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COMPRESSED BARYONIC MATTER

Hadrons in dense and hot matter and Chiral Symmetry Restoration

- High baryonic density matter
  - From the high density side : color superconducting phase (di-quark condensation))

    From the low density side : nucleonic (baryonic) matter (three-quark clustering), role of chiral symmetry (restoration) and color confinement implemented in effective theories
- In medium hadronic spectral functions
  - The rho meson and the axial-vector mixing : dilepton production

    Fluctuations of the quark condensate : in-medium scalar-isoscalar modes

I. HADRONS IN MEDIUM

Observable consequences of in-medium chiral dynamics

- Order parameter at finite ρ_B, T
  - Dropping of the quark condensate

$$R = \frac{\langle\langle \bar{q}q \rangle\rangle(\rho_B, T)}{\langle \bar{q}q \rangle_{vac}} = 1 - \sum_h \frac{\rho_h \Sigma_h}{f_\pi^2 m_\pi^2} + higherorder$$

In-medium hadronic spectral functions

- Evolution of the "centroids" (masses)

  No universal link between condensate and observable evolutions (masses, f_π,etc...)

- Shape of the hadronic spectral functions

  Softening/sharpening (σ) or broadening (K, ρ)
  Relation with χSR ?

  Simultaneous study of "chiral partners"

  Vector (ρ) $\longleftrightarrow$ Axial (a_1)

$$\mathcal{V}_k^\mu = \bar{q}\,\gamma^\mu \frac{\tau_k}{2} q, \quad \longleftrightarrow \quad \mathcal{A}_k^\mu = \bar{q}\,\gamma^\mu \gamma_5 \frac{\tau_k}{2} q$$

II. DILEPTON PRODUCTION

- Dilepton production rate from hot and dense matter

$$\frac{dN_{l\bar{l}}}{d^4x d^4q} = -\frac{\alpha^2}{6\pi^3 M^2} \frac{1}{e^{\beta q^0}-1} g_{\mu\nu} \left(\frac{1}{\pi} Im\Pi_V^{\mu\nu} \right.$$

Current-current correlator in the vector channel

$$\Pi_V^{\mu\nu}(q) = -i \int d^4x\, e^{\;iqx} \langle\langle \mathcal{V}^\mu(x), \mathcal{V}^\nu(0) \rangle\rangle (T, \rho_B)$$

Broadening and flatening of the rho meson spectral fonction

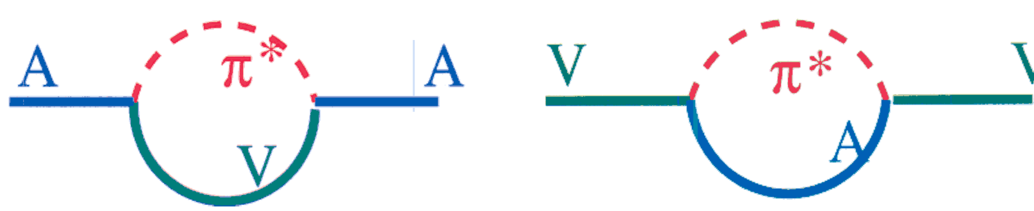
Lowering of the quark-hadron duality threshold $\Longleftrightarrow$ radiation from a chiral symmetry restored phase

- Theoretical ideas and approaches

Density expansion, many-body approaches, transport codes.

QCD sum rules, Weinberg sum rules,..

Dropping masses vs chiral partner mixing



II. *DILEPTON PRODUCTION*

- Many-body approaches

Effective hadronic theories : VDM + χS + phenomenology (πN, ρN, photoabsorption, decay rates,...)

