Chiral transition and some issues on the scalar mesons

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Multi-quark hadrons; four, five and more?
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§1 Introduction

Tricky points in hadron physics based on QCD:

1. QCD is written solely in terms of quark and gluon fields, while, only hadrons are observed in the low-energy regime.
   Why?

   The QCD vacuum$\neq$ the perturbative one.
   Hadrons are elementary excitations on top of the non-perturbative QCD vacuum.

2. Symmetries in (classical) QCD Lagrangian are not manifest;
   Color SU(3) —- Confinenment (Hadrons are white!)
   (Apprximate) chiral symmetry —- Spontaneously broken

The low-energy hadron physics is a study of the nature of QCD vacuum and hopefully its symmetry properties.

Hadron Physics $\sim$ condensed matter physics of the QCD vacuum +Atomic Physics. (Y. Nambu ('60))

Y. Nambu, **117** (1960), 648; Gauge invariance in Superconductivity
$\rightarrow$ Appearance of a collective mode in the broken phase coupling to the longitudinal part of the current.

Y. Nambu, PRL **4** (1960), 380;
Y. Nambu and G. Jona-Lasinio, **122** (1960), 345;
Dynamical model of elementary particles based on an analogy with superconductivity.

The pion ; a (massless) collective mode associated with the dynamical breaking of chiral symmetry.
A scalar meson with the mass $2m_f$ appears as another collective mode than the pion.

Chiral Transition = a phase transition of QCD vacuum*)

*): $\langle \bar{q}q \rangle$ being the order parameter.

Eg. Lattice QCD; F. Karsch, Nucl. Phys. Proc. Suppl. **83**, 14 (2000).

The wisdom of many-body theory tells us:

If a phase transition is of 2nd order or *weak* 1st order,
$\exists$ soft modes $\sim$ the fluctuations of the order parameter

For chiral transition,

$$\langle (:\bar{q}q:)^2 \rangle \sim \text{the } \sigma\text{-meson } (f_0)\, (I=0, J^{PC}=0^{++}).$$

$$\Downarrow$$

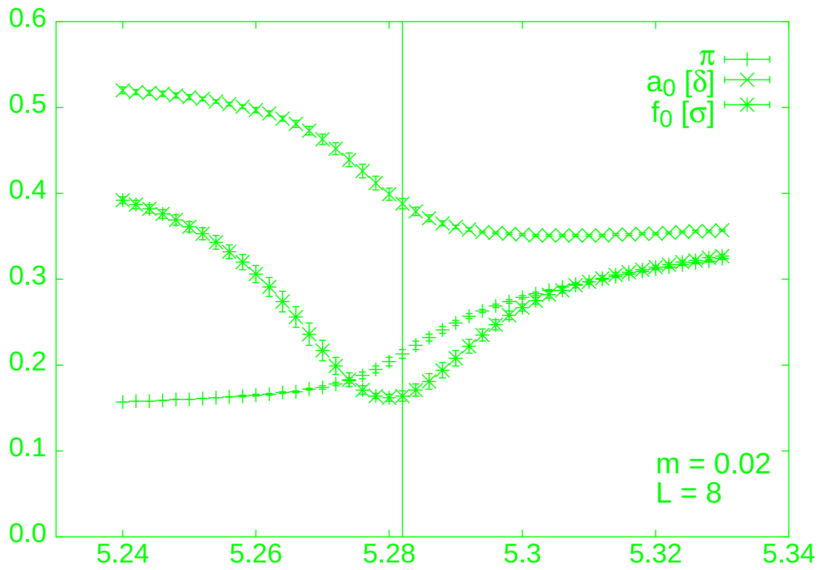
The σ meson becomes the soft mode of chiral transition at $T \neq 0$
and/or $\rho_B \neq 0$: $m_\sigma \to 0$, $\Gamma_\sigma \to 0$

T. Hatsuda and T.K.: Phys. Lett. **B145** (1984),7;
Phys. Rev. Lett. **55** (1985), 158.

Cf. Lattice Calculation of the *generalized masses*

F. Karsch, Lect. Note Phys. **583** (2002), 209. $N_f = 2$, $8^3 \times 4$;

Staggered fermion



$m_\sigma^2 = \chi_\sigma^{-1}$; $\quad \chi_\sigma = \langle(\bar{q}q)^2\rangle$.

