Meson Physics in LEPS2 : $U_A(1)$ anomaly and OZI rule

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$U_A(1)$ problem

Pseudoscalar meson nonet

$$m_\pi = 138\,\mathrm{MeV}$$
$$m_K = 496\,\mathrm{MeV}$$
$$m_\eta = 549\,\mathrm{MeV}$$
$$m_{\eta'} = 958\,\mathrm{MeV}$$

Vector meson nonet

$$m_\rho = \underline{770}\,\mathrm{MeV}$$
$$m_{K*} = 892\,\mathrm{MeV}$$
$$m_\omega = \underline{782}\,\mathrm{MeV} \sim \bar{u}u + \bar{d}d$$
$$m_\phi = 1019\,\mathrm{MeV} \sim \bar{s}s$$

- Why $m_\eta \neq m_\pi$?
- Why is η' meson so heavy?

if $\eta' \sim \bar{s}s$, then $m_{\eta'} \cong \sqrt{2m_K^2 - m_\pi^2} = 687\,\mathrm{MeV}$

$U_A(1)$ anomaly

$U_A(1)$ symmetry of the QCD action is explicitly broken by the quantum effect: **Anomaly**

$$\partial^\mu A^0_\mu = 2N_f \frac{g^2}{32\pi^2} G^a_{\mu\nu} \left(G^a\right)^{\mu\nu}$$

Spontaneous chiral symmetry breaking in QCD

$$\mathrm{SU_L(3)} \times \mathrm{SU_R(3)} \times \mathrm{U_V(1)} \to \mathrm{SU_V(3)} \times \mathrm{U_V(1)}$$

Number of the Goldstone boson is **8**

Dynamical mechanism of the U(1) symmetry breaking has not been understood yet!

- 1/Nc expansion approach
- Instanton approach

Three energy scales are similar.

1. Dynamical chiral symmetry breaking
2. Strange quark mass
3. $U_A(1)$ anomaly

It is important to treat these energy scales on an equal footing.

Partial restoration of $U_A(1)$ symmetry at finite density

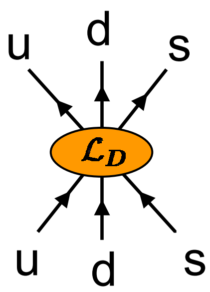
If dynamical origin of the $U_A(1)$ symmetry breaking is instanon induced quark detarminant interaction derived by ‘t Hooft,

At finite density, it is natural that $U_A(1)$ breaking interaction becomes weaker.

3 flavor Nambu-Jona-Lasinio Model

$$\mathcal{L} = \bar{q}(i\not{\partial} - m)q + \frac{g_s}{2}\sum_{a=0}^{8}\left[(\bar{q}\lambda_a q)^2 + (i\bar{q}\lambda_a\gamma_5 q)^2\right]$$
$$+ g_D\left[\det \bar{q}_i(1-\gamma_5)q_j + h.c.\right]$$

