Meson Propagation in Nuclear Matter

Jochen Wambach

ECT*, Trento, Italy

Frontiers in Nuclear and Hadronic Physics

Florence, February 20 to March 3, 2017

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

Outline

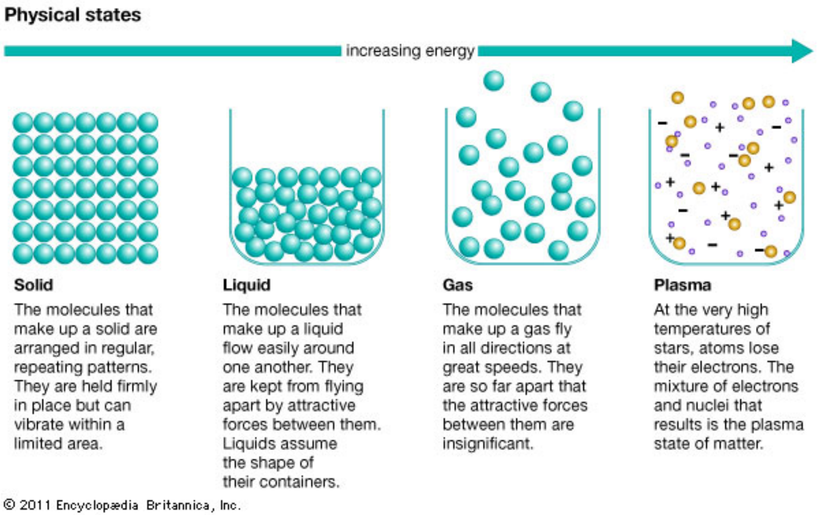
I) Strong-Interaction Matter

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

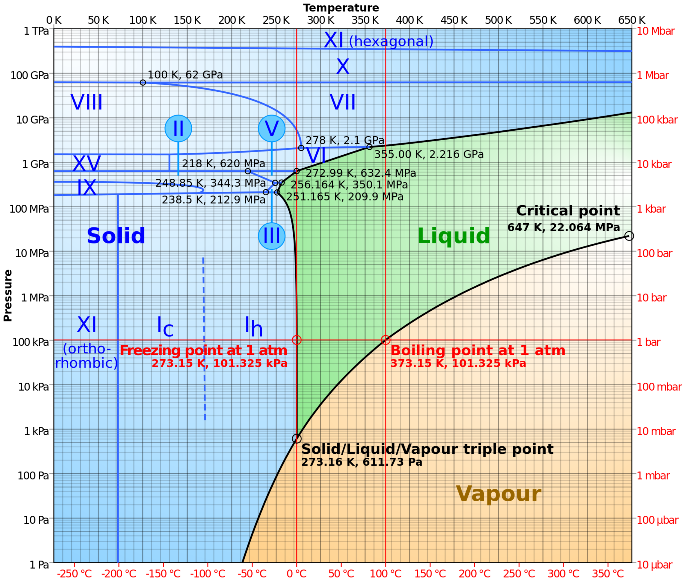
II) Hadrons in QCD Matter

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

States of Matter



Phase Diagram of H_2O

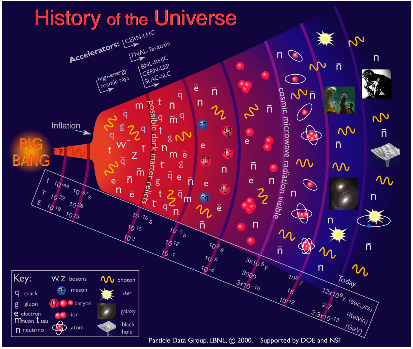


Landau Functions

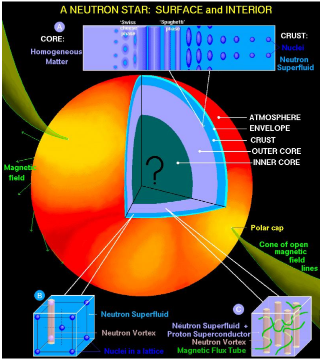
$\mathcal{L}_{\text{eff}}$	Spin system in $d = 3$
Fig. 6.3(a) Second order, $\frac{a}{2}\sigma^2 + \frac{b}{4}\sigma^4 - h\sigma$, controlled by $(a,\ h)$	Ising model $\begin{cases} \sigma \sim M \\ (a, h) \leftrightarrow (T, H) \end{cases}$
Fig. 6.3(b) First order, $\frac{a}{2}\sigma^2 - \frac{c}{3}\sigma^3 + \frac{b}{4}\sigma^4 - h\sigma$, 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

