Spectral Change of Hadrons and Chiral Symmetry

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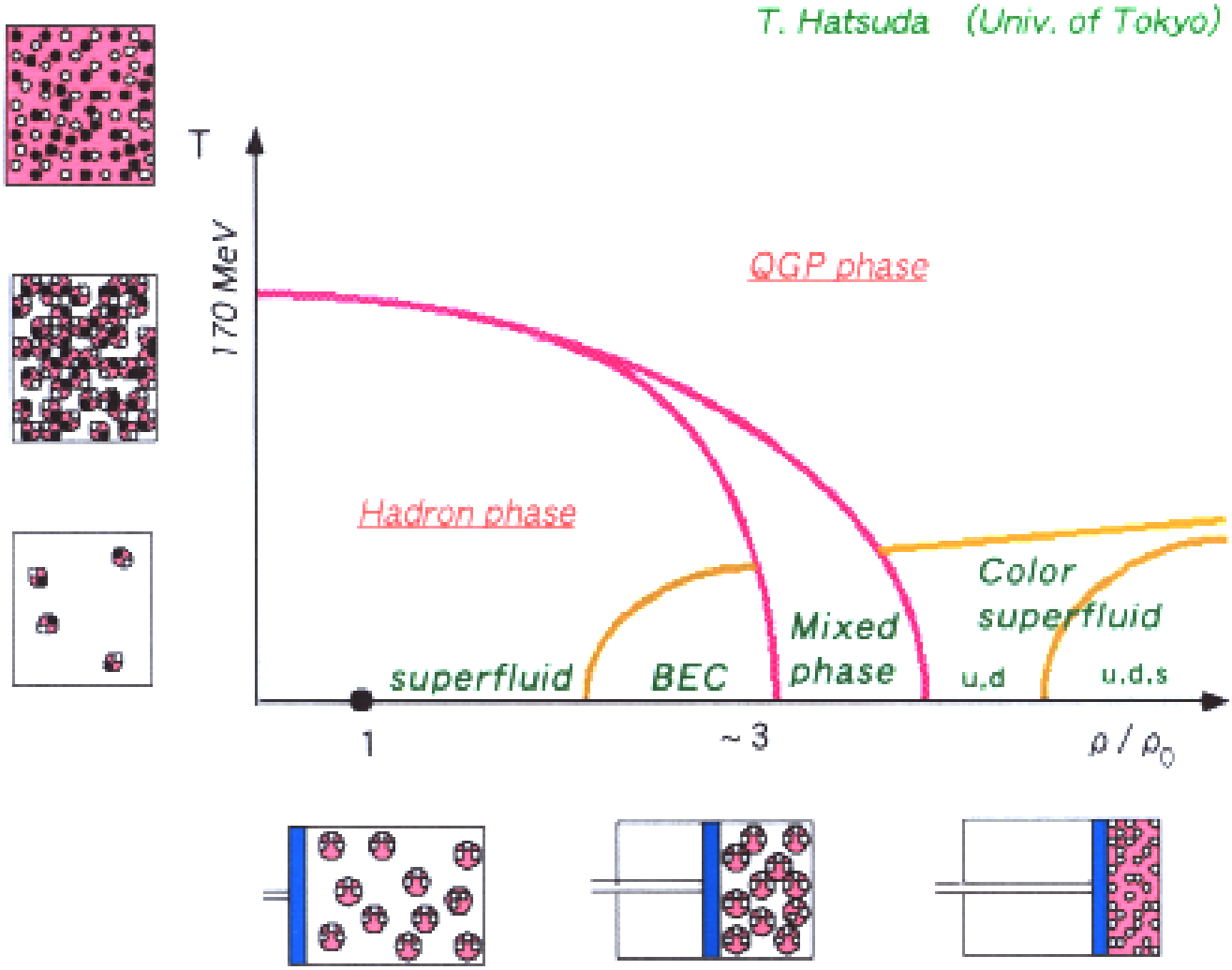


