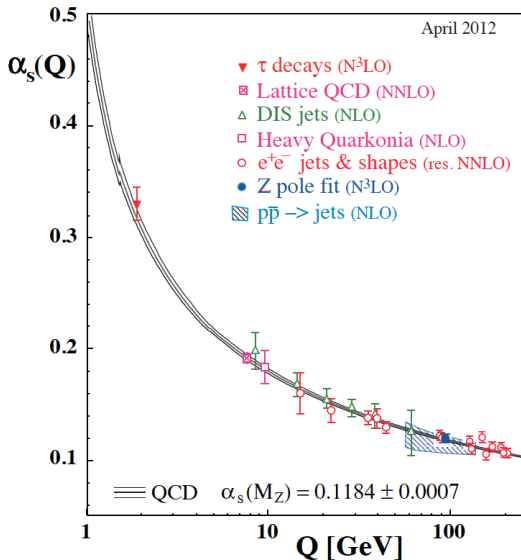
early universe (~ 10 ms)



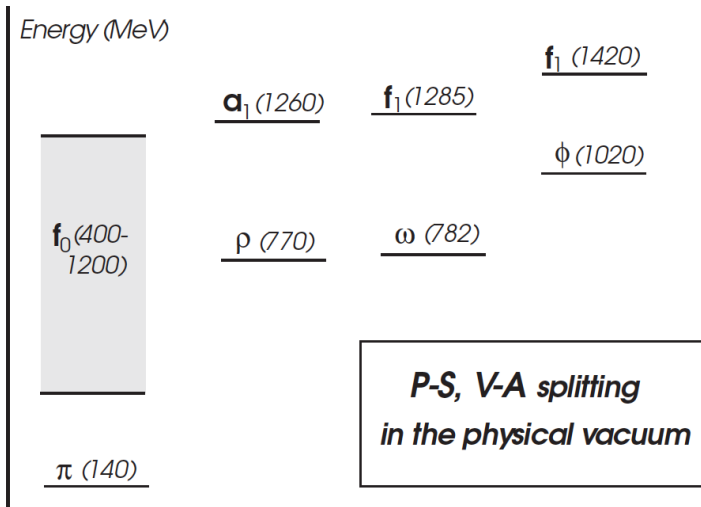
neutron star interior



Running of the Strong Coupling Constant α_s



Mass-splitting of Parity Partners



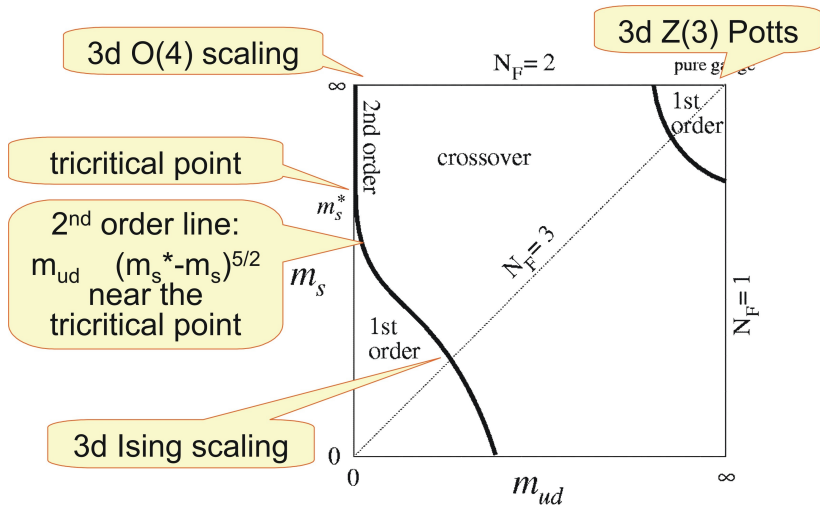
Symmetries of QCD and Breaking Pattern

symmetry	vacuum	high T	low T , high μ	order parameter	consequences
(local) color $SU(3)$	unbroken	unbroken	broken	diquark condensate	color super- conductivity
$Z(3)$ center symmetry	unbroken	broken	broken	Polyakov loop	confinement/ deconfinement
scale invariance	anomaly			gluon condensate	scale (Λ_{QCD}), running coupling
chiral symmetry $U_L(N_f) \times U_R(N_f) = U_V(1) \times SU_V(N_f) \times SU_A(N_f) \times U_A(1)$					
$U_V(1)$	unbroken	unbroken	unbroken	—	baryon number conservation
flavor $SU_V(N_f)$	unbroken	unbroken	unbroken	—	multiplets
chiral $SU_A(N_f)$	broken	unbroken	broken	quark condensate	Goldstone bosons, no degenerate states with opposite parity
$U_A(1)$	anomaly			topological susceptibility	violation of intrinsic parity