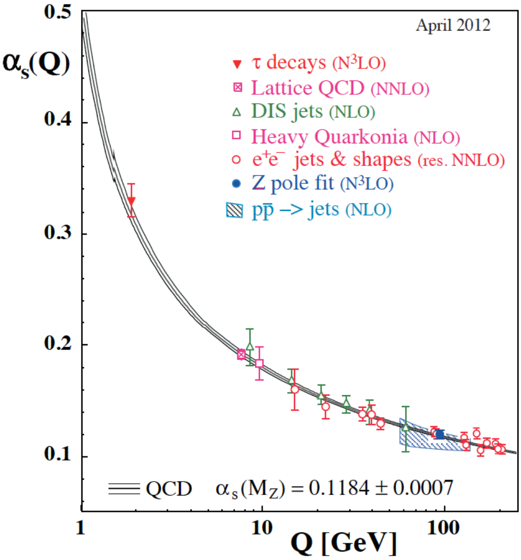
early universe (~ 10 ms)



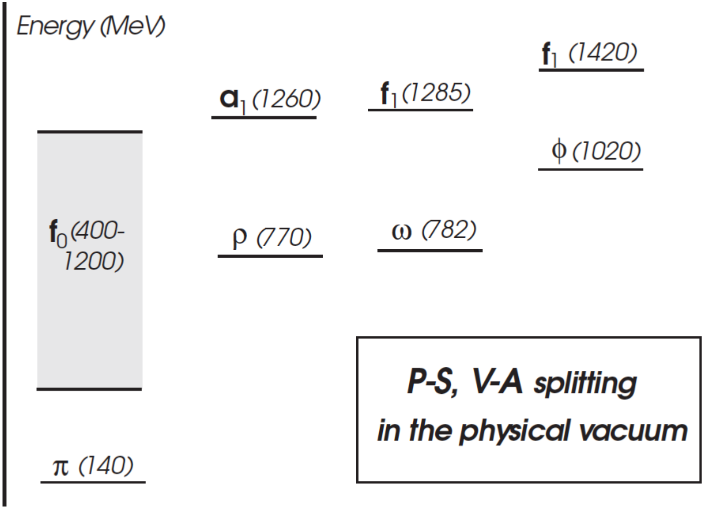
neutron star interior



Running of the Strong Coupling Constant α_s



Mass-splitting of Parity Partners



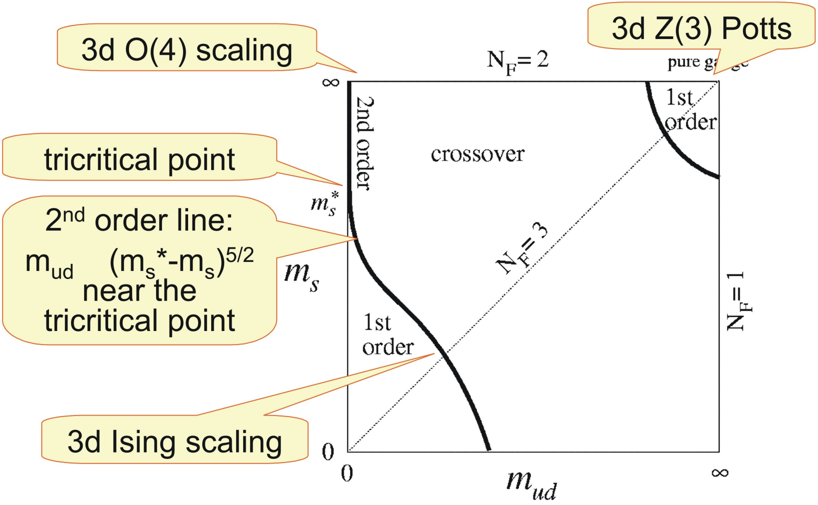
Symmetries of QCD and Breaking Pattern

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

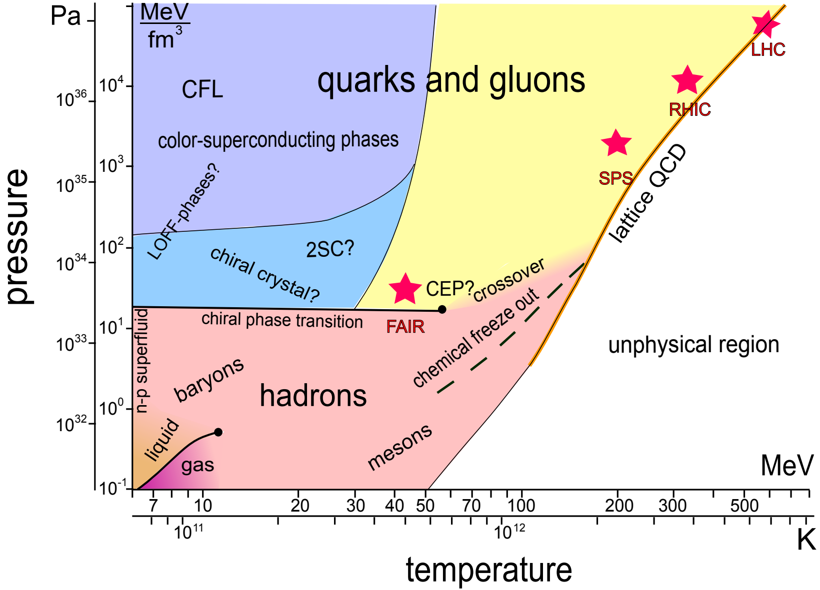
Landau Functions

$\mathcal{L}_{\rm eff}$	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 $\begin{cases}\sigma\sim M\\(a,h)\leftrightarrow(T,H)\end{cases}$	$N_c=3,\ N_f=2$ $\begin{cases}\sigma\sim\langle\bar{\rm u}{\rm u}+\bar{\rm d}{\rm d}\rangle\\(a,h)\leftrightarrow(T,m_{\rm ud})\end{cases}$ $N_c=2,\ N_f=0$ $\begin{cases}\sigma\sim\langle L\rangle\\(a,h)\leftrightarrow(T,1/m_{\rm Q})\end{cases}$