1. Chiral symmetry :

   breaking & restoration in QCD

2. In-medium hadrons :

   tracer of chiral structure of matter

3. Old idea revived :

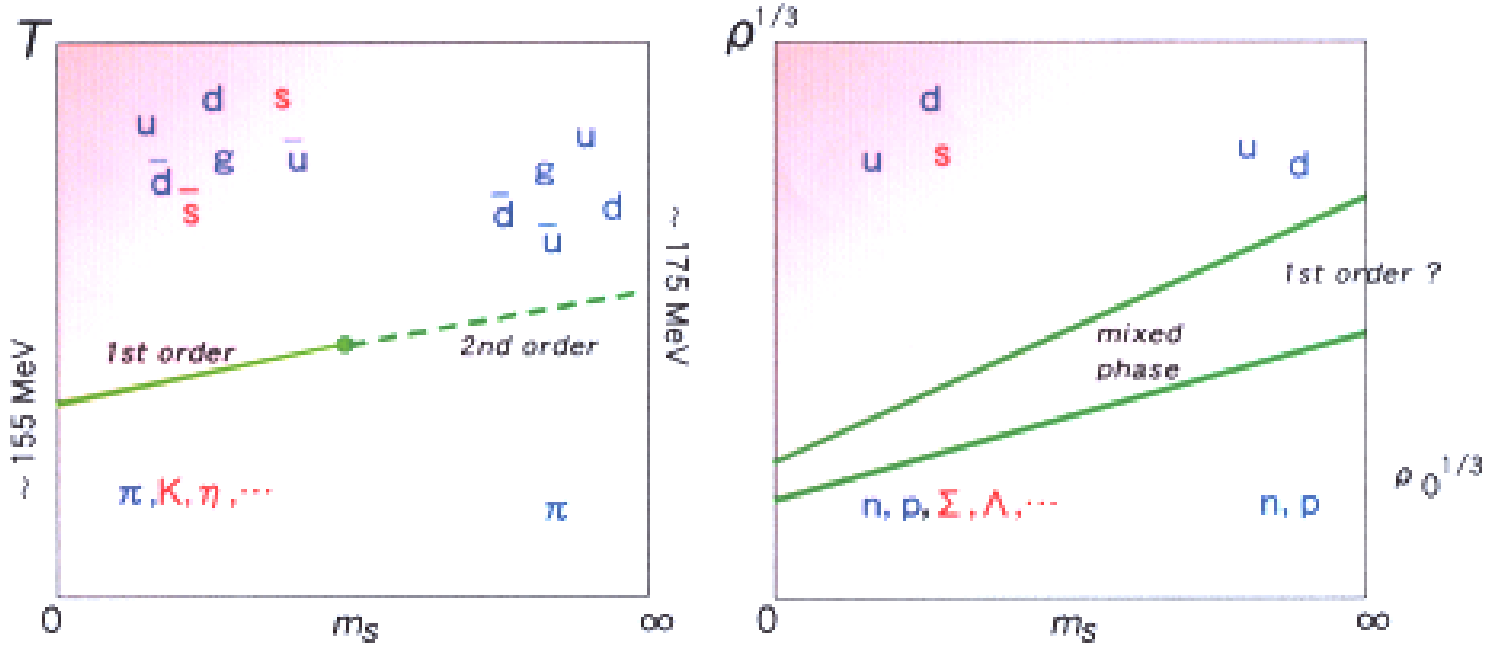
   spectral sharpening of the σ-meson

4. New direction :

   lattice QCD approach to in-medium hadrons

QCD phase structure

- $m_{u,d} \ll m_s \sim T_c \sim \rho_c^{1/3} \sim \Lambda_{QCD}$
- Chiral order parameter : $\langle \bar{q}q \rangle$ with $q = u, d$



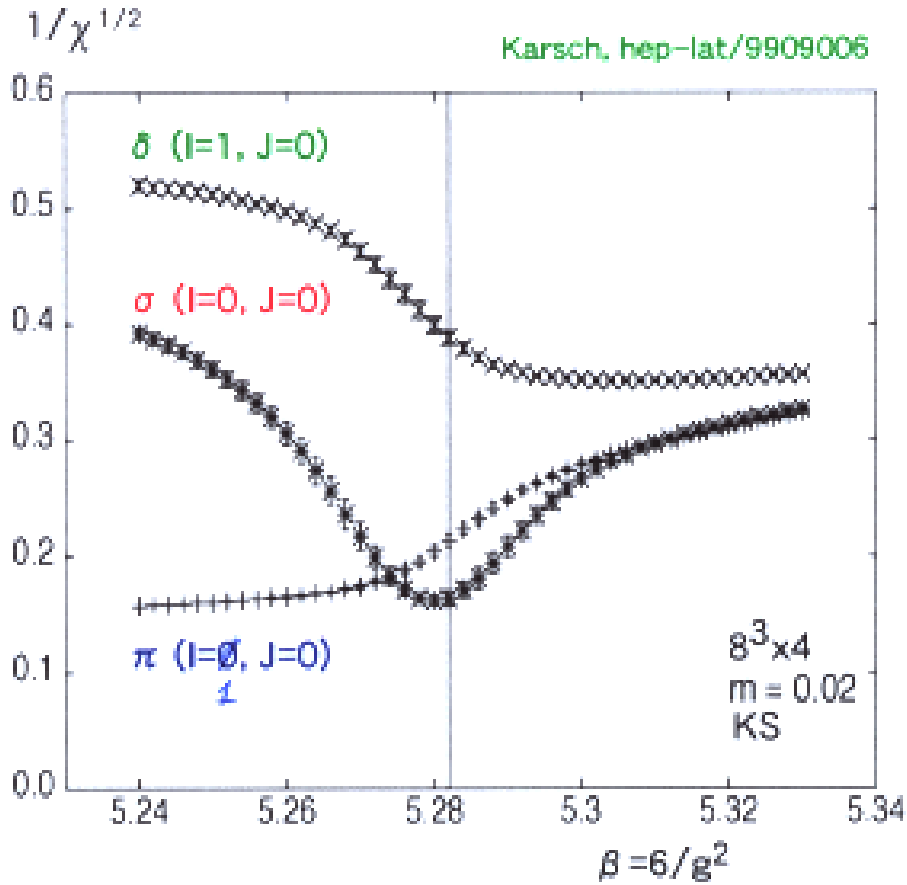
Hadronic correlations : Tracer of the phases

- Symmetry : $\langle S(x)S(y) \rangle \sim \langle P(x)P(y) \rangle$, $\langle A(x)A(y) \rangle \sim \langle V(x)V(y) \rangle$ as $\langle \bar{q}q \rangle \to 0$
- Dynamics : $\langle S(x)S(y) \rangle$, $\langle P(x)P(y) \rangle$, $\langle A(x)A(y) \rangle$, $\langle V(x)V(y) \rangle$ as $\langle \bar{q}q \rangle$ varies

Pisarski, PLB ('82), Kunihiro & T.H., PRL ('85) ,
Brown & Rho, PRL ('91), Lee & T.H., PRC ('92) ,
Rajagopal & Wilczek, NPB ('93) , ·····