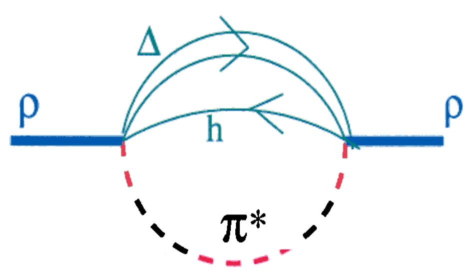
Coupling of the ρ to many-body excitations

- TEMPERATURE EFFECTS : meson gas (Rapp-Gale)

$$\pi\,\rho \longleftrightarrow \omega\,a_1 \qquad\qquad \mathit{Ch.SR}$$

- BARYONIC EFFECTS (Rapp-Wambach, GC et al, Friman et al, Peters et al)

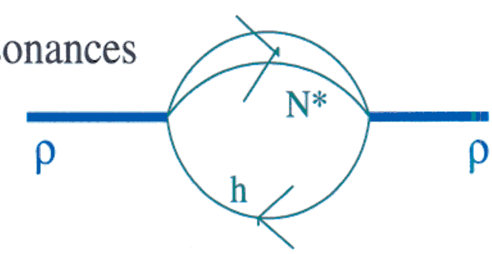
Pion cloud



Pisobars

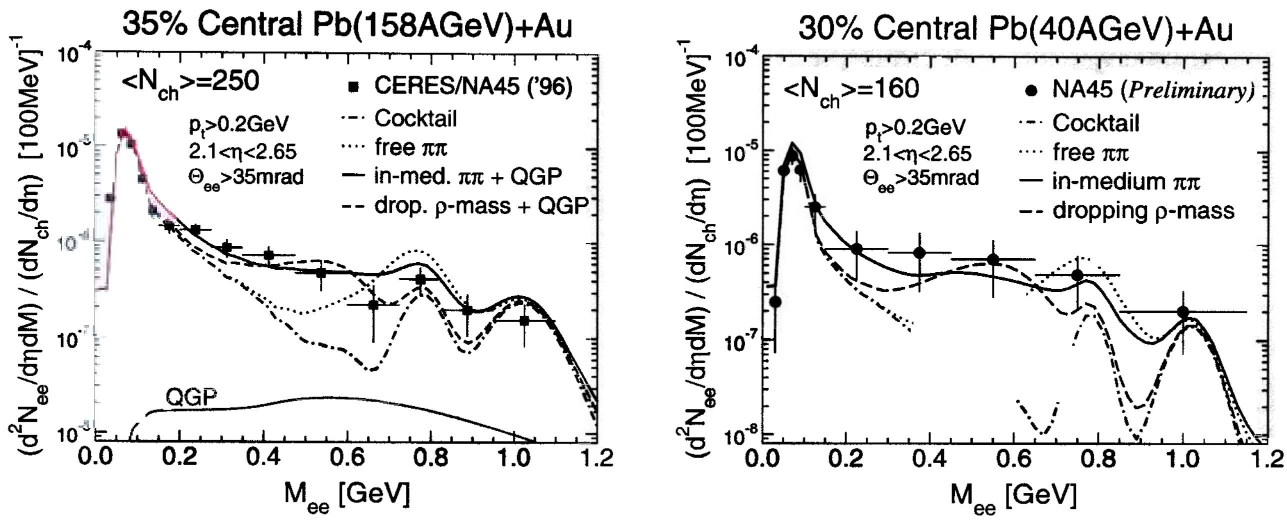
Vector (rho) - Axial baryonic current   Ch. SR

Baryonic resonances



Rhosobars

Dominant S wave (q=0) $N^*_{13}(1520)$: Strong medium effect



- Brodening and flatening dominated by baryonic effects

- Stronger effect at lower SPS energy *i.e.* higher baryonic density

- (Partial) Connection with (partial) chiral symmetry restoration : mixing of vector and axial correlators : Linked to the pionic part of the in-medium chiral condensate

- What is the chiral status of the $N^*(1520)$? Linked to a nucleon structure problem

III. SCALAR ISOSCALAR MODES

- High baryonic density matter

One central question : in-medium behaviour of scalar-isoscalar modes ?