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 $\begin{cases}\sigma\sim M\\(a,h)\leftrightarrow(T,H)\end{cases}$	$N_c=3,\ N_f=3$ $\begin{cases}\sigma\sim\langle\bar{\rm u}{\rm u}+\bar{\rm d}{\rm d}+\bar{\rm s}{\rm s}\rangle\\(a,h)\leftrightarrow(T,m_{\rm uds})\end{cases}$ $N_c=3,\ N_f=0$ $\begin{cases}\sigma\sim\langle L\rangle\\(a,h)\leftrightarrow(T,1/m_{\rm Q})\end{cases}$
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 $\begin{cases}\sigma\sim\tilde{M}\\(a,b,h)\leftrightarrow(T,H,\tilde{H})\end{cases}$	$N_c=3,\ N_f=2+1$ $\begin{cases}\sigma\sim\langle\bar{\rm u}{\rm u}+\bar{\rm d}{\rm d}\rangle\\(a,b,h)\leftrightarrow(T,m_{\rm s},m_{\rm ud})\\(a,b,h)\leftrightarrow(T,\mu,m_{\rm ud})\end{cases}$

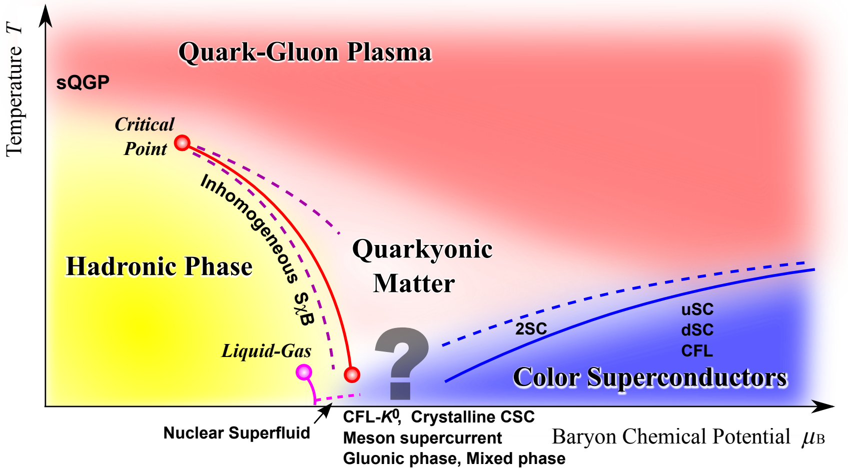
'Columbia' Plot



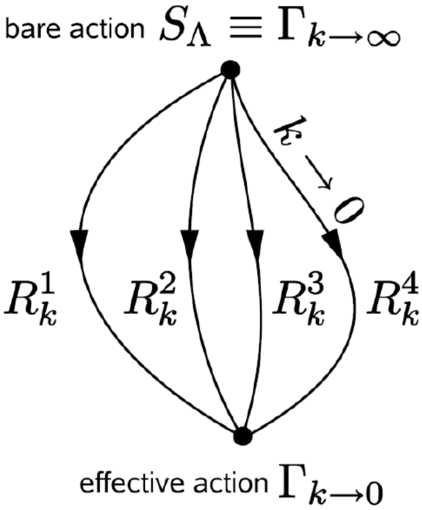
Phase Diagram of QCD Matter



Phase Diagram of QCD Matter

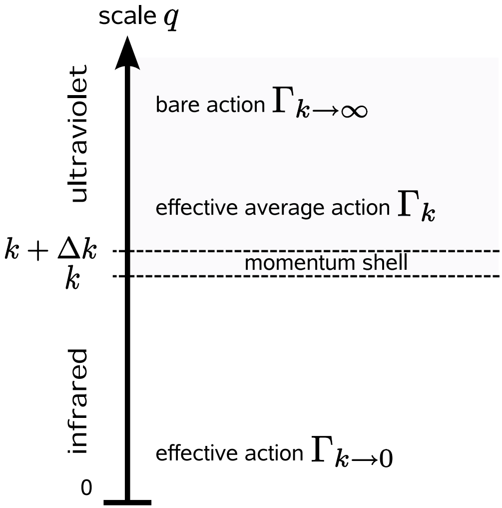


Flow



bare action $S_\Lambda \equiv \Gamma_{k\to\infty}$
$k \to 0$
R_k^1
R_k^2
R_k^3
R_k^4
effective action $\Gamma_{k\to 0}$