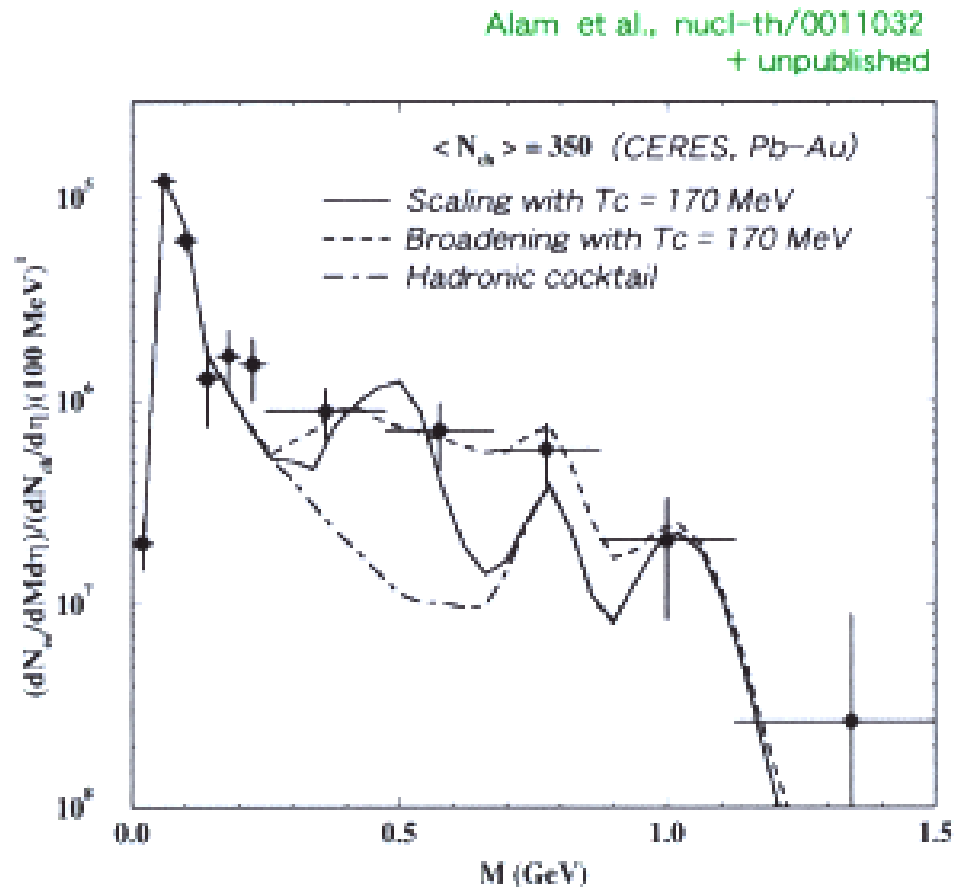
Hadronic susceptibility (χ)

$$\int \langle S(x_E)S(0)\rangle\, d^4x_E \rightarrow \int \langle P(x_E)P(0)\rangle\, d^4x_E$$



Dilepton spectrum

$$\frac{dR}{d^4x\,d^4q} \propto \mathrm{Im}\ F.T.\ \langle V(t,\vec{x})V(0)\rangle$$

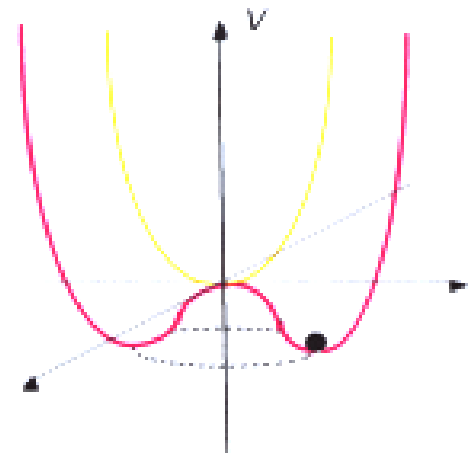


Spectral Function

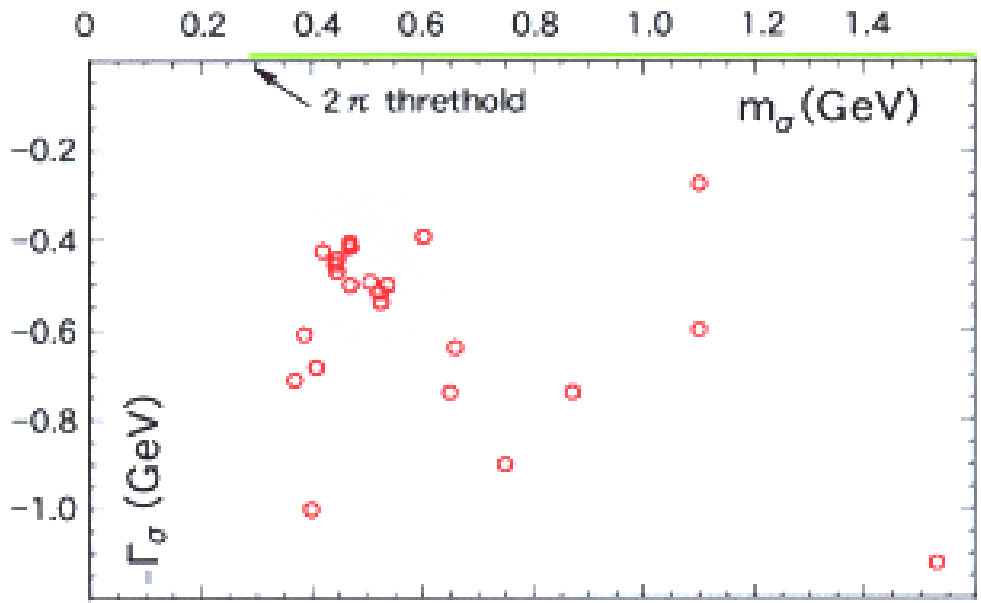
$$A(\omega,\vec{q}) = \mathrm{Im}\ \mathrm{F.T.}\langle H(t,\vec{x})H(0)\rangle$$

Mysterious scalar mesons

	QCD	EW theory
condensate	$\langle \bar{q}q \rangle$ $= -(225 \pm 25\ \mathrm{MeV})^3$	$\langle \phi \rangle = 246\ \mathrm{GeV}$
NG boson	pion $m_\pi^2 \propto -m \langle \bar{q}q \rangle$	absorbed in W and Z
Higgs mass width	σ (400 – 1200 MeV) $\Gamma_{\sigma \to 2\pi}$ $\sim$ 300 – 1000 MeV	h (114 GeV) ? $\Gamma_{h \to bb}$ $<$ 10 MeV



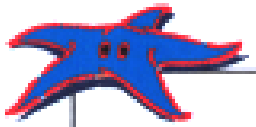
π : rotation
σ : vibration



$m_\sigma = \mathrm{Re}\sqrt{s_{pole}}$

$-\Gamma_\sigma = 2\,\mathrm{Im}\sqrt{s_{pole}}$

Rev. of Particle Properties ('00)



Broad "σ" in the vacuum :