1. The softening of σ
2. a degeneracy of the σ and π at high T
3. $U_A(1)$ symmetry not restored even at high T. $(m_\delta \leftrightarrow m_\pi)$

But, what is the siginificance of the σ in hadron physics?

Issues with the low-mass σ meson in QCD

In the constituent quark model; $J^{PC} = 0^{++} \rightarrow {}^3P_0$
$\longrightarrow$ mass in the 1.2 — 1.6 GeV region.

Some mechanism to down the mass;
(i) Color magnetic interaction between the di-quarks? (Jaffe)

(ii) The collectiveness of the scalar mode as the ps mode; a superposition of $q\bar{q}$ states $\leftarrow$ Chiral symmetry(NJL)

The significance of the σ meson in low energy hadron physics and QCD

1. The pole in this mass range observed in the pi-pi S-matrix. As a compilation of the pole positions of the σ obatined in the modern analyses, see Z. Xiao and H. Zheng, Nucl. Phys. **A695**, 273 (2001)

   Significance of respecting chiral symmetry, unitarity and crossing symmetry to reproduce the phase shifts both in the $\sigma\,(s)$- and $\rho\,(t)$-channels with a low mass σ pole; (Igi and Hikasa; Phys. Rev. **D59**, 034005 (1999)).

2. Seen in decay processes from heavy particles; $D^+ \to \pi^-\pi^+\pi^+$
   E. M. Aitala et al, Phys. Rev. Lett. **(86), 770 (2001).**

3. Responsible for the intermediate range attraction in the nuclear force.

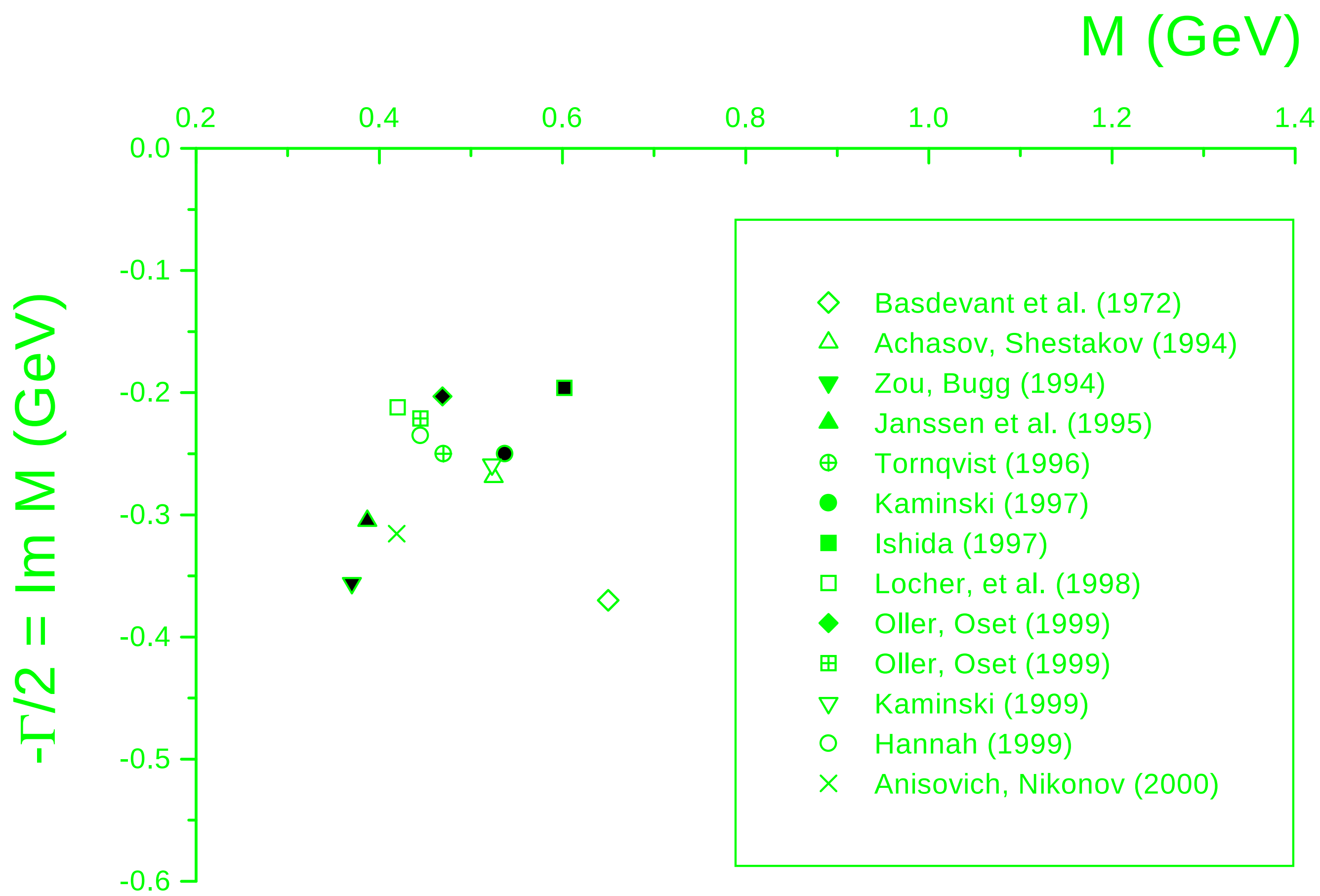
4. Accounts for $\Delta I = 1/2$ enhancement in $K^0 \to 2\pi$ compared with $K^+ \to \pi^+\pi^-$.
   E.P. Shabalin (1988); T. Morozumi, C.S. Lim and I. Sanda (1990).