Flow



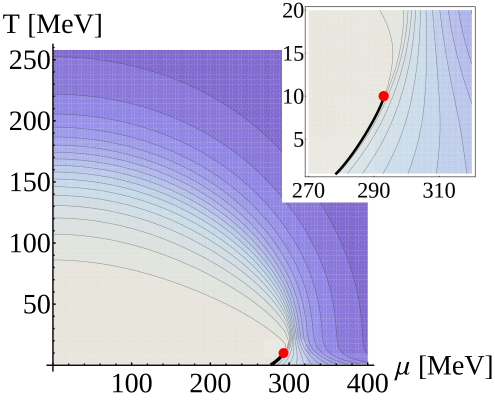
scale q
ultraviolet
bare action $\Gamma_{k\to\infty}$
effective average action Γ_k
$k+\Delta k$
momentum shell
k
infrared
effective action $\Gamma_{k\to 0}$
0

Momentum Flow of the Effective Potential

(Loading movie...)

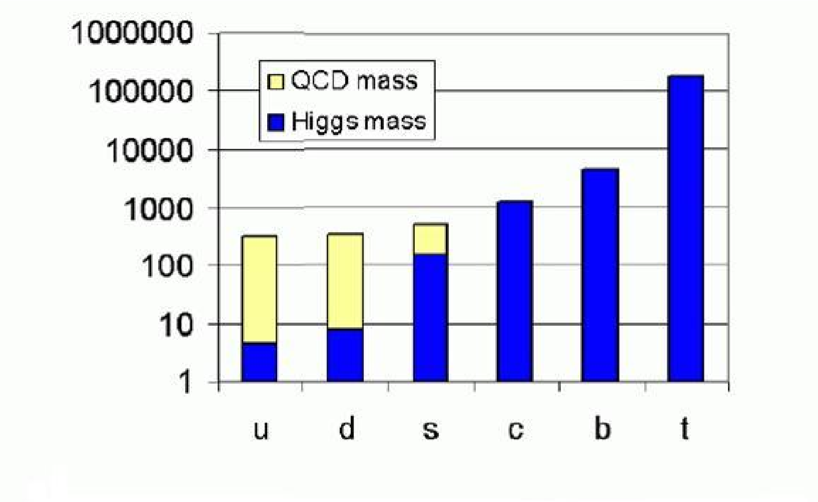
Phase diagram of the Quark-Meson Model

- 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

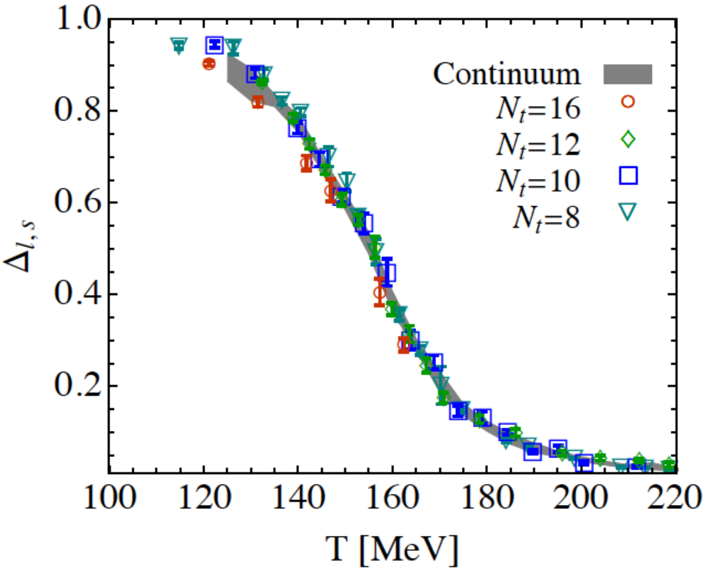


[R.-A. T., N. Strodthoff, L. v. Smekal, and J. Wambach, Phys. Rev. **D 89**, 034010 (2014)]