- Order parameter $\mathcal{M}^{ij}$ $\quad \psi_R^j \psi_L^i$

$$\langle \mathcal{M}^{ij} \rangle \neq 0 \qquad \mathcal{M} \rightarrow V_L \mathcal{M} V_R^\dagger$$

$$\mathcal{M} = \left(\frac{\bar{\psi}\psi}{2} \right) + i\vec{\tau}\cdot \left(i\bar{\psi}\gamma_5 \frac{\vec{\tau}}{2}\psi \right) \qquad \sigma + i\vec{\tau}\cdot\vec{\pi}$$

  - σ meson : amplitude fluctuation of the condensate
  - pion phase fluctuation of the condensate

But $\quad \sigma \rightarrow \pi\pi \quad$ Large σ width

- In-medium "σ meson"
  - Chiral symmetry restoration : softening (hardening) of the spectral function (dropping of the sigma mass and chiral condensate)
  - Coupling of the sigma to in-medium $\pi\pi$: softening
  - Role of the nucleonic polarization or confinement ?

III. SCALAR ISOSCALAR MODES

Chiral effective theory

NJL type : $M \sim -2G\,\langle\langle \bar{q}q \rangle\rangle(\rho, T)$

Hadronic theories : $\langle\langle \sigma \rangle\rangle \sim \langle\langle \bar{q}q \rangle\rangle(\rho, T)$

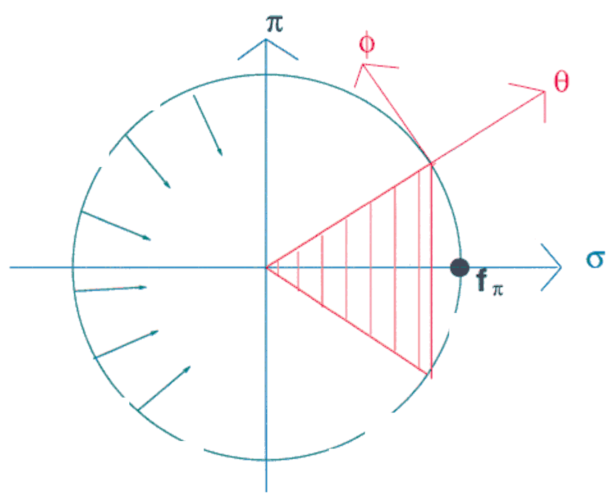
Alternative : $\sigma + i\,\tau \cdot \vec{\pi} = \Theta\, U \qquad (\theta + f_\pi)\, e^{i\,\tau \cdot \vec{\phi}_\pi}$

- $\vec{\phi}$ New pion field : orthoradial soft mode

– • θ is chiral invariant : fluctuation of the chiral radius to be identified with the "sigma meson " of the Walecka model

$$R = 1 - \frac{\langle \phi_\pi^2 \rangle(\rho)}{2\, f_\pi^2} \qquad \frac{|\langle \theta \rangle|(\rho)}{f_\pi}$$

- Pionic fluctuation : $\langle \phi_\pi^2 \rangle$
- Shrinking of the chiral radius : $\langle \Theta \rangle$ decreases



Manifestations of χS Restauration

- Pionic fluctuations $\Longleftrightarrow$ Axial-vector mixing
- Scalar field (Θ) $\Longleftrightarrow$ Dropping of the masses

III. *SCALAR ISOSCALAR MODES*

In-medium spectral function or $T_{\pi\pi}^{I=J=0}$

- In-medium $\sigma\pi\pi$

Coupling of the sigma (with vacuum mass and couplings) to dressed pions

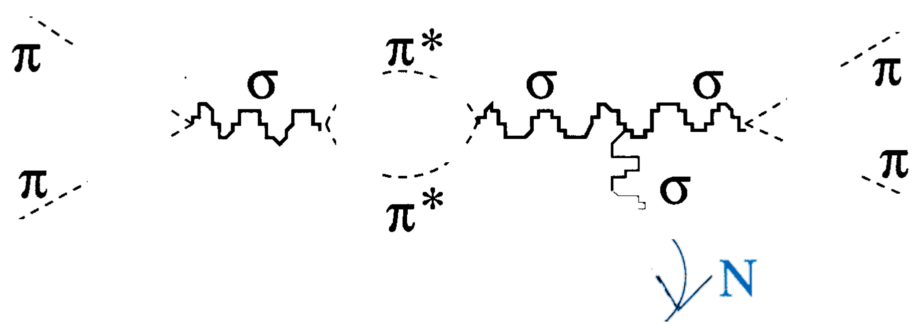
σ pole in the complex plan moves at lower energies with a reduced width (Oset et al) $\rightarrow$ Shift of the the invariant mass spectrum in $A(\gamma\,,\,\pi^0\pi^0)$ observed by the TAPS collaboration