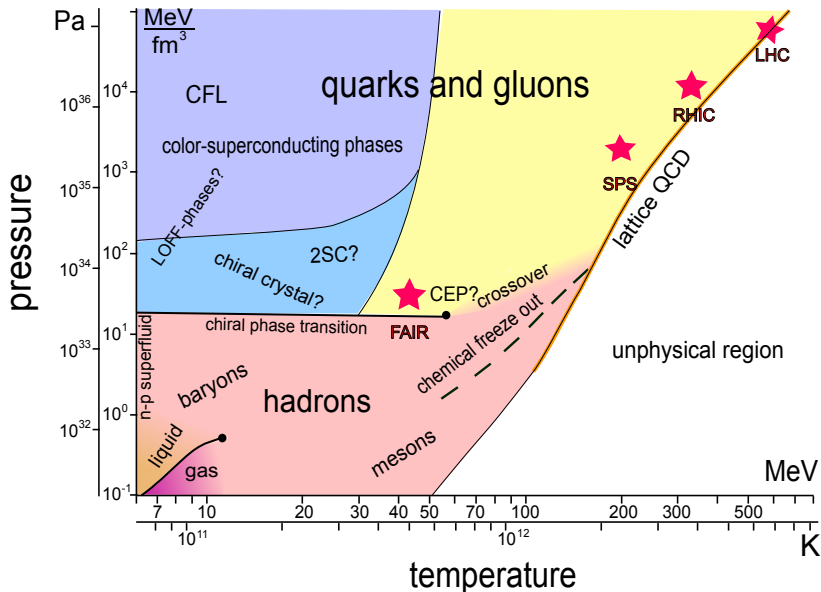
Landau Functions

\mathcal{L}_{eff}	Spin system in $d = 3$	QCD
Fig. 6.3(a) Second order, $\frac{a}{2}\sigma^2 + \frac{b}{4}\sigma^4 - h\sigma$, controlled by (a, h)	Ising model $\left\{ \begin{array}{l} \sigma \sim M \\ (a, h) \leftrightarrow (T, H) \end{array} \right.$	$N_c = 3, N_f = 2$ $\left\{ \begin{array}{l} \sigma \sim \langle \bar{u}u + \bar{d}d \rangle \\ (a, h) \leftrightarrow (T, m_{\text{ud}}) \end{array} \right.$ $N_c = 2, N_f = 0$ $\left\{ \begin{array}{l} \sigma \sim \langle L \rangle \\ (a, h) \leftrightarrow (T, 1/m_Q) \end{array} \right.$
Fig. 6.3(b) First order, $\frac{a}{2}\sigma^2 - \frac{c}{3}\sigma^3 + \frac{b}{4}\sigma^4 - h\sigma$, controlled by (a, h)	Z(3) Potts model $\left\{ \begin{array}{l} \sigma \sim M \\ (a, h) \leftrightarrow (T, H) \end{array} \right.$	$N_c = 3, N_f = 3$ $\left\{ \begin{array}{l} \sigma \sim \langle \bar{u}u + \bar{d}d + \bar{s}s \rangle \\ (a, h) \leftrightarrow (T, m_{\text{uds}}) \end{array} \right.$ $N_c = 3, N_f = 0$ $\left\{ \begin{array}{l} \sigma \sim \langle L \rangle \\ (a, h) \leftrightarrow (T, 1/m_Q) \end{array} \right.$
Fig. 6.5 Tricritical behavior, $\frac{a}{2}\sigma^2 + \frac{b}{4}\sigma^4 + \frac{c}{6}\sigma^6 - h\sigma$, controlled by (a, b, h)	model for metamagnet $\left\{ \begin{array}{l} \sigma \sim \tilde{M} \\ (a, b, h) \leftrightarrow (T, H, \tilde{H}) \end{array} \right.$	$N_c = 3, N_f = 2 + 1$ $\left\{ \begin{array}{l} \sigma \sim \langle \bar{u}u + \bar{d}d \rangle \\ (a, b, h) \leftrightarrow (T, m_s, m_{\text{ud}}) \\ (a, b, h) \leftrightarrow (T, \mu, m_{\text{ud}}) \end{array} \right.$