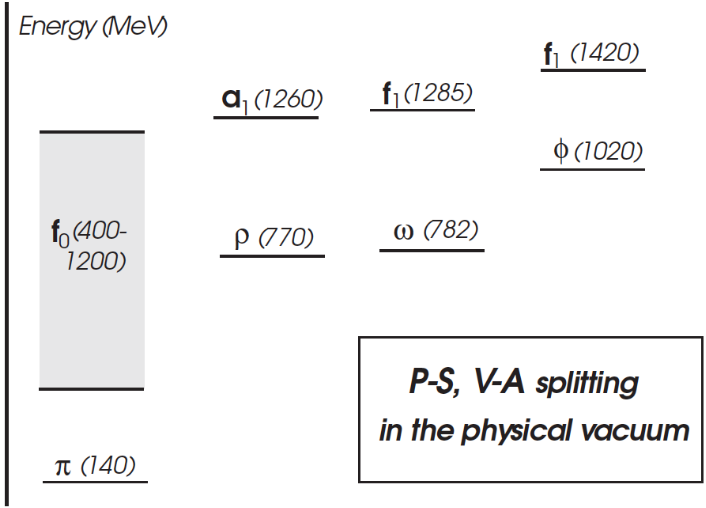
Generation of Mass in QCD



Temperature Evolution of the Chiral Condensate



Mass-splitting of Parity Partners

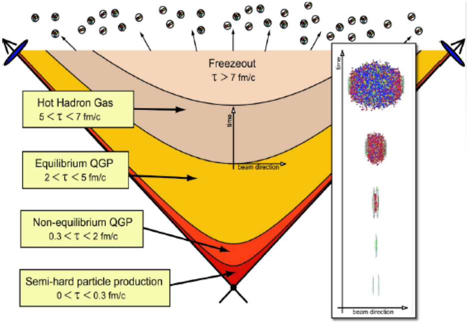


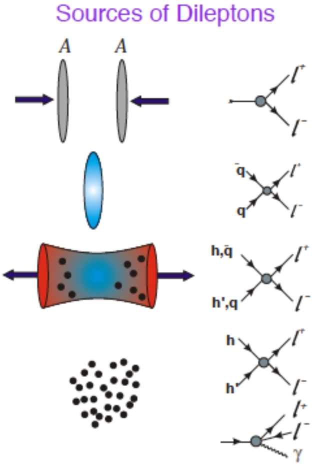
Heavy-ion Collisions and Photons

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

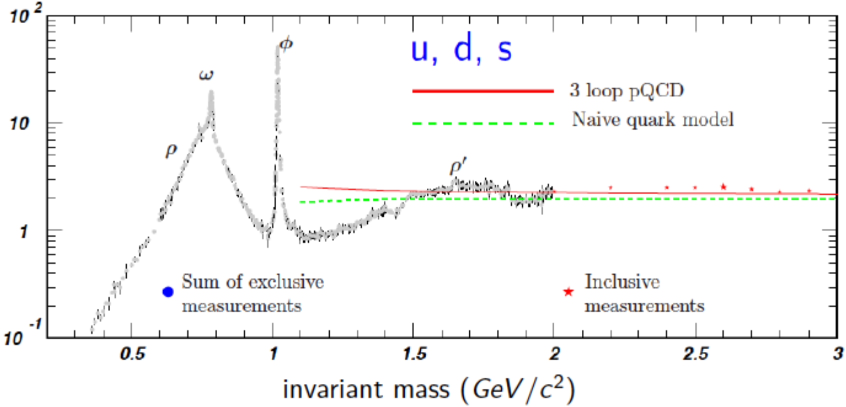
→ leave the interaction zone undisturbed

E. Feinberg 1976, E. Shuryak 1978





e^+e^- - annihilation in the vaccum



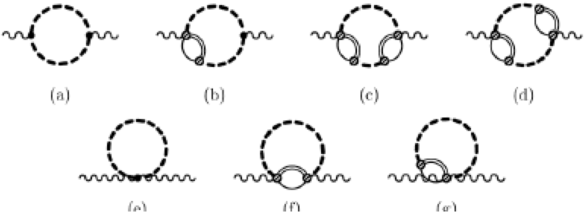
$$\text{quarks}: \quad \mathcal{R}^q = N_c \sum_i e_i^2 = 3\left(\frac{4}{9}+\frac{1}{9}+\frac{1}{9}\right) = 2$$

Vector-meson Selfenergies

ρ-meson selfenergy:

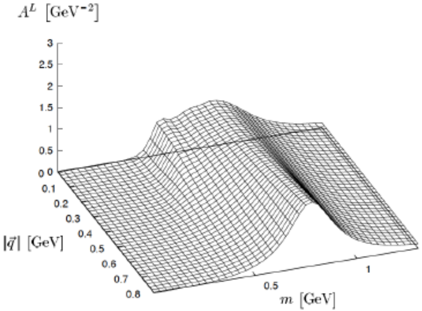
$$\Sigma_{\rho}^{L/T} = \Sigma_{\rho\pi\pi}^{L/T} + \Sigma_{\rho M}^{L/T} + \Sigma_{\rho B}^{L/T}$$

vertex corrections from dressed pions:



Spectral Function

ρ-spectral functions: (low temperature)