- Chiral symmetry restoration

Softening (and sharpening) of a collective scalar-isoscalar mode *i.e.* the particle representing the amplitude fluctuation of the order parameter around the minimum of the effective potential

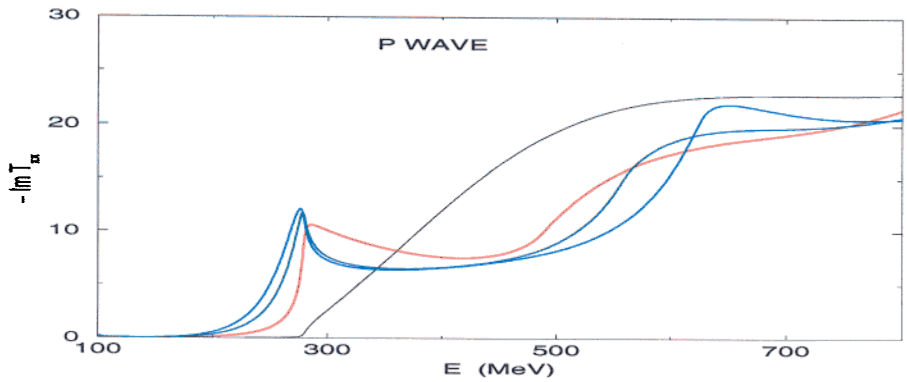
Precursor effect of χ SR : Sharp structure near the 2π threshold in σ and $\pi\pi$ strength function at ρ_d such that :

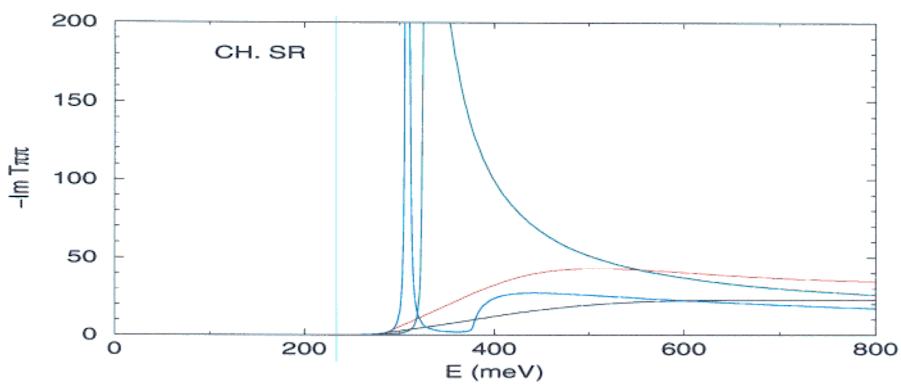
$m_\sigma = 2\,m_\pi$ (Hatsuda et al)

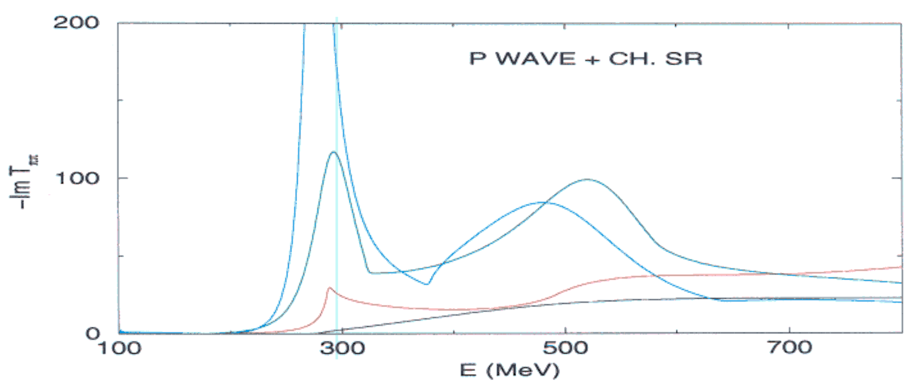


III. SCALAR ISOSCALAR MODES

- Model calculation : In-medium $T_{\pi\pi}$ (Linear sigma model (NJL), $\pi\pi$ phase shifts)