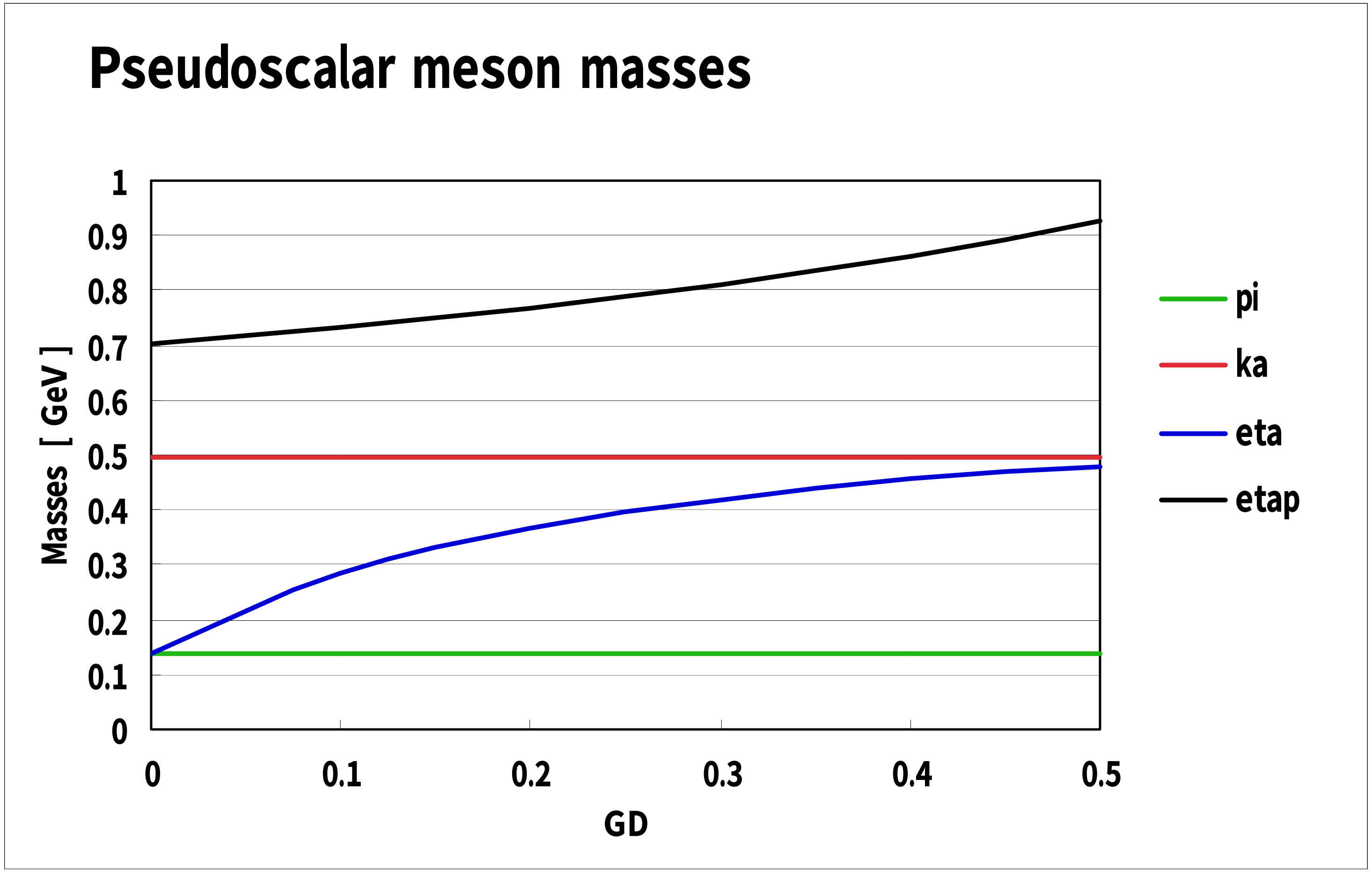
explicit breaking the $U_A(1)$ sym.



Kobayashi, Maskawa Prog.Theor.Phys.44, 1422 (70)
G. 't Hooft, Phys.Rev.D14,3432 (76)

For a review, T. Hatsuda and T. Kunihiro, Phys. Rep. 407, 205 (1994).

Pseudoscalar meson masses in NJL Model



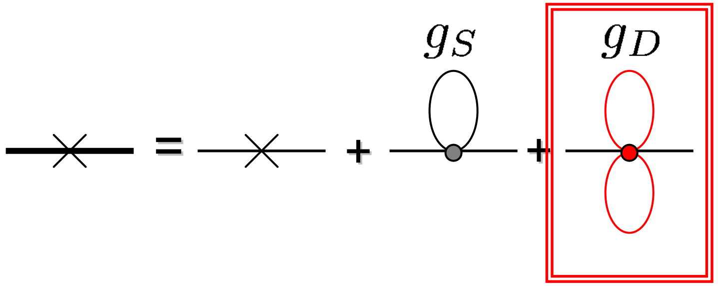
M. Takizawa, et al., Nucl. Phys. A 507, 611 (1990)