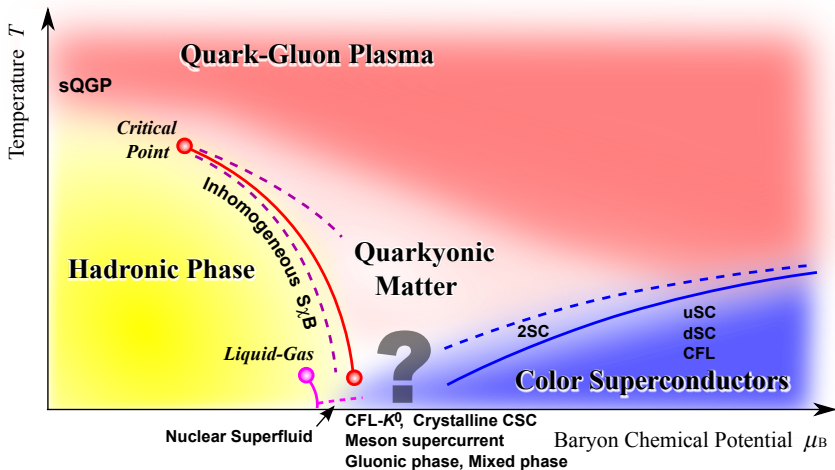
'Columbia' Plot



Phase Diagram of QCD Matter

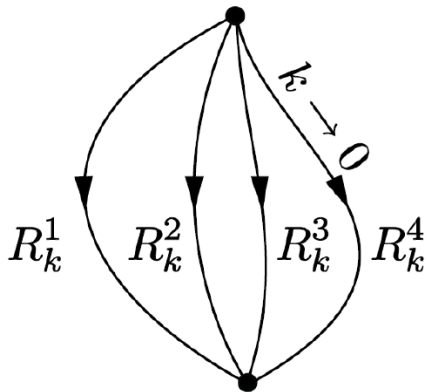


Phase Diagram of QCD Matter



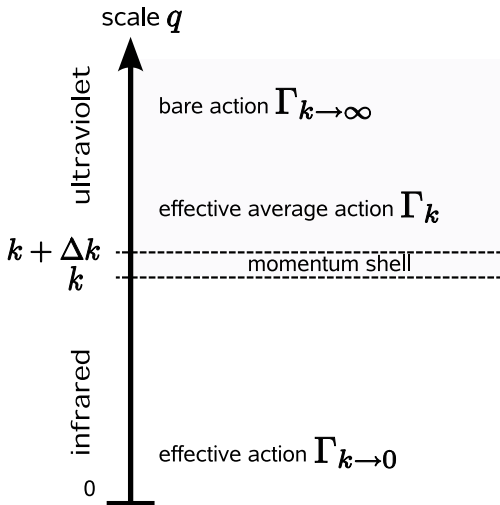
Flow

bare action $S_\Lambda \equiv \Gamma_{k \rightarrow \infty}$



effective action $\Gamma_{k \rightarrow 0}$

Flow

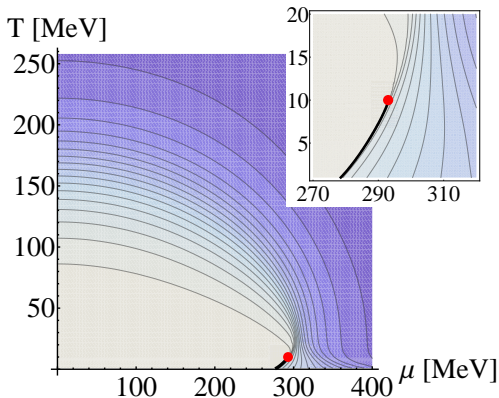


Momentum Flow of the Effective Potential

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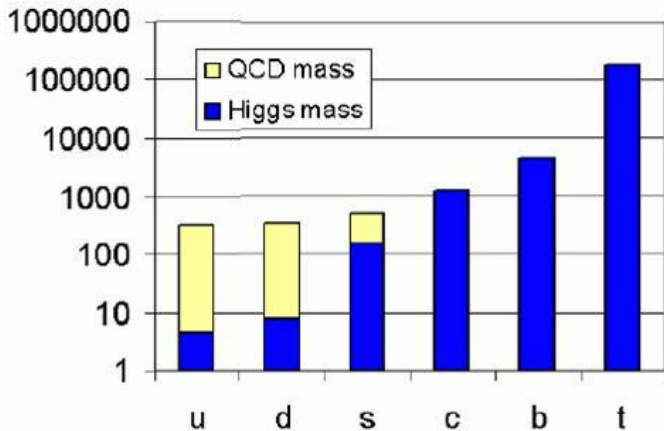
Phase diagram of the Quark-Meson Model

- ▶ chiral order parameter σ_0 decreases towards higher T and μ
- ▶ a crossover is observed at $T \approx 175$ MeV and $\mu = 0$
- ▶ critical endpoint (CEP) at $\mu \approx 292$ MeV and $T \approx 10$ MeV
- ▶ vacuum: $\sigma_0 = 93.5$ MeV, $m_\pi = 138$ MeV, $m_\sigma = 509$ MeV, $m_q = 299$ MeV