III. SCALAR ISOSCALAR MODES

Four-quark condensate

$$\langle 0|(\bar{q}q)^2|0\rangle = \langle 0|\bar{q}q|0\rangle\langle 0|\bar{q}q|0\rangle + \sum_n \langle 0|\bar{q}q|n\rangle\langle n|(\bar{q}q)|0\rangle$$

$|n$ 2π scalar-isoscalar modes .e σ mesor

- Model calculation

Effective linear sigma model with in-medium modified couplings (m_σ, f_π, m_π) from chiral symmetry restoration (NJL)

Unitarization : $\pi\pi$ loop with pion p-wave dressing from nuclear physics i.e. $\Delta - h$

$$\kappa_2(\rho) = \frac{\langle(\bar{q}q)^2\rangle(\rho)}{\langle\bar{q}q)\rangle^2(\rho)} = 1 + \frac{1}{f_\pi^2(\rho)}\int_0^{\Lambda_P}\frac{d\mathbf{P}}{(2\pi)^3}\int_0^\infty dE\left(\frac{-1}{\pi}\right) ImD_\sigma(\boldsymbol{E},\mathbf{P})$$

ρ/ρ_0	m_σ	m_π	f_π	$\Delta\kappa_2$
0	1000		93	0
0.5	890	140.3	87	0.33
1	795	143.1	79	0.88
1.5	649	148.7	69	1.39
2	510	161	56	3.74

III. SCALAR ISOSCALAR MODES

Matter stability in chiral theories

Energy density of dense nuclear matter

$$\epsilon(\rho,\sigma) = \sum_{p<p_F} \sqrt{(p^2 + M_N^*(\langle\sigma\rangle)} + V(\langle\sigma\rangle) + C_V\,\rho^2$$

- NJL (Bentz, Thomas, Birse) : Nucleon$\equiv$ diquark-quark state. $M_q = g_q\,\langle\sigma\rangle$
- Chiral relativistic theories : $\sigma = \Theta \equiv$ chiral invariant scalar field. $M_N^* = g\,\langle\Theta\rangle$

NO STABILITY

Decrease of the curvature of the effective potential when $\langle\sigma\rangle$ drops

A sizeable $\frac{\partial^2 M_N}{\partial\sigma^2}$ can stabilize the matter

NEED OF CONFINEMENT EFFECT

NJL : Infrared cutoff

QMC : Polarization of the nucleon : Influence of the scalar field on the confined quark wave functions

IV. SCALAR-ISOSCALAR MODES

Model calculation

$$\mathcal{H} = N^\dagger\left(-i\,\vec{\alpha}\cdot\nabla + \beta\, M_N\left(1 + \frac{\theta}{f_\pi} + C\,\frac{\theta^2}{f_\pi^2}\right)\right)N$$

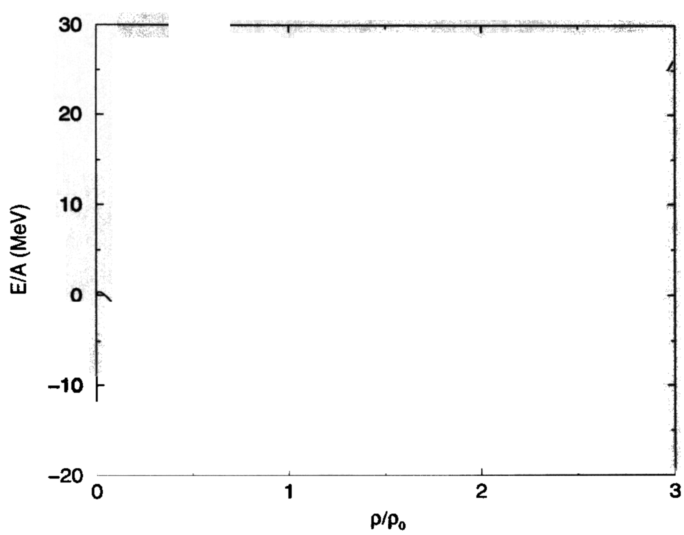
$$+\frac{m_\theta^2}{8\,f_\pi^2}\left((\theta + f_\pi)^2 \qquad f_\pi^2)^2 + g_\omega\,\omega\,N^\dagger N \qquad \frac{1}{2}\,m_\omega^2\,\omega^2\right.$$

$g_{\theta NN} = M_N/f_\pi \simeq 10, \qquad m_\theta \simeq 800\,MeV$

Extra θ^3, θ^4 terms constrained by chiral symmetry *i.e.* from the Mexican hat potential.