NJL model at finite density

Gap equations for quarks

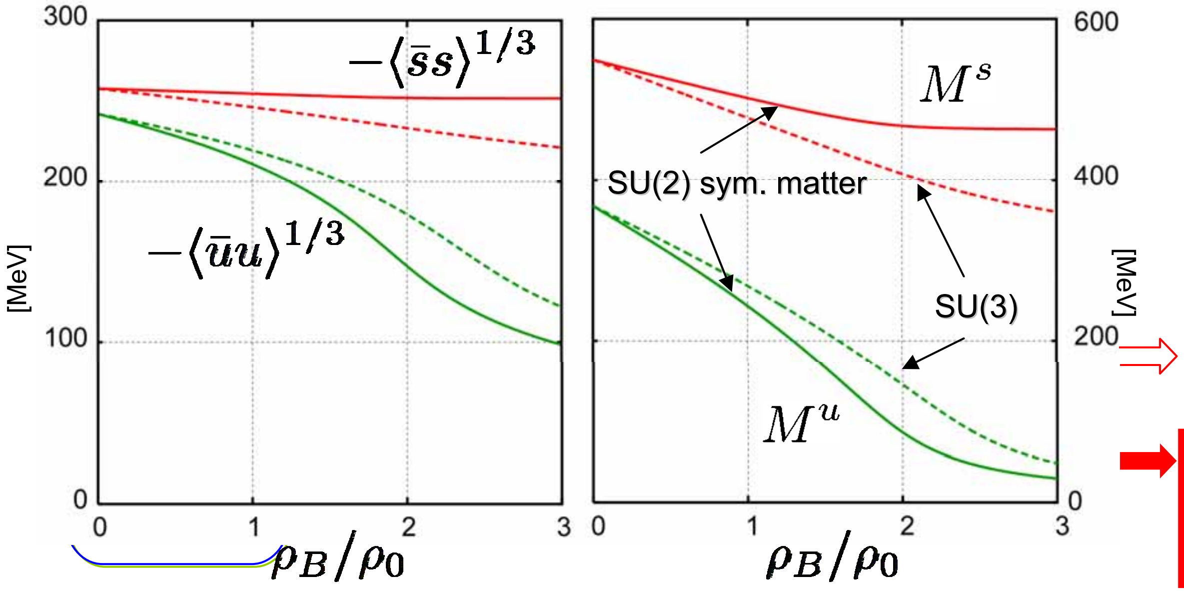
$$\begin{cases} M^u = m^u - 2g_S\langle\bar{u}u\rangle - 2g_D\langle\bar{d}d\rangle\langle\bar{s}s\rangle \\ M^d = m^d - 2g_S\langle\bar{d}d\rangle - 2g_D\langle\bar{s}s\rangle\langle\bar{u}u\rangle \\ M^s = m^s - 2g_S\langle\bar{s}s\rangle - 2g_D\langle\bar{u}u\rangle\langle\bar{d}d\rangle \end{cases}$$

flavor mixing terms



condensate in finite T/ρ

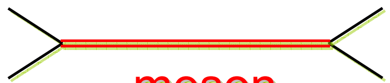
$$\langle\bar{q}q\rangle = -2N_C\int\frac{d^3p}{(2\pi)^3}\frac{M}{E_p}(1 - n_p(T,\mu) - \bar{n}_p(T,\mu))$$