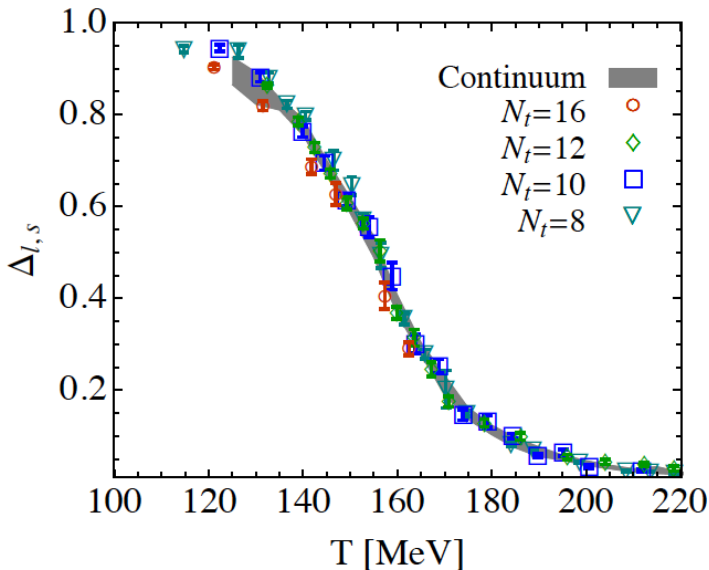


[R.-A. T., N. Strodthoff, L. v. Smekal, and J. Wambach, Phys. Rev. D **89**, 034010 (2014)]

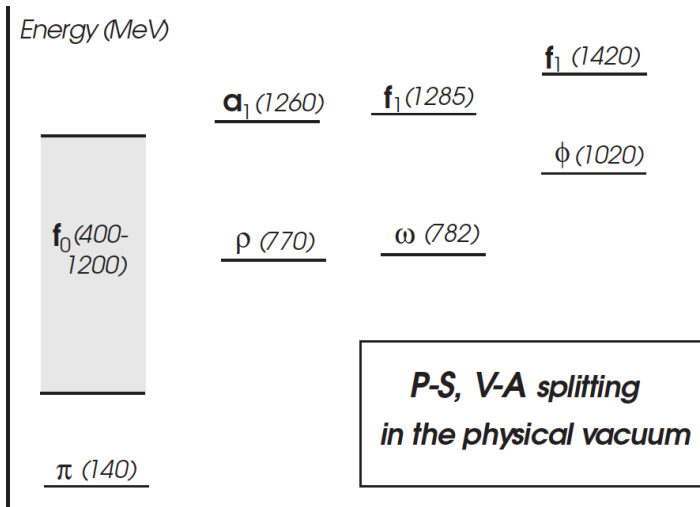
Generation of Mass in QCD



Temperature Evolution of the Chiral Condensate



Mass-splitting of Parity Partners

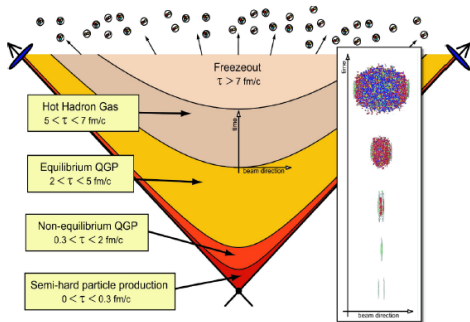


Heavy-ion Collisions and Photons

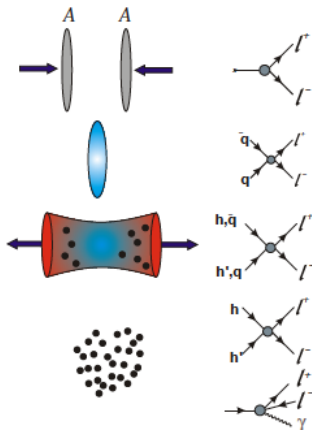
as compared to the size of the fireball **photons have a long mean free path**