$\Gamma_\sigma \sim m_\sigma$ by $\sigma \to \pi\pi$

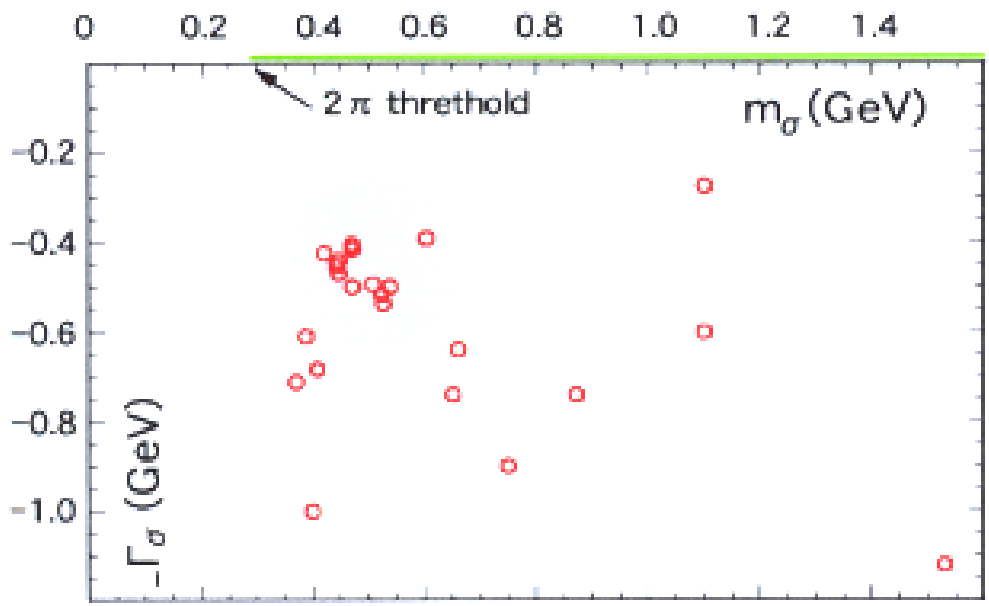
$|\sigma\rangle \sim |\sigma_B\rangle + |\pi\pi\rangle + \cdots$

Sharp "σ" in the medium

- $\Gamma_\sigma \to 0$ as $m_\sigma \to 2m_\pi$
- strong $\pi\pi$ attraction near threshold

$\Leftrightarrow$ "σ" $\to 2\gamma$, l^+l^-
$\pi A \to (\pi\pi)_{I=J=0} A'$

Kunihiro & T.H., PL B185 ('87), Weldon, PL B274 ('92),
Chiku & T.H., PR D57 ('98), Volkov et al., PL B424 ('98),
Kunihiro, Shimizu and T. H., PRL 82 ('99), Oller, hep-ph/0007349 ···



$m_\sigma = \mathrm{Re}\sqrt{s_{pole}}$

$-\Gamma_\sigma = 2\,\mathrm{Im}\sqrt{s_{pole}}$

Rev. of Particle Properties ('00)

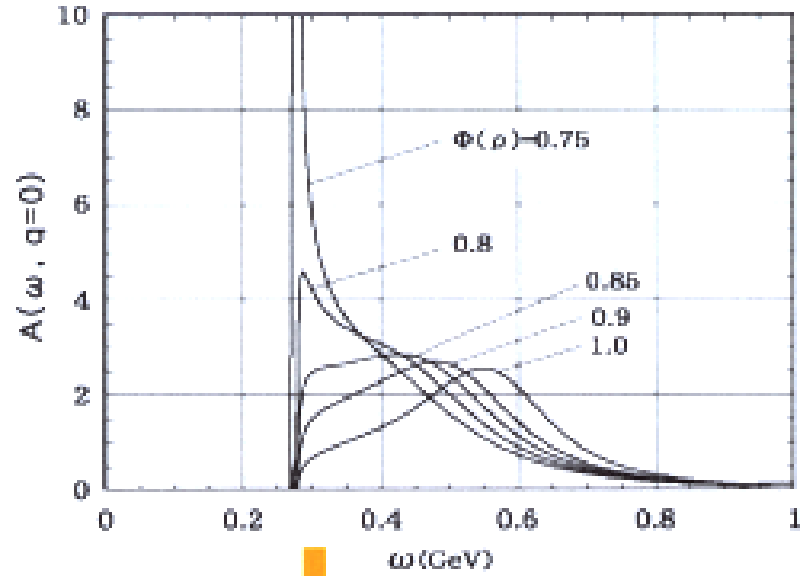
$$\Phi(\rho) = \frac{\langle \bar{q}q \rangle}{\langle \bar{q}q \rangle_0}$$

$$= 1 - \frac{\rho}{f_\pi^2 m_\pi^2}\left[\Sigma_{\pi N} + m\frac{d}{dm}\left(\frac{E(\rho)}{N}\right)\right]$$

$$= 1 - (0.34 \pm 0.08)\frac{\rho}{\rho_0} + \cdots$$

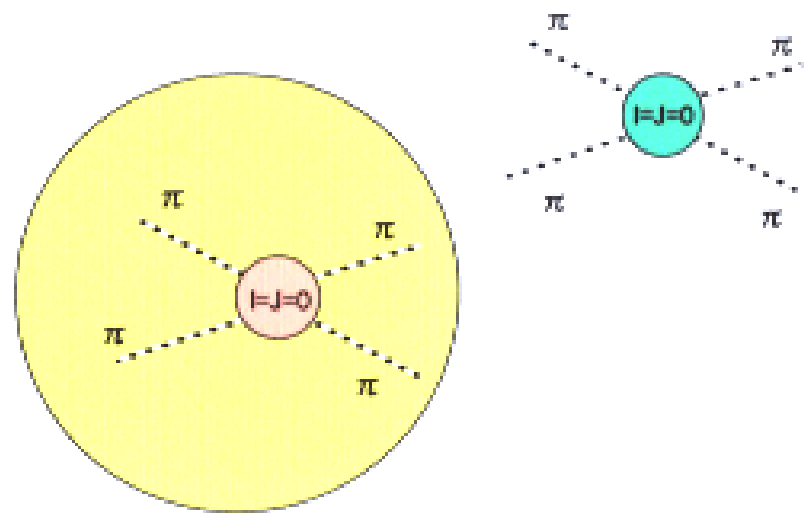
Drukarev and Levin, Prog. Nucl. Part. Phys. ('91)