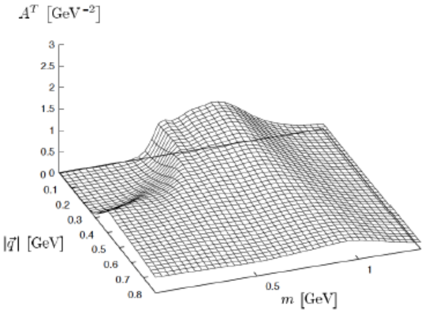
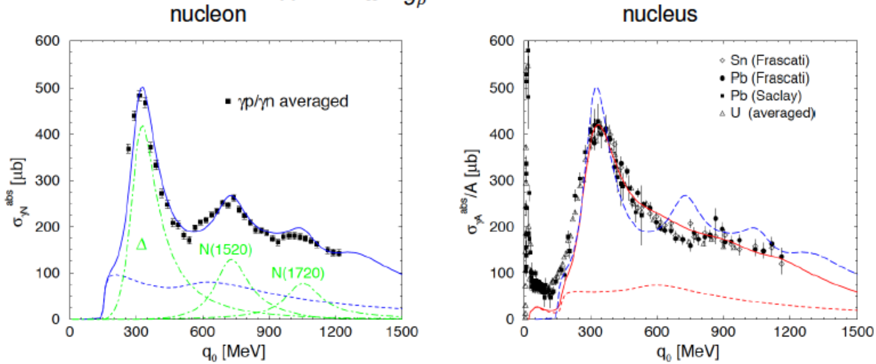


Photo-absorption as a Test

photo-absorption cross section:

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

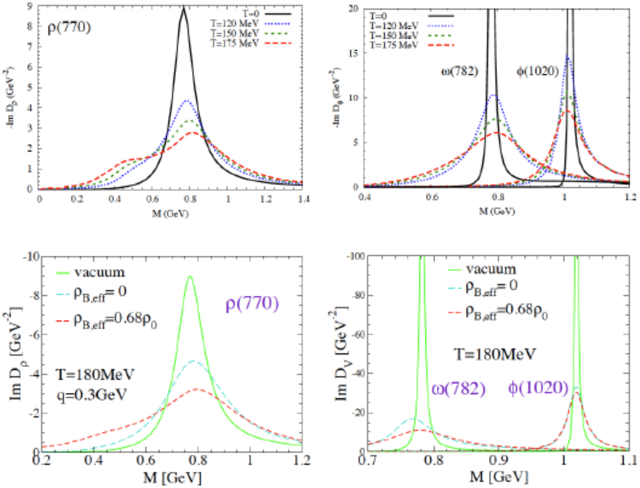


In-medium ρ-meson under HIC conditions

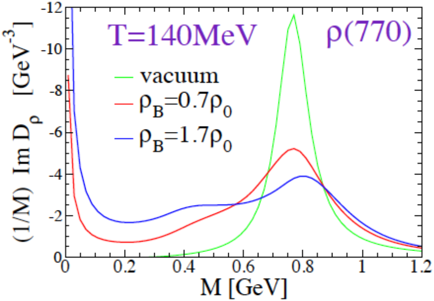
ρ-meson | ω and ϕ-meson

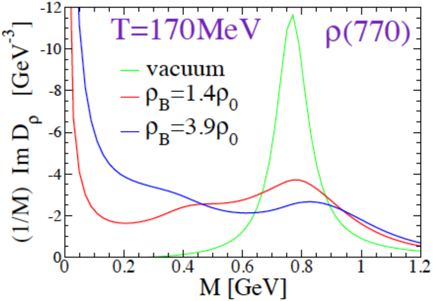
SPS
$\sqrt{s_{NN}}$=17 GeV

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

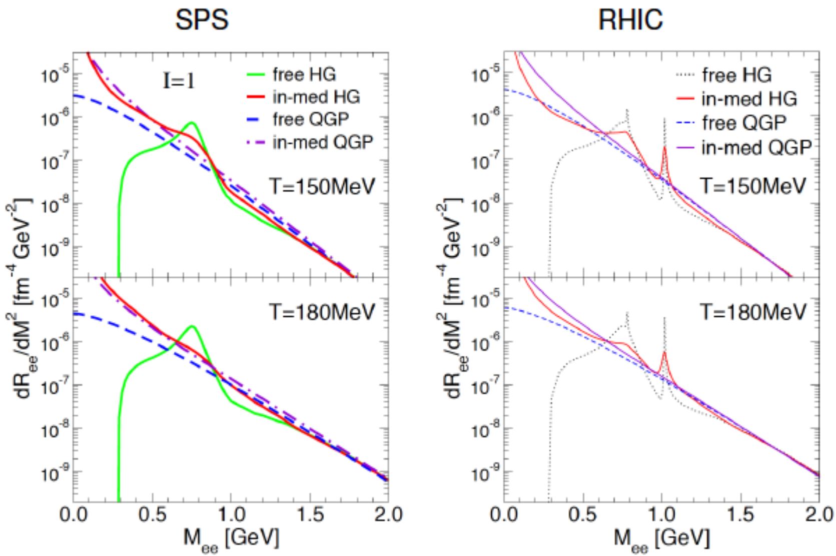


Spectral Function weighted by $1/M$

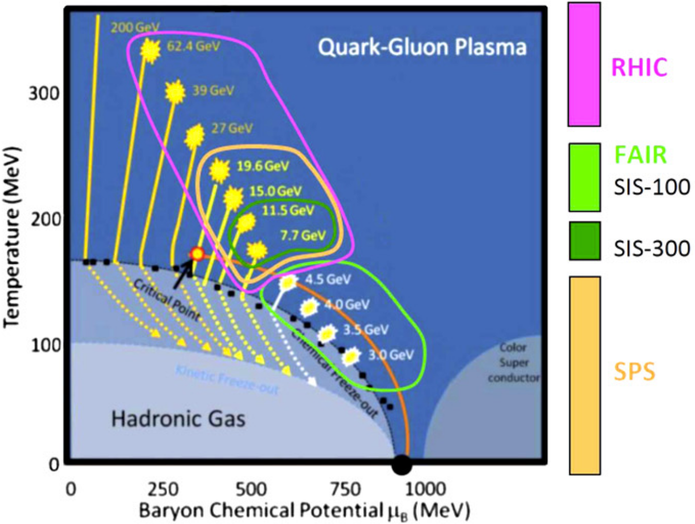




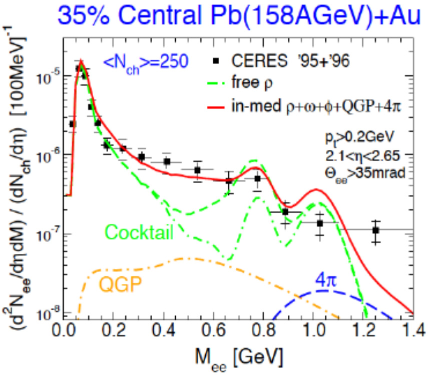
Dilepton Rates

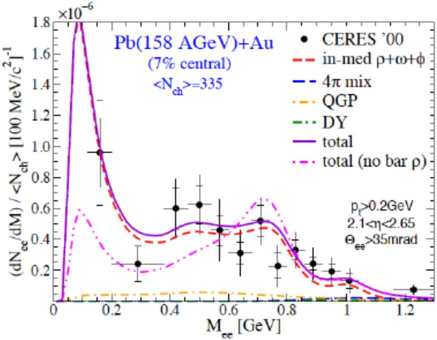


Dilepton Rates and the Phase Diagram



Dilepton Data CERES

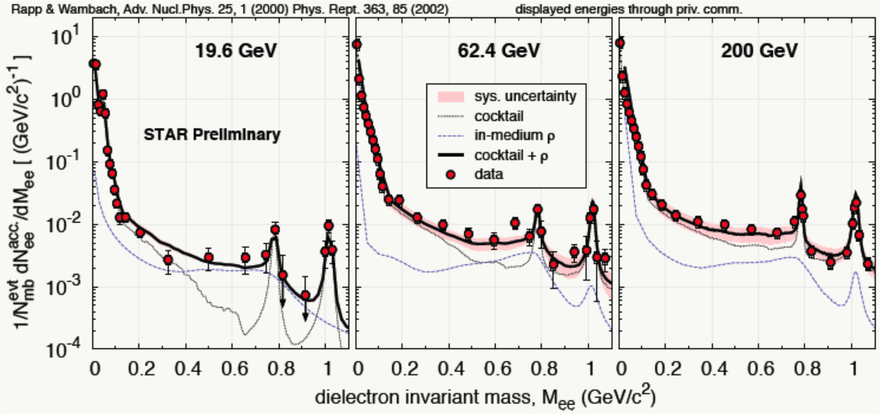




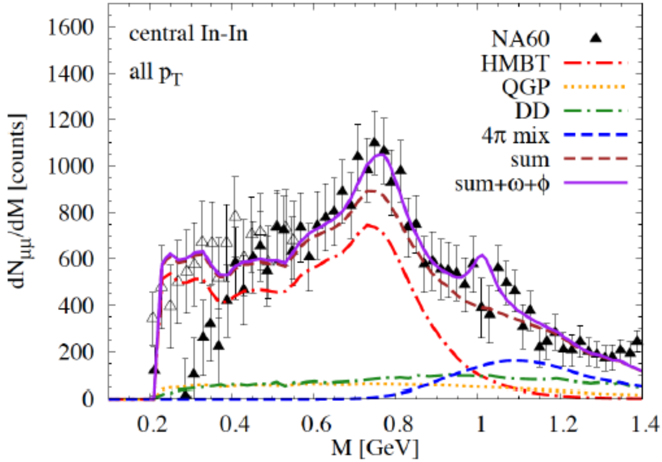
G. Agakichiev et al. (CERES/NA45 Collaboration), Eur. Phys. J. C 41, 475 (2005)
D. Adamova et al. (CERES/NA45 Collaboration), Phys. Lett. B 666, 425 (2008)