→ leave the interaction zone undisturbed

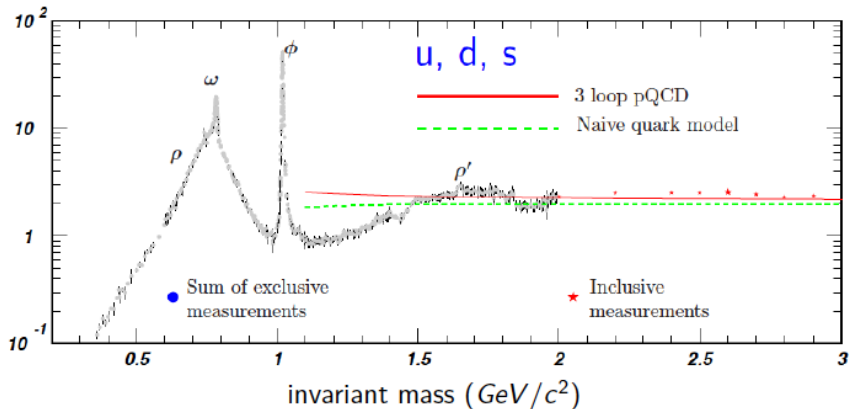
E. Feinberg 1976, E. Shuryak 1978



Sources of Dileptons



e^+e^- - annihilation in the vacuum

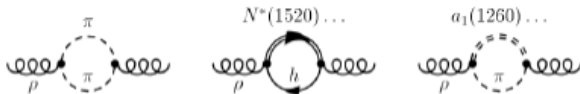


$$\text{quarks : } \mathcal{R}^q = N_c \sum_i e_i^2 = 3 \left(\frac{4}{9} + \frac{1}{9} + \frac{1}{9} \right) = 2$$

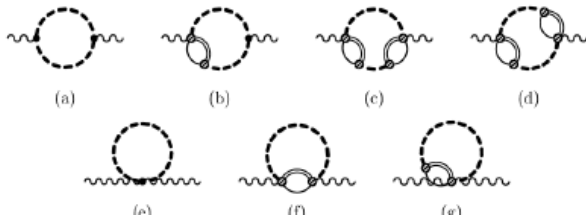
Vector-meson Selfenergies

ρ -meson selfenergy:

$$\Sigma_{\rho}^{L/T} = \Sigma_{\rho\pi\pi}^{L/T} + \Sigma_{\rho M}^{L/T} + \Sigma_{\rho B}^{L/T}$$



vertex corrections from dressed pions:



Spectral Function

ρ -spectral functions: (low temperature)

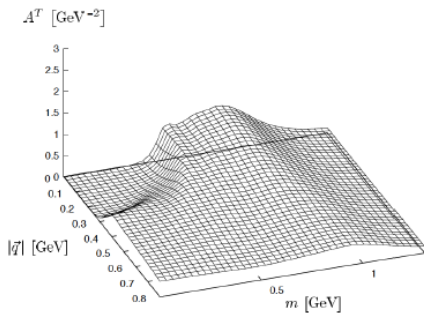
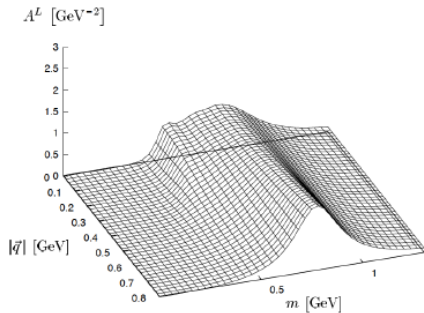
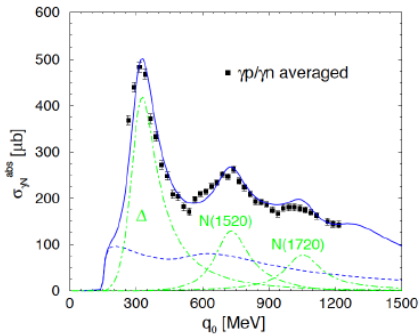


Photo-absorption as a Test

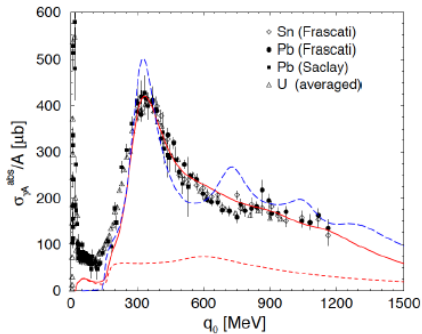
photo-absorption cross section:

$$\frac{\sigma_\gamma}{A} = -\frac{4\pi\alpha}{\omega} \frac{m_\rho^4}{g_\rho^2} \text{Im} D_\rho^T(\omega, |\vec{q}| = \omega)$$

nucleon

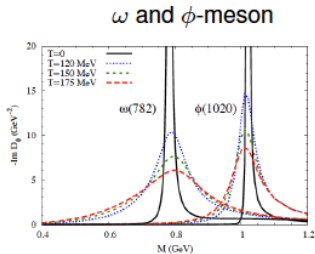
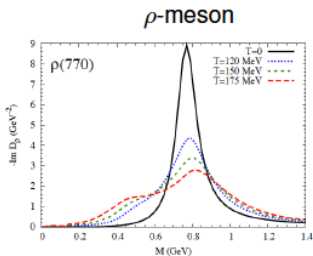