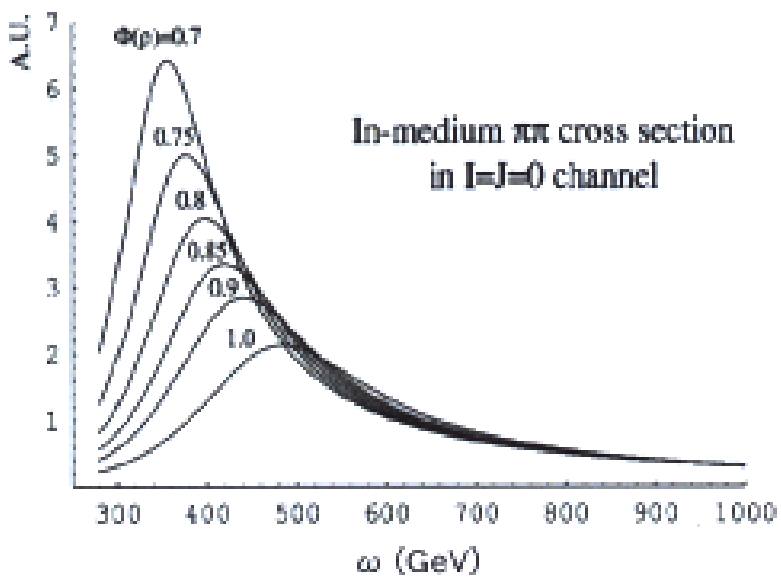
Spectral function of σ in nuclear matter



Kunihiro, Shimizu & T.H., PRL 82 ('99)

soft $\bar{q}q$ vibration in matter

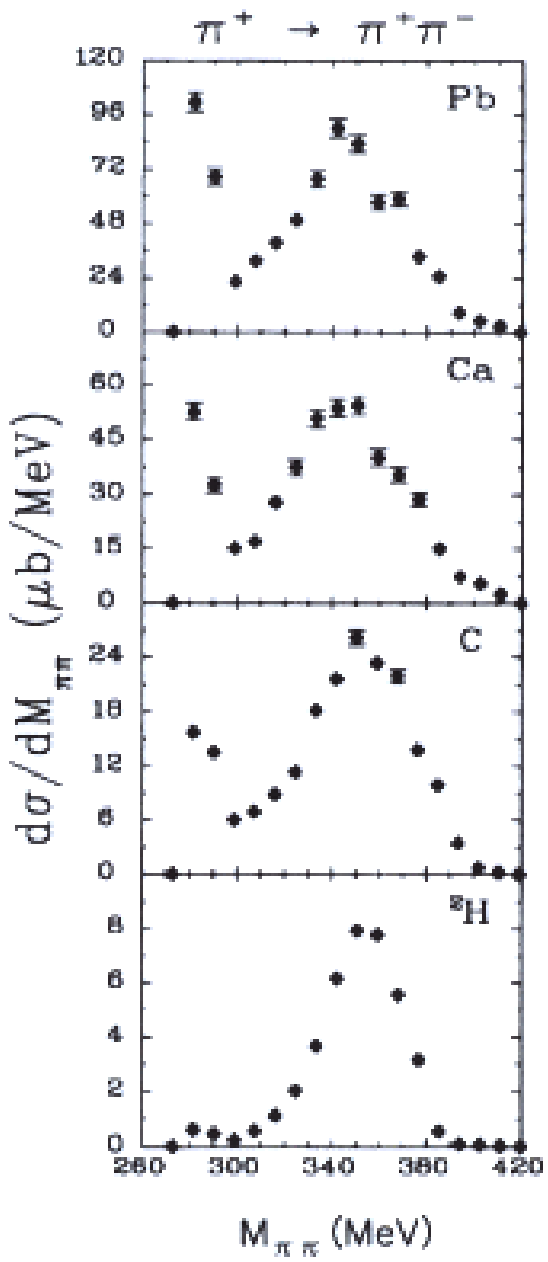




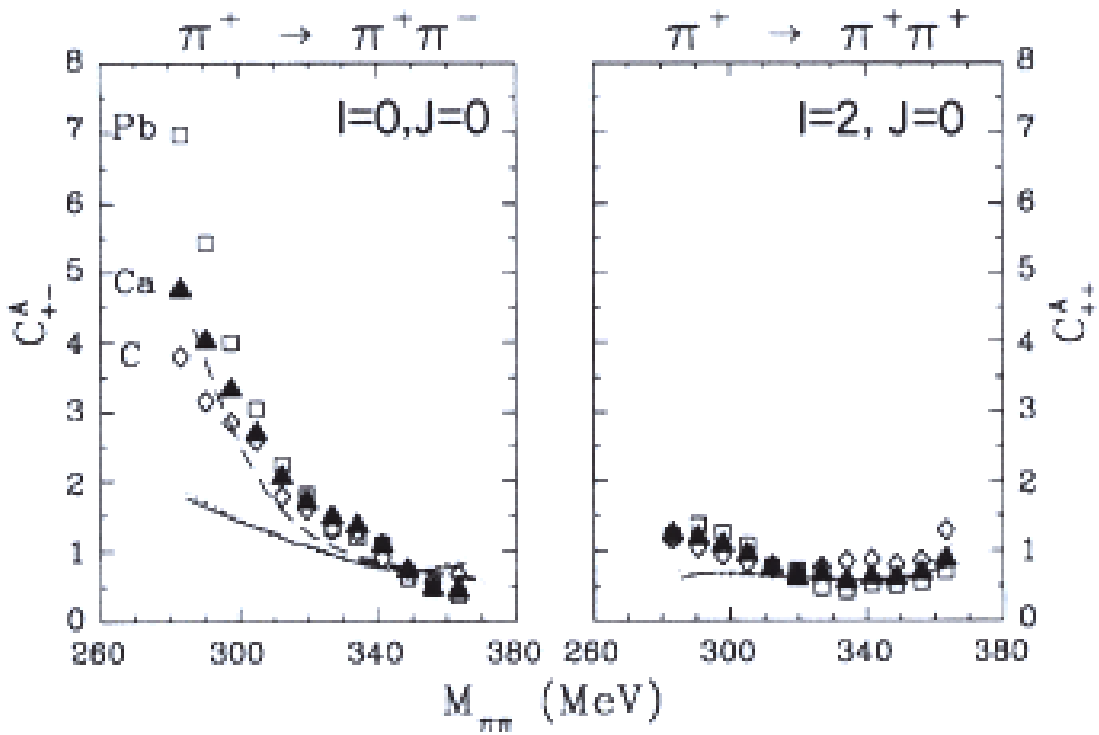
Jido, Kunihiro & T.H., PR D63 ('01)

$\pi A \rightarrow (\pi\pi)_{J=0} A'$

CHAOS Collaboration,
PRL 77 ('96); NP A677 ('00) .