5. π-N sigma term $\Sigma_{\pi N} \sim$ 40-50 MeV.(naively $\sim$ 15 MeV)
   $\leftarrow$ enhanced by the collectiveness of the σ. T.Hatsuda and T.K.(1990) ; see the next slide.

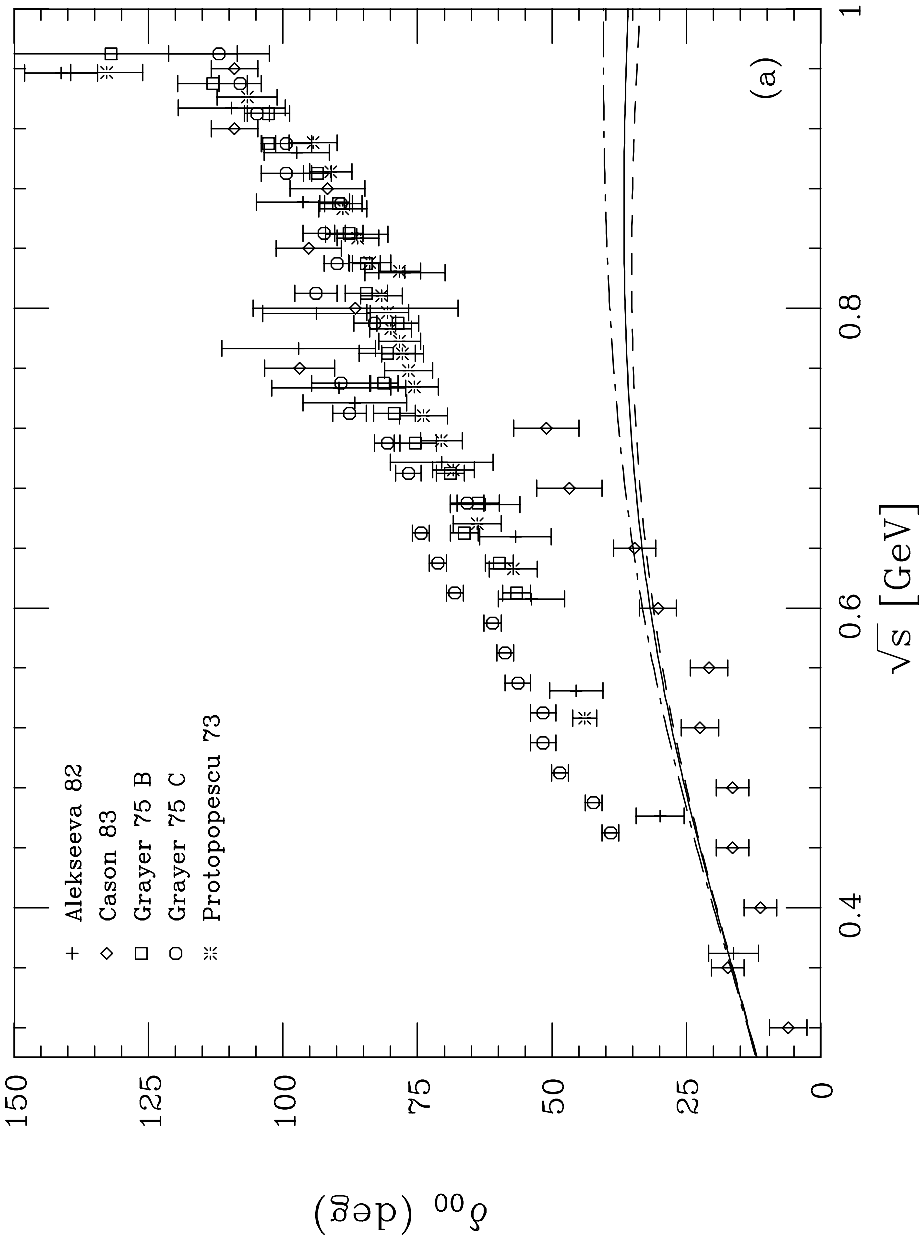
6. the σ = the quantum fluctuation of the order parameter$\sim$ the Higgs particle in the WSG model:
   $\to m_\sigma$ = 400-800 MeV, $\Gamma \sim m_\sigma$. (prediction in NJL-like models and mended symmetry of Weinberg.)