nucleus

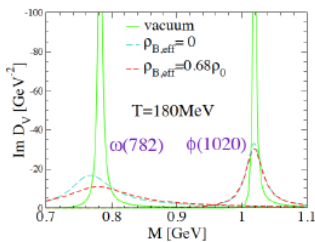
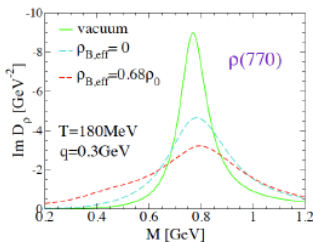


In-medium ρ -meson under HIC conditions

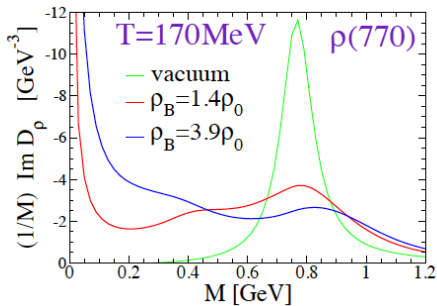
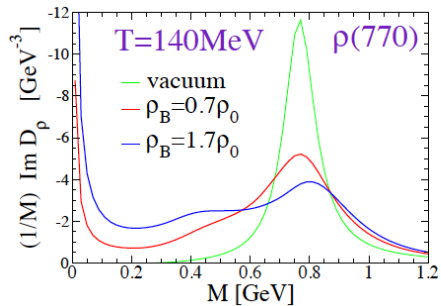
SPS
 $\sqrt{s_{NN}}=17 \text{ GeV}$



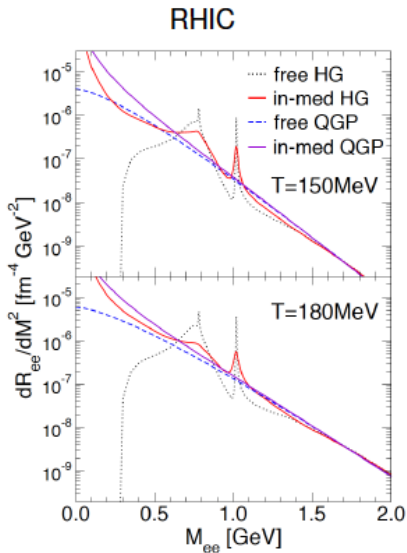
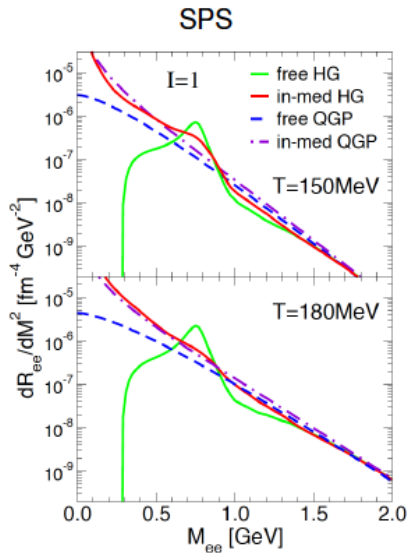
RHIC
 $\sqrt{s_{NN}}=200 \text{ GeV}$