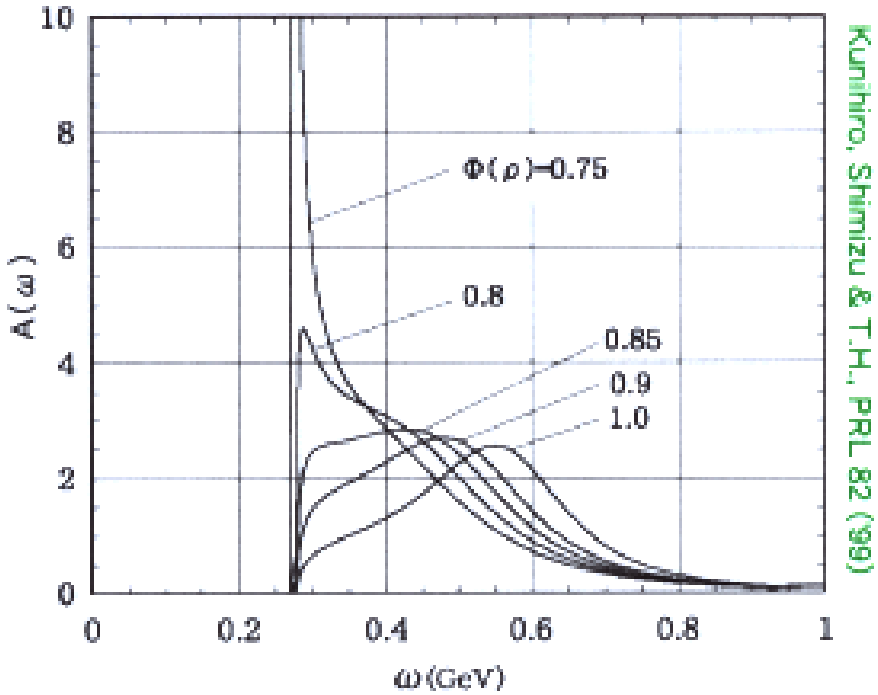
$T_\pi^{in} = 283$ MeV, $(T_\pi^{out}) \sim 50$ MeV



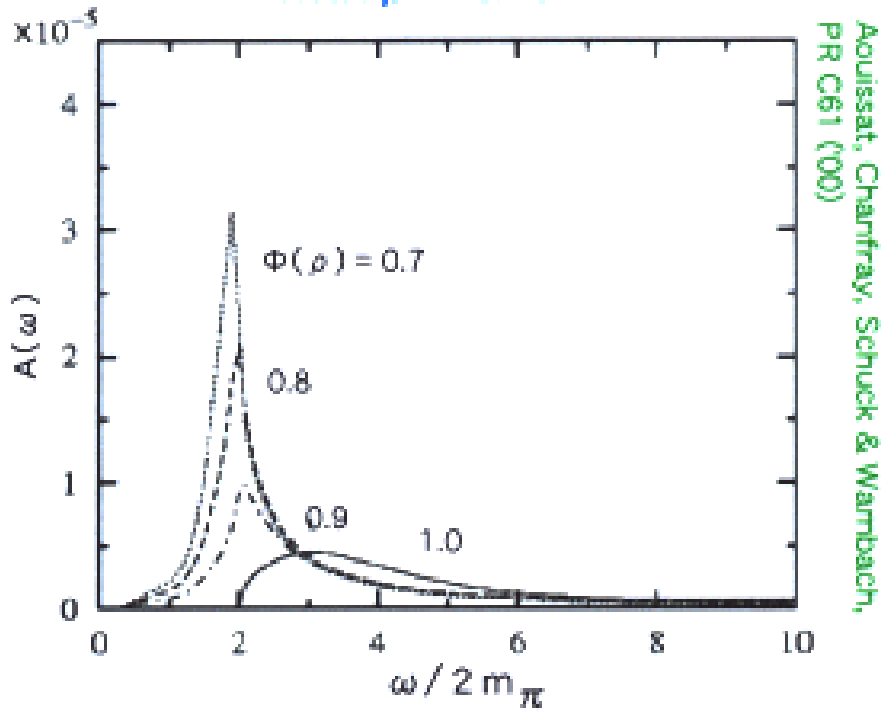
— π–N–Δ dynamics alone :
Rapp et al., PR C59 ('99)
Vicente-Vacas and Oset, PR C60 ('99)

— Softening in I=J=0 channel :
Aouissat, Chanfray, Schuck and Wambach, PR C61 ('00)

Spectral function of σ in nuclear matter



with p−h and Δ−h

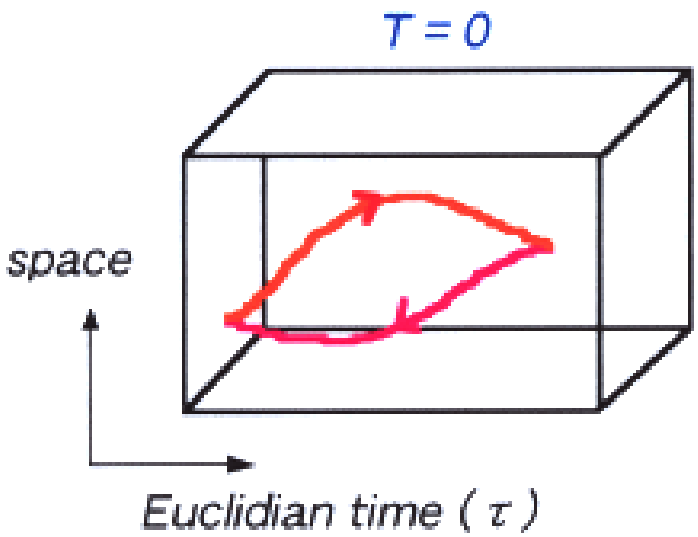


Hadronic correlations in lattice QCD

CP-PACS @ Tsukuba

- Traditional tool : asymptotic analysis

$$D(\tau) = \int \langle H(\tau,\vec{x}) H(0) \rangle \, d^3x \underset{\tau \to \infty}{\sim} e^{-m\tau}$$