$C \simeq 1$: Nucleon polarization (QMC model) needed !

Short range repulsion : g_ω^2/m_ω^2 : $m_\omega \simeq 780\,MeV$, $g_\omega \simeq 6$



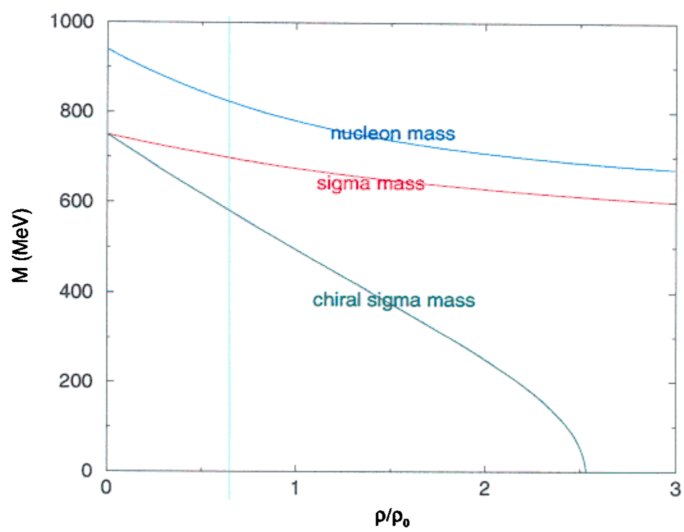
IV. SCALAR-ISOSCALAR MODES

- In-medium sigma mass

$$m_\sigma^{*2} = \frac{\partial^2 \epsilon}{\partial \Theta^2}$$

"Confining" term : $\frac{\theta^2}{f_\pi^2} + \frac{1}{3}\frac{\theta^3}{f_\pi^3}$