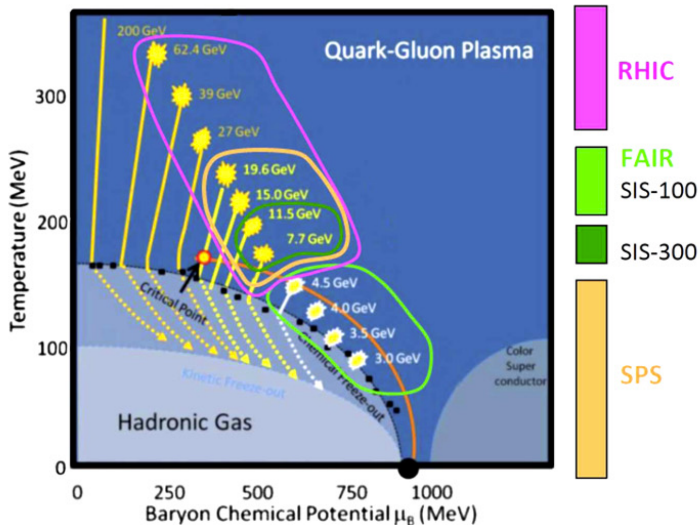
Spectral Function weighted by $1/M$



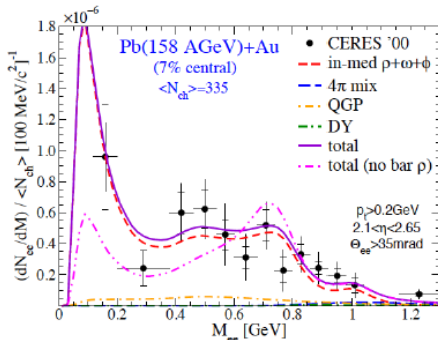
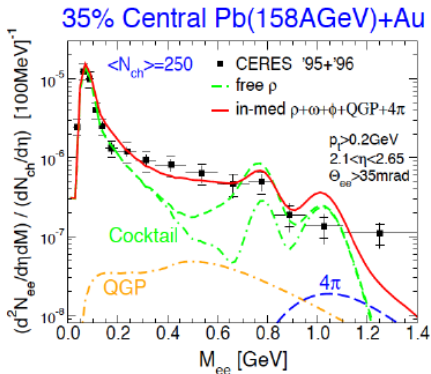
Dilepton Rates



Dilepton Rates and the Phase Diagram



Dilepton Data CERES

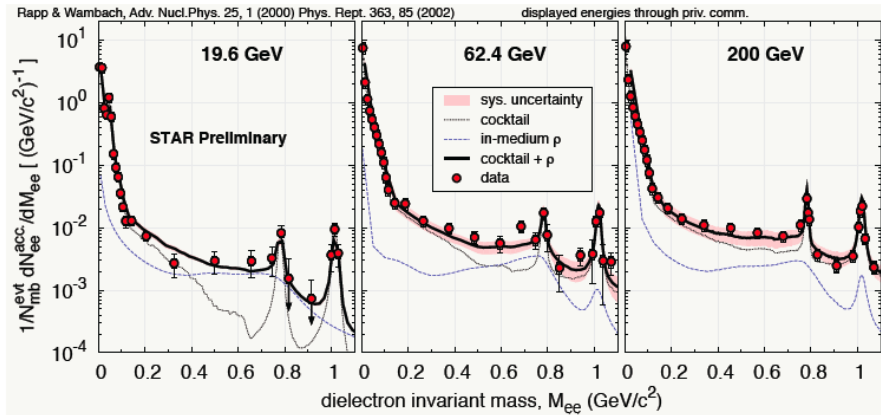


G. Agakichiev et al. (CERES/NA45 Collaboration), Eur. Phys. J. C 41, 475 (2005)

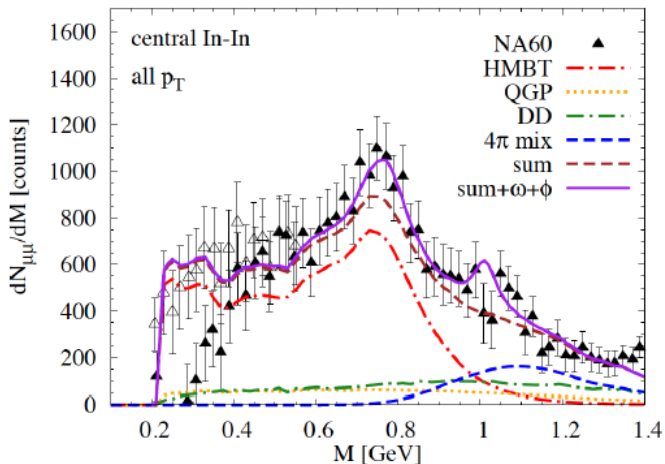
D. Adamova et al. (CERES/NA45 Collaboration), Phys. Lett. B 666, 425 (2008)