MEM ⇒ P[A|D]

(i) No parametrization of $A(\omega)$

(ii) unique solution for $D(\tau) \to A(\omega)$

(iii) Statistical significance of $A(\omega)$

Asakawa, Nakahara & T.H.,
PRD ('99) , hep-lat/0011040

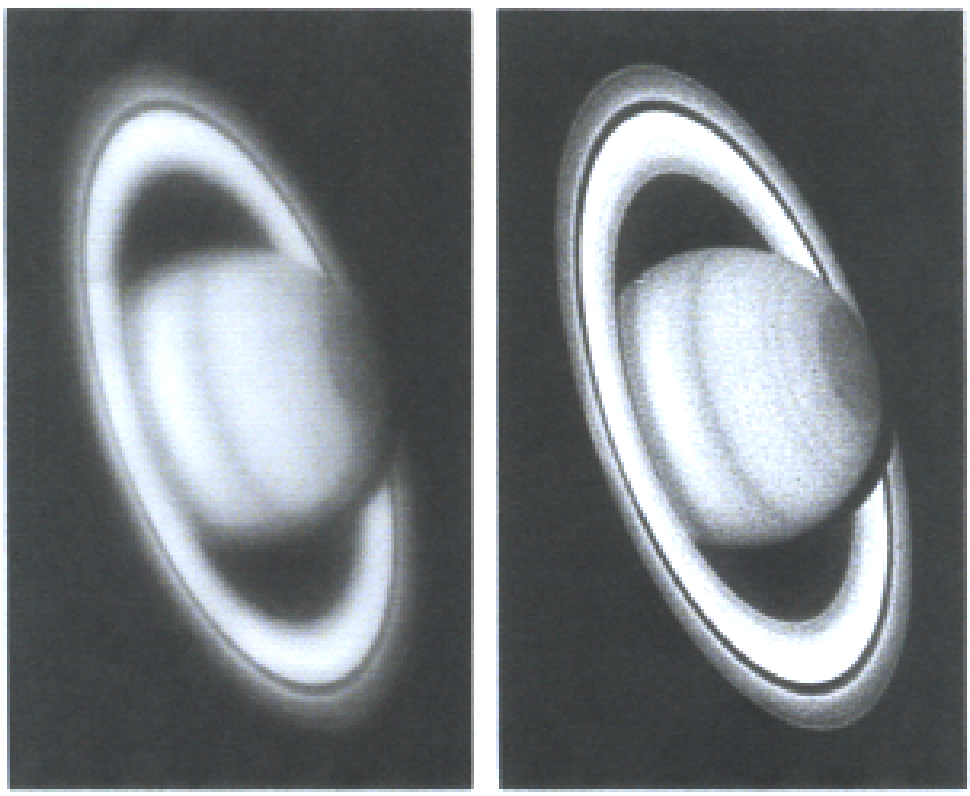
- New approach : Maximal Entropy Method (MEM)

$$D(\tau) = \int_0^\infty e^{-\omega\tau} \, A(\omega) \, d\omega \qquad (\text{use all } \tau)$$

MEM Image Reconstruction

The girl's portrait

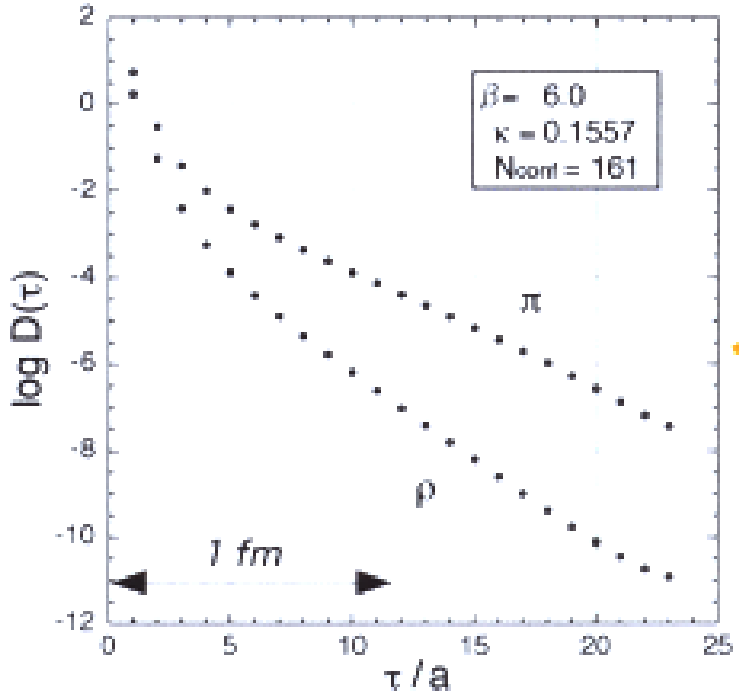
The Image of Saturn



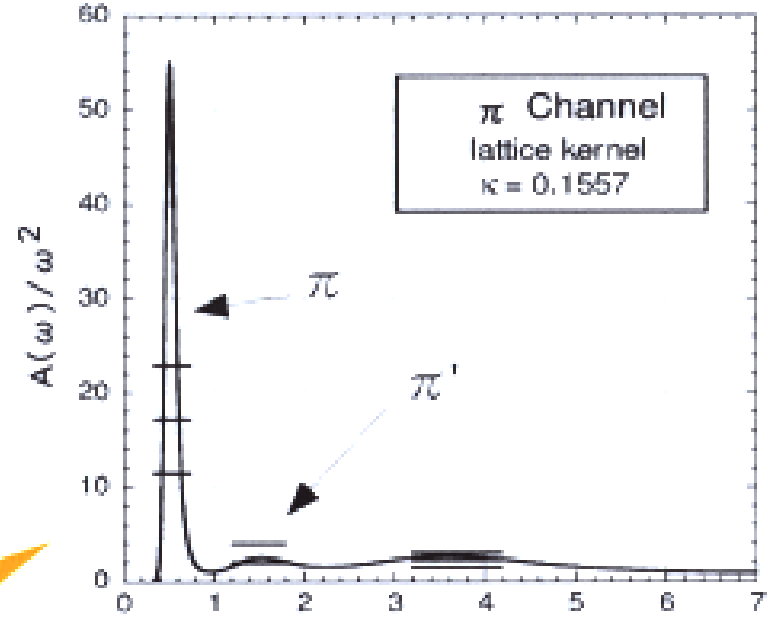
From N. Wu, "The Maximum Entropy Method" (1997)