$m_\sigma = 750\, MeV, \quad g_\omega = 6.8$

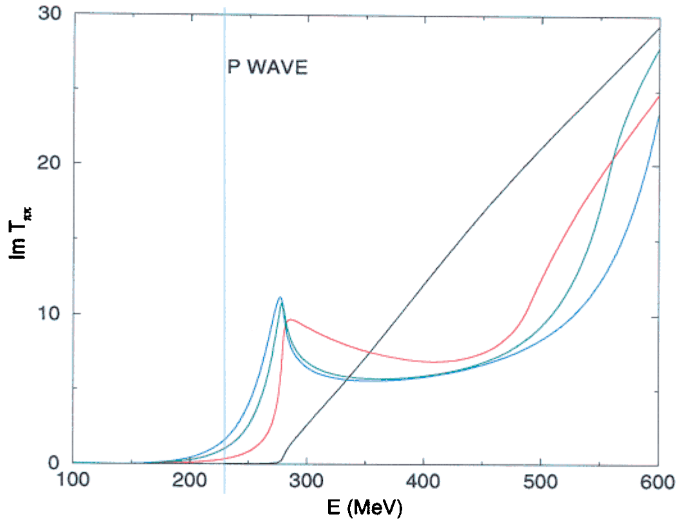


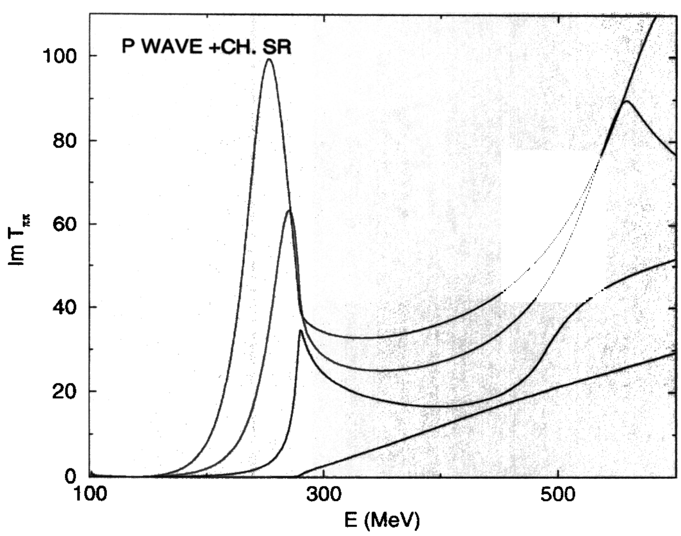
Very weak density dependence : "confinement" compensates chiral dropping

The scalar susceptibility (scalar quark density fluctuations) $\chi_S \sim 1/m_\sigma^{*2}$ does not increase but seems to saturate in the range $2 - 3\,\rho_0$

IV. SCALAR-ISOSCALAR MODES

- $\pi\pi$ Strength function : Parameter set 1





Main effect : Dropping of the condensate

$$\lambda_{\sigma\pi\pi} = \frac{m_\sigma^{*2} \quad m_\pi^2}{\langle\Theta\rangle}$$

IV. SCALAR SUSCEPTIBILITY

Scalar susceptibility

Define the Scalar susceptibility from the scalar correlator *i.e.* the correlator of the scalar quark density fluctuations :

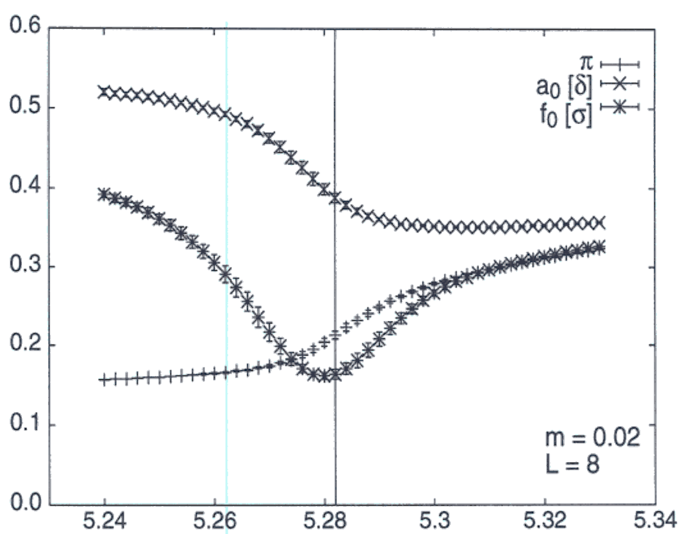
$$\chi_s = \frac{\partial \langle\langle \bar{q}\, q \rangle\rangle}{\partial m} = \int dt\, d\vec{r}\, \langle\langle \delta\, \bar{q}\, q(0,0),\, \delta\, \bar{q}\, q(\vec{r},t) \rangle\rangle$$

$$\delta\, \bar{q}\, q(\vec{r},t) = \bar{q}\, q(\vec{r},t) \; - \; \langle \bar{q}\, q \rangle$$

- Thermal susceptibility (from lattice, Karsch et al)

- Near the phase transition the scalar susceptibility (fluctuations of the order parameter) becomes large

- Above the critical point : degeneracy between the chiral partners π and σ



SCALAR SUSCEPTIBILITY

Finite density susceptibilities (M

$$\to \quad \frac{\langle \bar q\, q\rangle_{vac}}{f_\pi}\,\sigma(\vec r,$$

$$\bar q\, i\,\gamma_5\,\frac{\vec\tau}{2} q(\vec r, t) \quad \to \quad \frac{\langle \bar q\, q\rangle_{vac}}{f_\pi}\,\vec\Phi(\vec r, t$$

- Scalar susceptibility

- Quark density fluctuations carried by the scalar field σ

$$\chi_S = \frac{\langle \bar q\, q\rangle^2_{vac}}{f^2} \int dt\, d\vec r\, \langle\langle \delta\sigma(0,0),\, \delta\sigma(\vec r, t)\rangle\rangle$$

$$\chi_S = \frac{\langle \bar q\, q\rangle^2_{vac}}{f^2}\, Re D_\sigma(\omega \quad 0\,,\, \mathbf{q} = 0)$$