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

Dilepton Data STAR



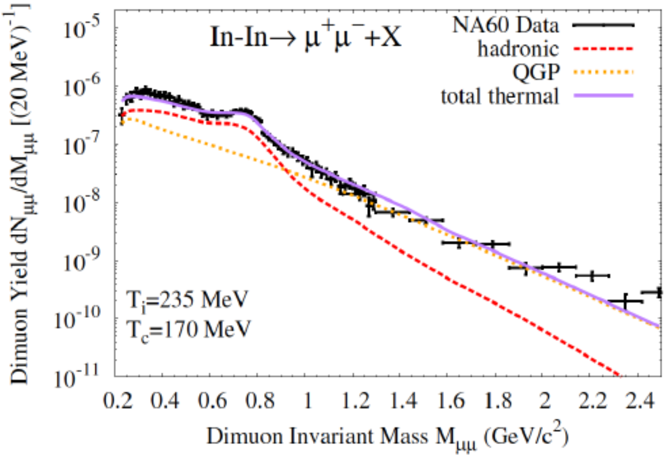
Dilepton Data SPS NA60



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

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

Dilepton Data SPS NA60

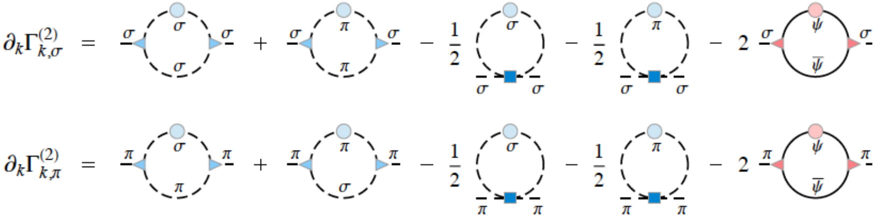


R. Rapp and H. van Hees, arXiv:1411.4612 [hep-ph]

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



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

(Loading movie...)

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

(Loading movie...)

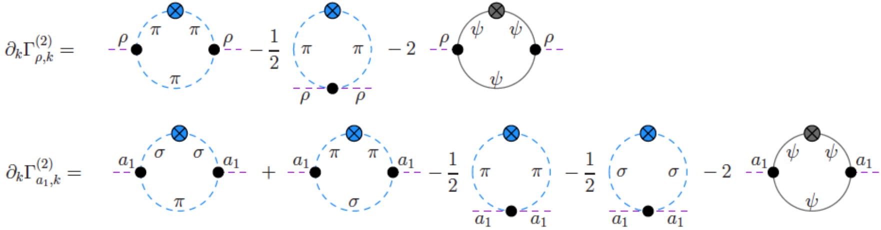
Sigma Spectral Function with increasing T at $\mu = 0$

(Loading movie...)

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

(Loading movie...)

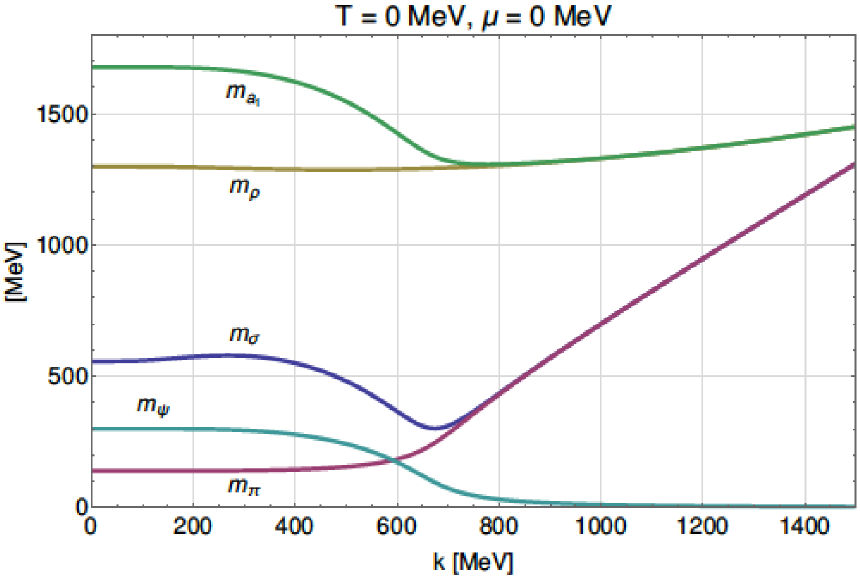
Flow Equations for Vector-Meson Two-point Functions



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

(Loading movie...)

ρ and a_1 Mass Flow



ρ and a_1 Pole Masses