$$n(T,\mu) = \frac{1}{e^{(E_p-\mu)/T}+1}$$

Fermi distribution function

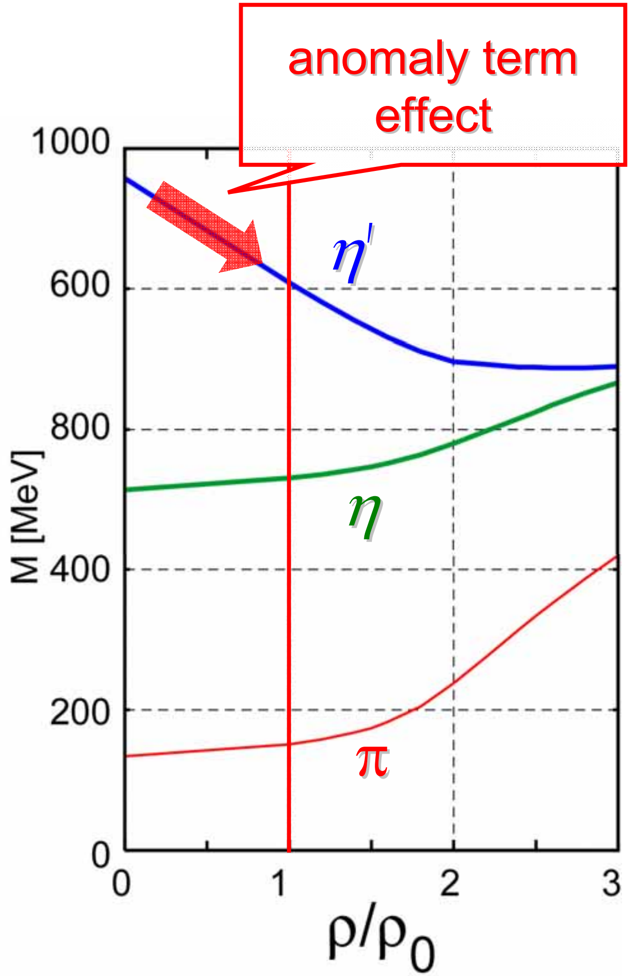
partial restoration in medium



meson

meson properties (mass)

SU(2) symmetric matter $\rho_u = \rho_d,\ \rho_s = 0$



H. Nagahiro, M. Takizawa and S. Hirenzaki, Phys. Rev. C 74, 045203 (2006)

parameters (in vacuum)

P. Rehberg, et al., PRC53(96)410.

Λ = 602.3 [MeV]
$g_S \Lambda^2$ = 3.67
$g_D \Lambda^5$ = -12.36
$m_{u,d}$ = 5.5 [MeV]
m_s = 140.7 [MeV]

$M_{u,d}$ = 367.6 [MeV]
M_s = 549.5 [MeV]
$\langle \bar{u}u \rangle^{1/3}$ = -241.9 [MeV]
$\langle \bar{s}s \rangle^{1/3}$ = -257.7 [MeV]
$m_{\eta'}$ = 958 [MeV]
m_η = 514 [MeV]
m_π = 135 [MeV]

η and η' mass shifts @ ρ_0

$\Delta m_{\eta'} \sim -150$ MeV @ ρ_0

$\Delta m_\eta \sim +20$ MeV @ ρ_0

We can see the large medium effect even at normal nuclear density.
-> Hirenzaki-san's talk

η and η' mesons at finite density

η: Mass shift of η is rather small.
How about mixing angle? Maybe large!

$\eta \to \gamma\gamma$ Decay width, Primakoff effect results are smaller than $e^+ e^- \to e^+ e^- \eta$ ones

η': Mass reduction of η' is rather large.
η' mesic nuclei

Mass spectrum of light scalar meson nonet

Scalar meson nonet

$$m_{a0} = 985\,\mathrm{MeV}$$
$$m_{\kappa} \sim 900\,\mathrm{MeV}$$
$$m_{\sigma} \sim 700\,\mathrm{MeV}$$
$$m_{f0} = 980\,\mathrm{MeV}$$

•Why $m_{ao} \neq m_{\sigma}$?

Vector meson nonet

$$m_{\rho} = \underline{770}\,\mathrm{MeV}$$
$$m_{K*} = 892\,\mathrm{MeV}$$
$$m_{\omega} = \underline{782}\,\mathrm{MeV} \sim \bar{u}u + \bar{d}d$$
$$m_{\phi} = 1019\,\mathrm{MeV} \sim \bar{s}s$$

•Why $m_{\kappa} < m_{a0}$?

$(\bar{q}q)(\bar{q}q)$ structure of scalar mesons explain this spectrum, naturally!

D. Black, A.H. Fariborz, S. Moussa, S. Nasri, and J. Schechter,
Phys.Rev. D 64 (2001) 014031, and references therein.

Instanton induced $U_A(1)$ breaking interaction give rise to flavor mixing not only to pseudoscalar channel but also in scalar channel.

a_0 - σ mass difference

K. Naito, M. Oka, M. Takizawa, T. Umekawa, Prog. Theor. Phys. 109 (2003) 969

Three flavor NJL model results

Model parameters

$$m_u = m_d = 8\ MeV, \quad m_s = 193\ MeV$$

$$Cutoff \quad \Lambda = 783\ MeV$$

Results

$$M_u = M_d = 325\ MeV, \quad M_s = 529\ MeV$$

$$\langle \bar{u}u \rangle^{1/3} = -216\ MeV, \quad \langle \bar{s}s \rangle^{1/3} = -226\ MeV,$$