The poles of the S-matrix in the complex mass plane (GeV) for the σ meson; complied in

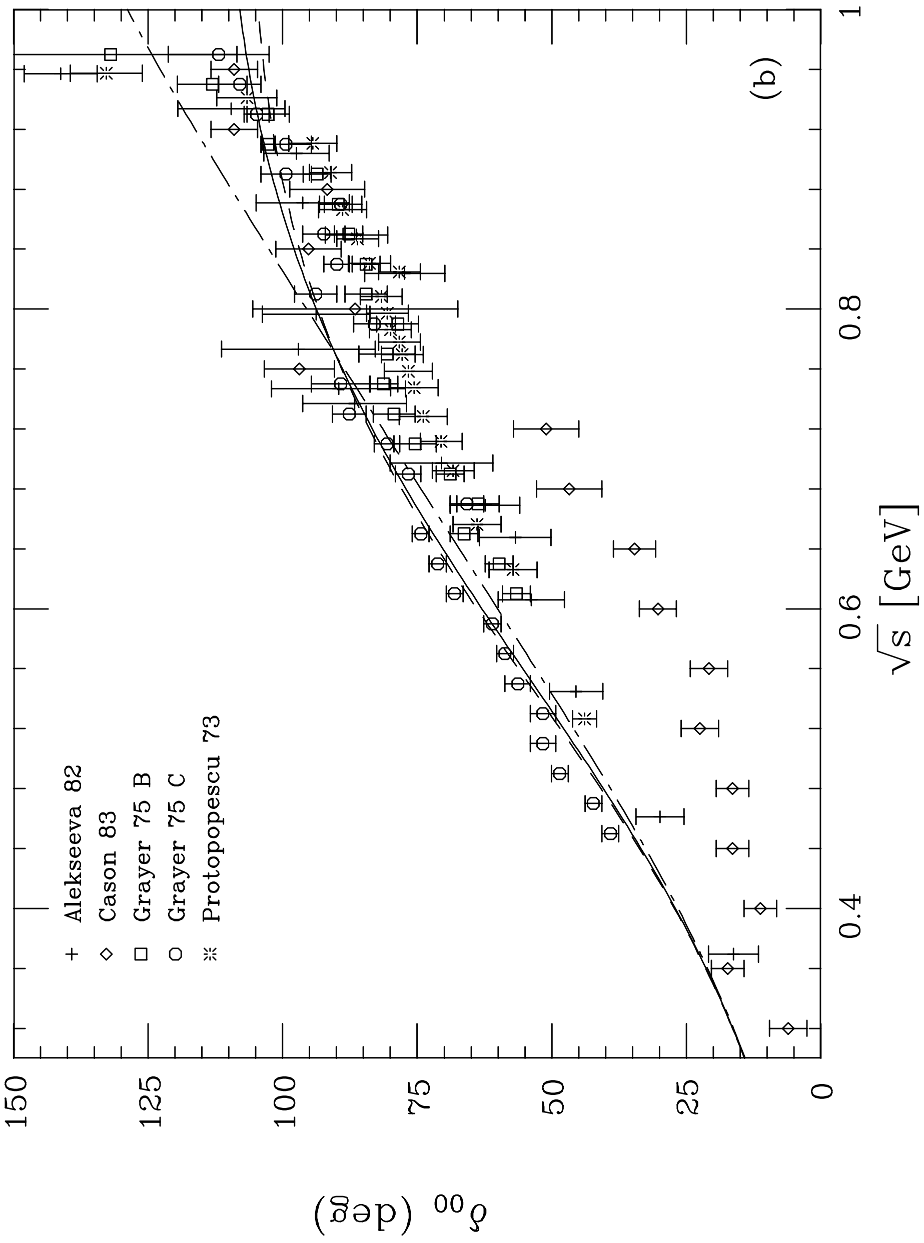
(Z. Xiao and H. Z. Zheng, Nucl. Phys. **A695** (2001), 273)