- Sharp (in-medium) sigma $D_\sigma(r) = e^{-m^*_\sigma r}/r \quad \to \quad \chi_S \sim 1 \; m^{*2}_\sigma$
infinite range fluctuations

- Scalar density fluctuations transmitted by the sigma meson, relayed by the nucleons *i.e.* coupling to NN^{-1}. $\Longleftrightarrow$ increase the range of the fluctuations

$$D_\sigma = D^0_\sigma + D^0_\sigma\, \Pi_{SS}\, D^0_\sigma$$

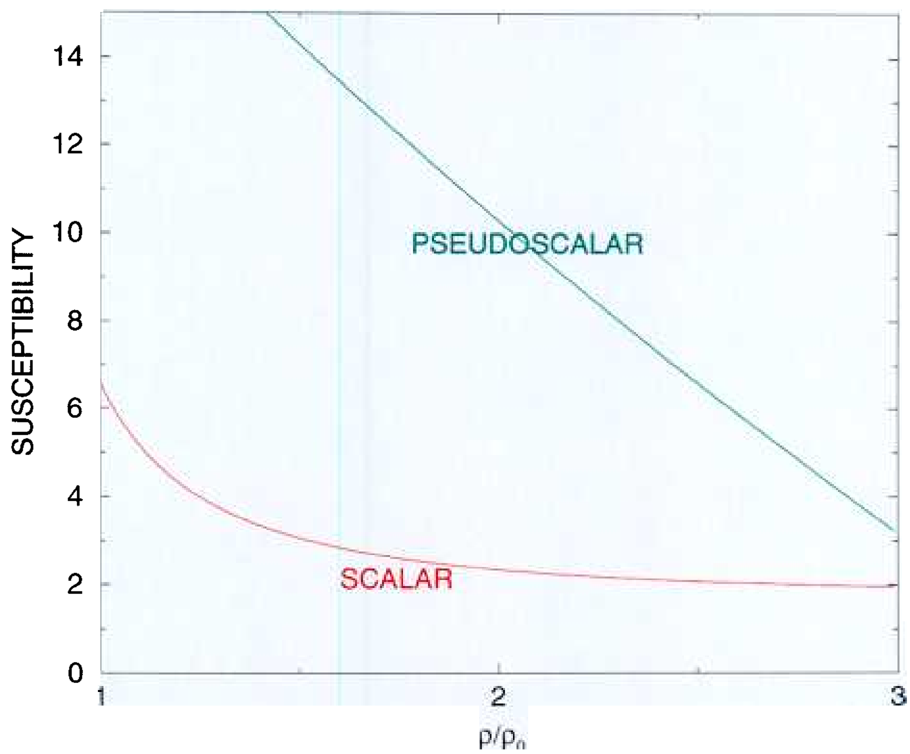
$$D_\sigma = D^0_\sigma \left(1 + \frac{g_S^2}{m_\sigma^2}\,\frac{9}{K}\right)_{\rho=\rho_0}$$

IV. SCALAR SUSCEPTIBILITY

- Model calculation

$$D_\sigma = D^0_\sigma \frac{m_\sigma^2}{m_\sigma^{*2}} \left(1 + \frac{g_S^{*2}}{m_\sigma^{*2}} \Pi(0,0) \right)$$

$$\Pi(0,0) \qquad \frac{\left(-2\, M_N^*\, k_F/\pi^2\right)}{1 - \left(\frac{g_V^2}{m_V^2} - \frac{g_S^{*2}}{m_\sigma^{*2}}\right) \left(-2\, M_N^*\, k_F/\pi^2\right)}$$



V. CONCLUSION

• Dilepton production : Broadening of the vector meson spectral function driven by baryonic effect. Connection to chiral restoration only partially understood

• Study of high baryonic density matter : Need for a consistent description incorporating :

In-medium chiral dynamics (coupling to the condensate)

baryon (nucleon) structure and confinement

• Support from lattice at finite density (spectral functions, susceptibilities,..)