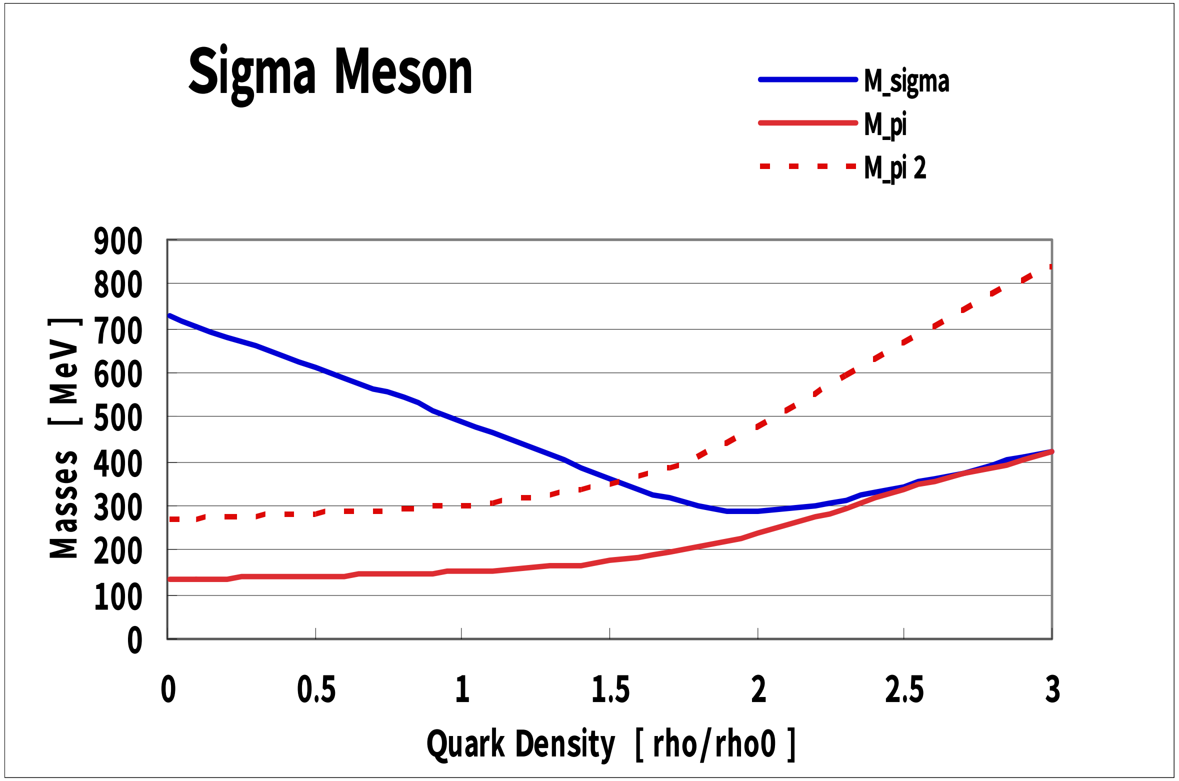
$$m_\pi = 138.0\ MeV, \quad m_K = 495.7\ MeV, \quad m_\eta = 510\ MeV$$