Igi and Hikasa; Phys. Rev. **D59**, 034005 (1999)



(A) No σ pole;



(B) With σ pole;

Light quark contents of baryons

B	$\langle \bar{u}u \rangle_B$	$\langle \bar{d}d \rangle_B$	$\langle \bar{s}s \rangle_B$
P (938)	4.97 (2)	4.00 (1)	0.53 (0)
Λ^0 (1115)	3.63(1)	3.63(1)	1.74(1)
Δ^{++} (1232)	3.66(2)	0.76 (0)	0.26 (0)
Ω^- (1672)	0.72 (0)	0.72 (0)	3.71 (3)

T.K. and T. Hatsuda, Phys. Lett. **B240** (1990) 209

The numbers in ( ) are those in the naive quark model. The quark content = **the scalar charge** may be enhanced by **the collective mode**, the collective σ mode in the scalar channel!

Cf.**the quadrupole electric charge** enhanced by **the quadrupole giant resonance**.

$$\downarrow$$

$$\begin{aligned} \Sigma_{\pi N} &= \hat{m}\langle \bar{u}u + \bar{d}d \rangle_N \\ &= 5.5\text{MeV} \times (4.97 + 4) \\ &\simeq 50\,\text{MeV} \\ &>> 5.5 \times (2+1) \simeq 17\,\text{MeV} \end{aligned}$$

with $y \equiv 2\langle \bar{s}s \rangle_N / \langle \bar{u}u + \bar{d}d \rangle_N = 0.12$

The empirical value of π-N Sigma term is reproduced due to the enhancement of the scalar charge due to the σ-mesonic collective mode!

(The small but finite value of y reflects the small flavor mixing in the scalar mesons.)

Wait!

Is the pole observed in the pi-pi phase shift really the σ as the quantum fluctuation of the order parameter of the chiral transition?

A change of the environment $\rightarrow$ a change of the mode coupled to the order parameter

$\Downarrow$

Production of the σ-meson in nuclear medium

Useful for exploring the existence of the σ and the possible restoration of chiral symmetry at finite density.

T. K., Prog. Theor. Phys. Suppl. **120**(1994), 75

What is a good observables to see the softening in the sigma channel in nuclear medium?

Notice:

A particle might loose it identity when put in a medium.

Eg.

$\sigma \leftrightarrow 2\pi$, $\sigma \leftrightarrow$ p-h, π+p-h, Δ-h, $\pi + \Delta$-h ...

$$\Downarrow$$

Need of calculation of Strength function

The surprise was,

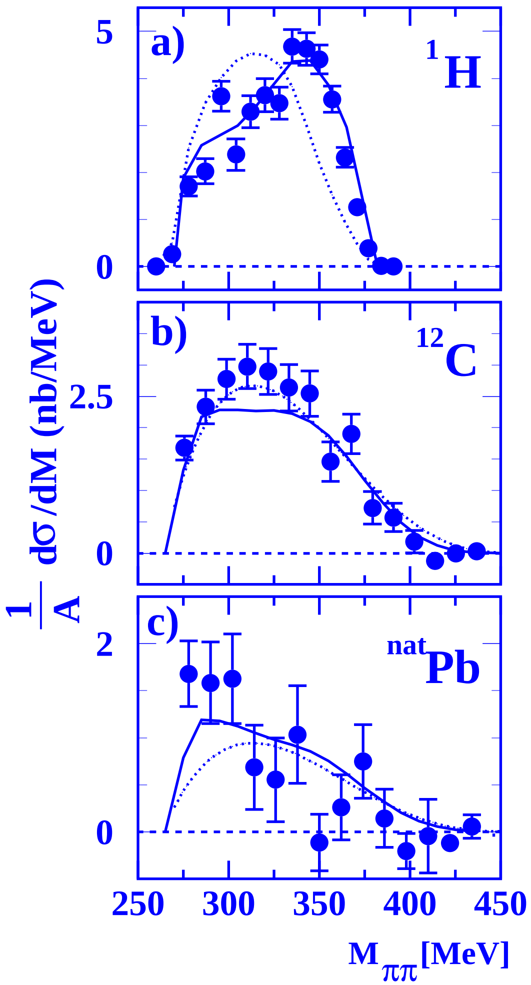
Such an enhancement had been seen by an Experiment by CHAOS*)!, at $T = 0$ but at $\rho_B \neq 0$