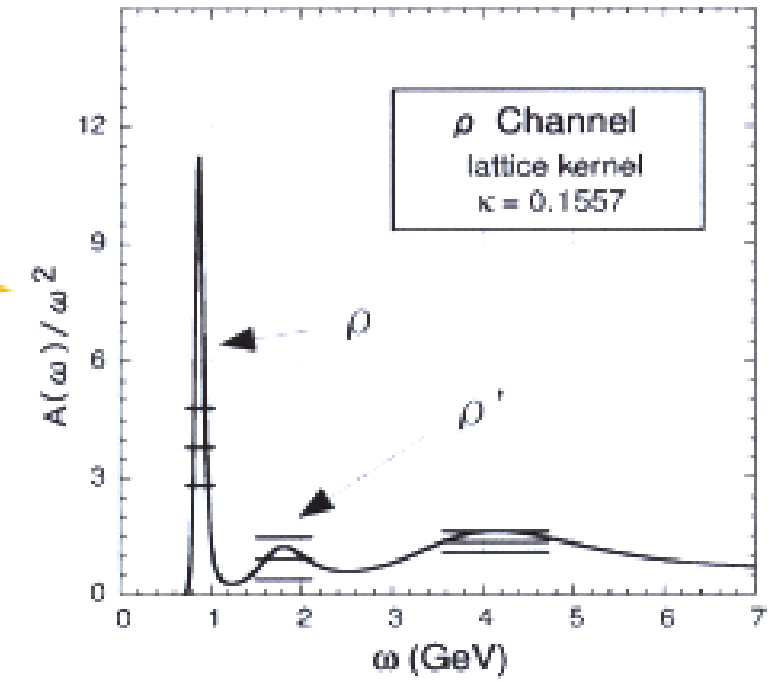
Spectral functions in π & ρ channels at $T = 0$

quenched approximation
lattice size: $20^3 \times 24$



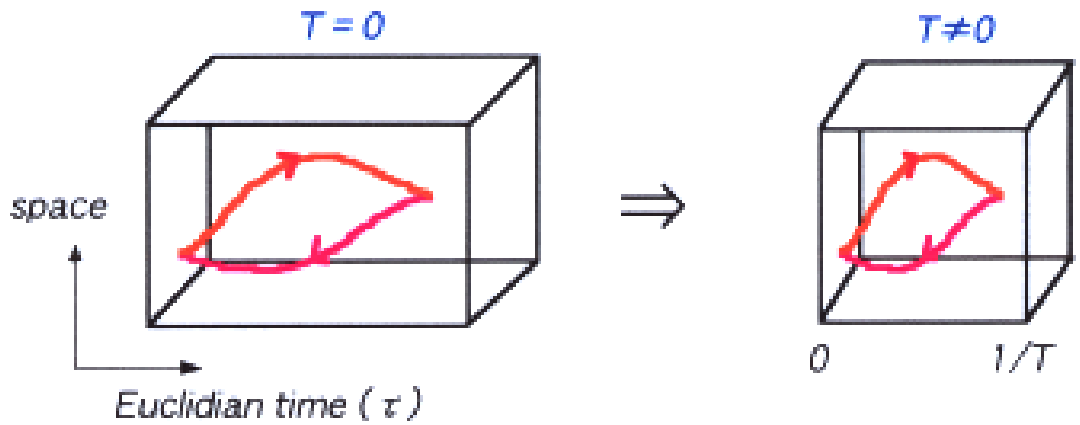
MEM



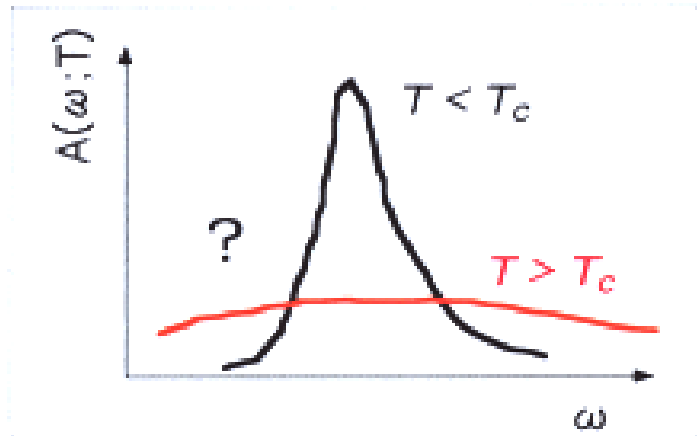


Asakawa, Nakahara & T.H., PRD ('99), hep-lat/0011040

Hadronic correlations at finite T in lattice QCD



$$D(\tau;T) = \int_0^\infty \frac{e^{-\omega\tau} + e^{+\omega(\tau - 1/T)}}{1 - e^{-\omega/T}} A(\omega;T)\, d\omega$$



Lattice QCD + MEM provides a clue to study in-medium hadrons (ρ , J/Ψ , ⋯)

preliminary studies are started :

Asakawa, Nakahara & T.H., in progress.
Oevers, Davies & Shigemitsu, hep-lat/0009031,
Wetzorke & Karsch, hep-lat/0008008.

Summary

T. Bayes 1702–1761

1. QCD phase transition :

   $T_c \sim 170$ MeV , $\rho_c \sim (3-9)\,\rho_0$?

2. In-medium hadrons :

   tracer of the chiral structure of matter

   change of $\langle \bar{q}q \rangle \Leftrightarrow \langle H(x)\,H(y) \rangle$

3. Old idea revived :

   Broad " σ " in the vacuum → Sharp " σ " in matter ⟷ strong $\pi\,\pi$ correlation in matter (CHAOS data)

4. New direction :

   MEM (Maximum Entropy Method) + lattice QCD

   ⇒ first principle studies of the hadronic spectral functions $A(\omega, q\,;\,T)$ ⟷

   - low-mass dileptons
   - J/Ψ suppression

   etc