H. van Hees and R. Rapp, Nucl. Phys. A 806, 339 (2008)

Dilepton Data STAR



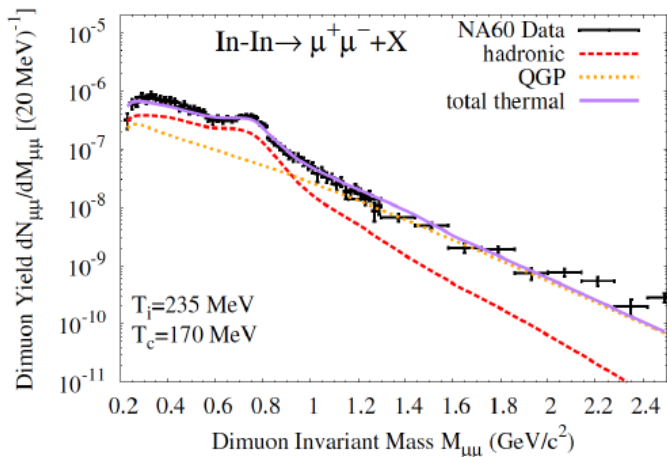
Dilepton Data SPS NA60



H. van Hees and R. Rapp, Phys. Rev. Lett. 97, 102301 (2006)

S. Damjanovic, Nucl.Phys. A774, 715 (2006)

Dilepton Data SPS NA60



R. Rapp and H. van Hees, arXiv:1411.4612 [hep-ph]

R. Arnaldi et al. (NA60 Collaboration), Eur. Phys. J. C 61, 711 (2009)

H. J. Specht (NA60 Collaboration), AIP Conf.Proc. 1322, 1 (2010)

Flow Equations for Mesonic Two-point Functions

$$\partial_k \Gamma_{k,\sigma}^{(2)} = \text{Diagram 1} + \text{Diagram 2} - \frac{1}{2} \text{Diagram 3} - \frac{1}{2} \text{Diagram 4} - 2 \text{Diagram 5}$$

Diagram 1: A dashed circle with a blue dot at the top. Two external lines labeled σ enter from the left and exit to the right, each with a blue arrow pointing into the circle.

Diagram 2: A dashed circle with a blue dot at the top. Two external lines labeled π enter from the left and exit to the right, each with a blue arrow pointing into the circle.

Diagram 3: A dashed circle with a blue dot at the top and a blue square at the bottom. Two external lines labeled σ enter from the left and exit to the right, each with a blue arrow pointing into the circle.

Diagram 4: A dashed circle with a blue dot at the top and a blue square at the bottom. Two external lines labeled π enter from the left and exit to the right, each with a blue arrow pointing into the circle.

Diagram 5: A solid circle with a red dot at the top and a red square at the bottom. Two external lines labeled σ enter from the left and exit to the right, each with a red arrow pointing into the circle.

$$\partial_k \Gamma_{k,\pi}^{(2)} = \text{Diagram 1} + \text{Diagram 2} - \frac{1}{2} \text{Diagram 3} - \frac{1}{2} \text{Diagram 4} - 2 \text{Diagram 5}$$

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Diagram 5: A solid circle with a red dot at the top and a red square at the bottom. Two external lines labeled π enter from the left and exit to the right, each with a red arrow pointing into the circle.

Flow of the Sigma and Pion Spectral Functions in vacuum at $\vec{q} = 0$

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Sigma and Pion Spectral Function

with increasing T at $\mu = 0$ and $\vec{q} = 0$

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Sigma Spectral Function with increasing T at $\mu = 0$

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Pion Spectral Function with increasing T at $\mu = 0$

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Flow Equations for Vector-Meson Two-point Functions

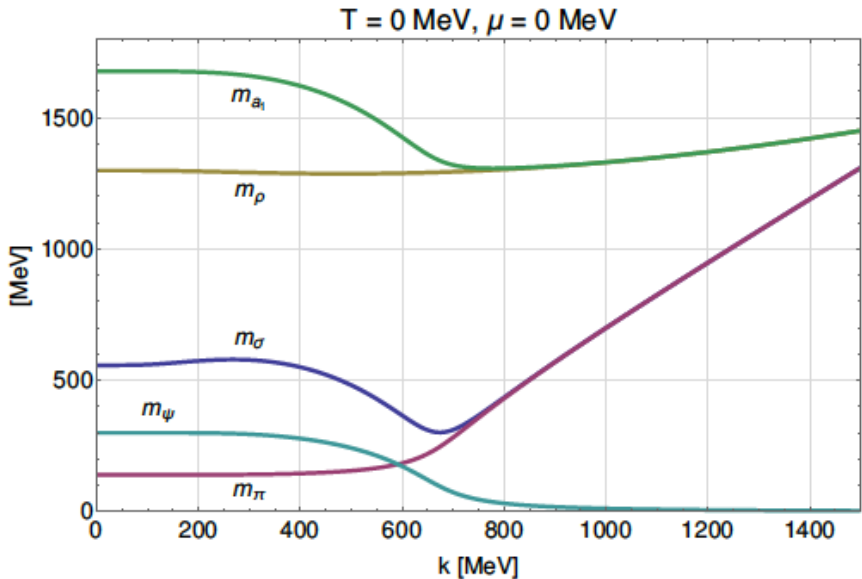
$$\partial_k \Gamma_{\rho,k}^{(2)} =$$

$$\partial_k \Gamma_{a_1,k}^{(2)} =$$

ρ and a_1 Spectral Function with increasing T at $\mu = 0$ and $\vec{q} = 0$

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ρ and a_1 Mass Flow



ρ and a_1 Pole Masses