*); A($\pi^+, \pi^+\pi^\pm$)A' (A$= 2 \to 208$)

F. Bonutti et al, Phys. Rev. Lett. **77** (1996), 603.;

Nucl. Phys. **A677**, 123(2000)

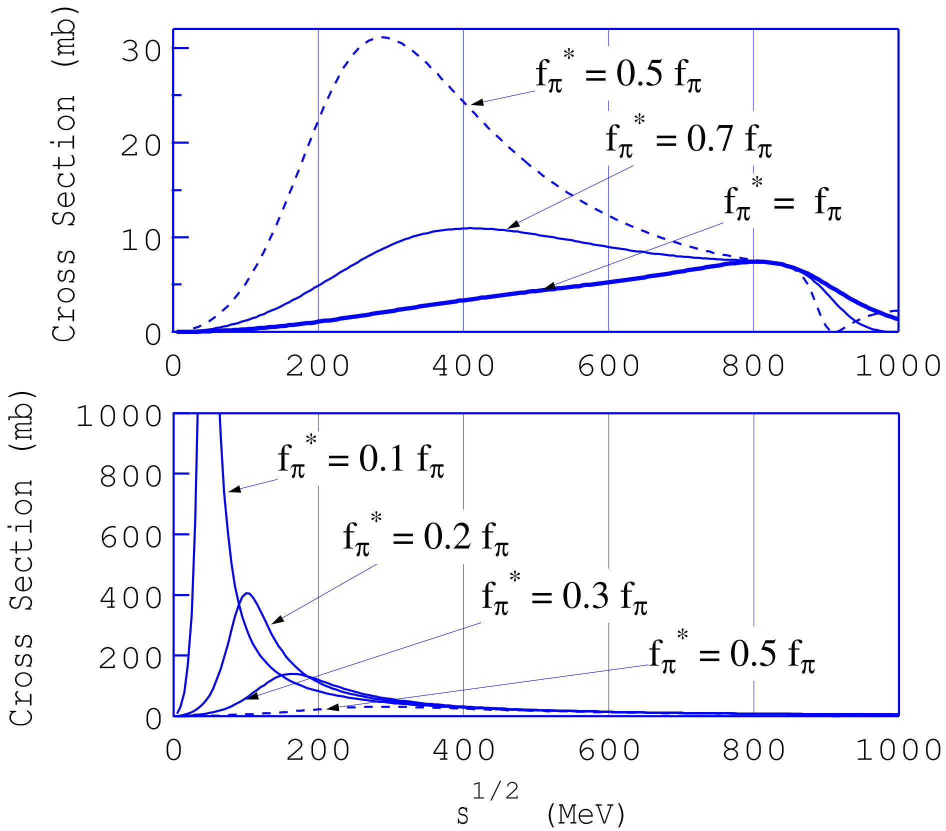
Differential cross sections of the reaction $A(\gamma, \pi^0\pi^0)A'$



J.G. Messchendorp et al, Phys. Rev. Lett. **89** (2002), 222302.

Calculation of the strength function at $\rho_B \neq 0$

T. Hatsuda, T. K. and H. Shimizu, Phys. Rev. Lett.**82**(1999), 2840.
D. Jido, T. Hatsuda and T. K., Phys. Rev. **D63**, 011901 (2001)
K. Yokokawa, T. Hatsuda, A. Hayashigaki and T. K., PR **C66**, 022201 (2002)