$$m_\sigma = 650\ MeV, \quad m_{a0} = 816\ MeV,$$

$$m_{K0} = 1002\ MeV, \quad m_{f0} = 1164\ MeV$$

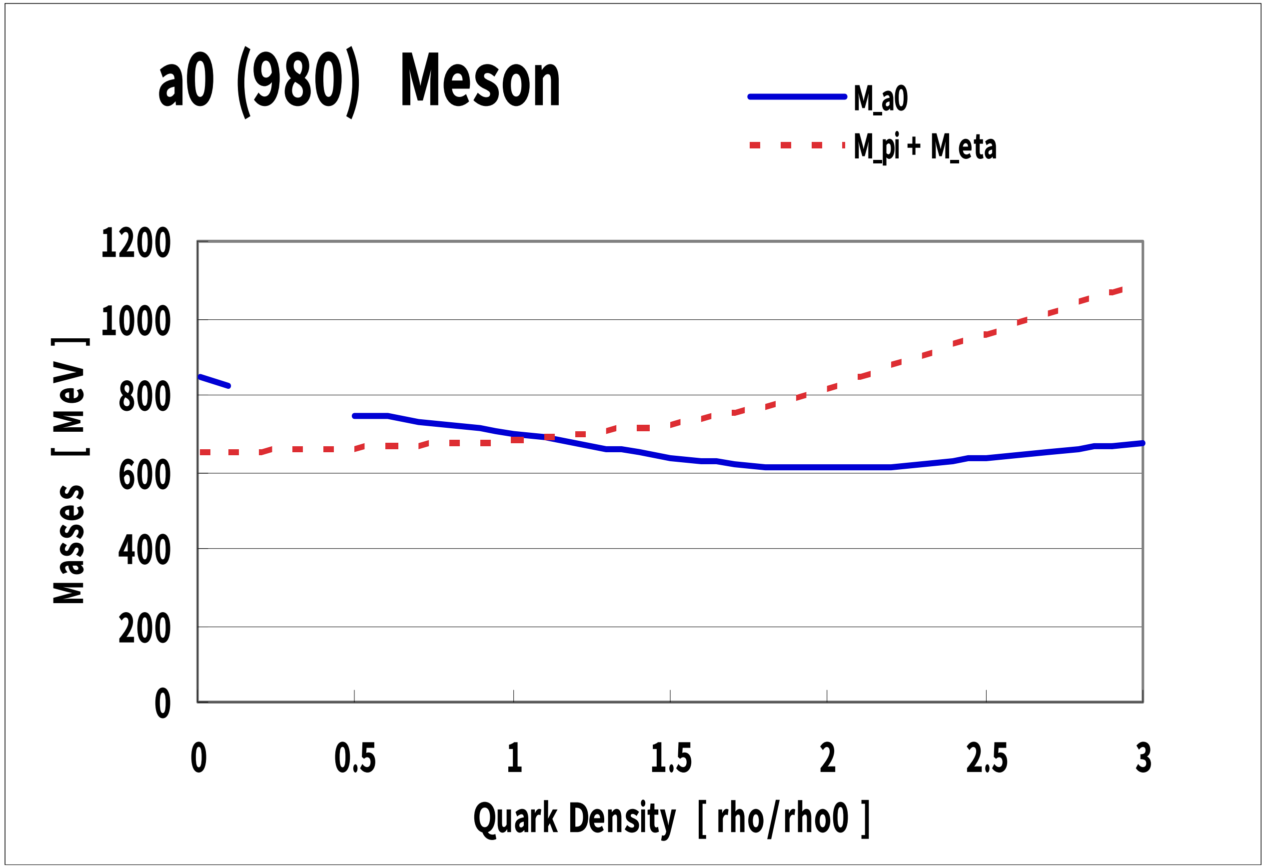
Scalar mesons at finite density

Naïve NJL model result.



More elaborate work including sigma-pi-pi coupling:
T. Hatsuda, T. Kunihiro and H. Shimizu, Phys. Rev. Lett. 82, 2840 (1999)

Naïve NJL model result.



If instanton induced UA(1) breaking interaction becomes weaker rather quickly as density increases, we have a chance to observe the shape a0(980) state at density below rho0.

OZI rule in vector mesons

- OZI rule is well satisfied in vector meson sector.
- In J/psi case, asymptotic freedom of QCD can explain it, however, ω-ϕ meson case, the explanation is rather difficult.
- Since nuclear medium is not flavor U(3) invariant, OZI rule may be broken.

OZI rule in light quark (u,d) sector

- OZI rule in u,d-quark sector for vector meson is badly broken.

ρ mesons are isovetor and ω is isoscalar.
If OZI rule is not broken,

$$\rho^0 \approx \bar{u}u, \quad \omega \approx \bar{d}d$$

In the case of pseudoscalar mesons,
$U_A(1)$ anomaly explains it. Very small $\pi^0 - \eta$ mixing.

Therefore, pion loop effects may give rise to the OZI violation of the vector mesons in the u,d-quark sector.

Summary

- Dynamics of the $U_A(1)$ symmetry breaking eta and eta’ mesons
- Structure of the scalar mesons
- OZI violation at finite density?