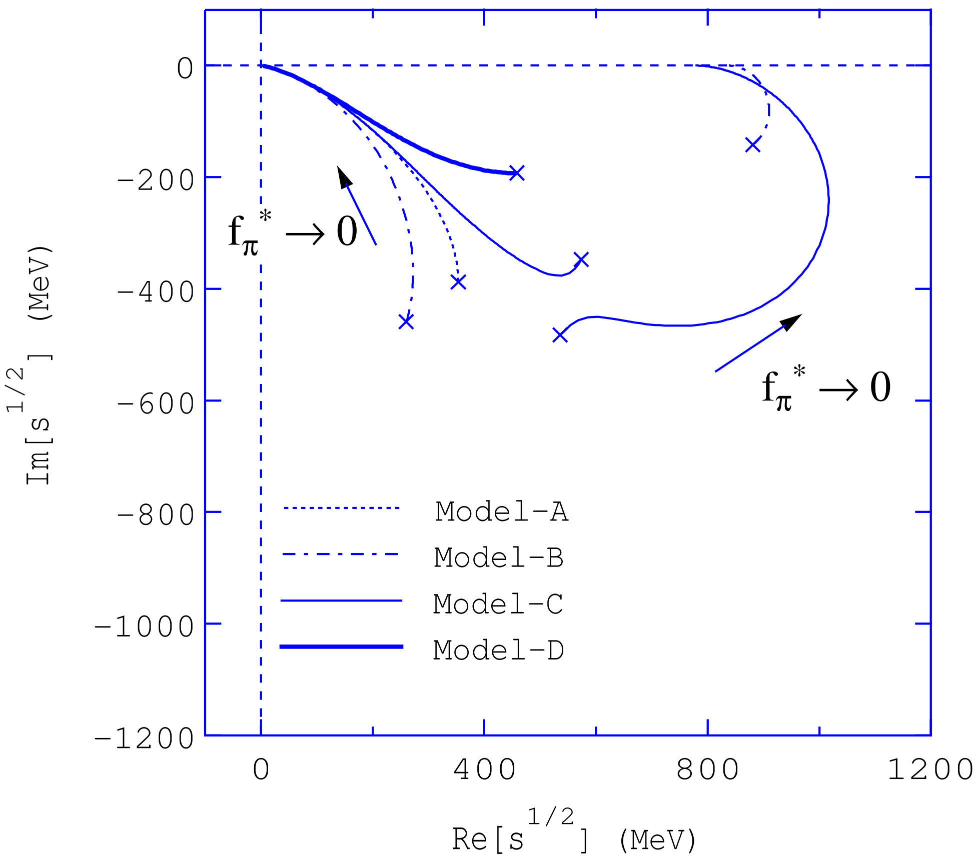


The T matrix in the N/D method.

The in-medium π-π cross sections in I=J=0 channel. The upper (lower) panel shows the case of small (large) restoration corresponding to $0.5f_\pi < f_\pi^* < f_\pi$ $(0.1f_\pi < f_\pi^* < 0.5f_\pi)$.

Chiral restoration in the nuclear medium can lead to the required enhancement near the $2m_\pi$ threshold!

The softening of the sigma meson pole in the 2nd Riemann SheetK. Yokokawa et al (2002):



The movement of the poles in $I=J=0$ channel along with the the decrease of f_π^*. The crosses are the pole positions in the vacuum.

§Summary

1. The σ meson as the quantum fluctuation of the order parameter of the chiral transition may account for various phenomena in hadron physics which otherwise remain misterious.

2. There have been accumulation of experimental evidence of the σ pole in the pi-pi scattering matrix.
$\Leftarrow$ chiral symmetry, analyticity and crossing symmetry.

3. Partial restoration of chiral symmetry in hot and dense medium as represented by the decreasing f_π leads to a softening of the σ meson pole in the 2nd Riemann sheet even in the non-linear realization of chiral symmetry.

4. Even a slight restoration of chiral symmetry in the hadronic matter leads to a peculiar enhancement in the spectral function in the σ channel near the $2m_\pi$ threshold.

5. Such an enhancement might have been observed in the reaction
A($\pi^+(\gamma)$, $(\pi^+\pi^-)_{I=J=0}$)A' .

6. Further theoretical and experimental works are needed to confirm the above.

Recent development: N_c dependence

T. Schaefer('03); Instanton liq. model ($\sim$ NJL)
At $N_c = 3$, The low mass σ exists which is a linear combination of $q\bar{q}$ and $(q\bar{q})^2$.

Larger N_c, m_σ goes up and σ being mainly composed of $q\bar{q}$.

c.f. J. R. Pelaez
M. Harada et al.

SCALAR collaboration ('03); hep-lat/0310312