How do diquark fluctuations and chiral soft modes affect di-lepton production in the deconfined phase

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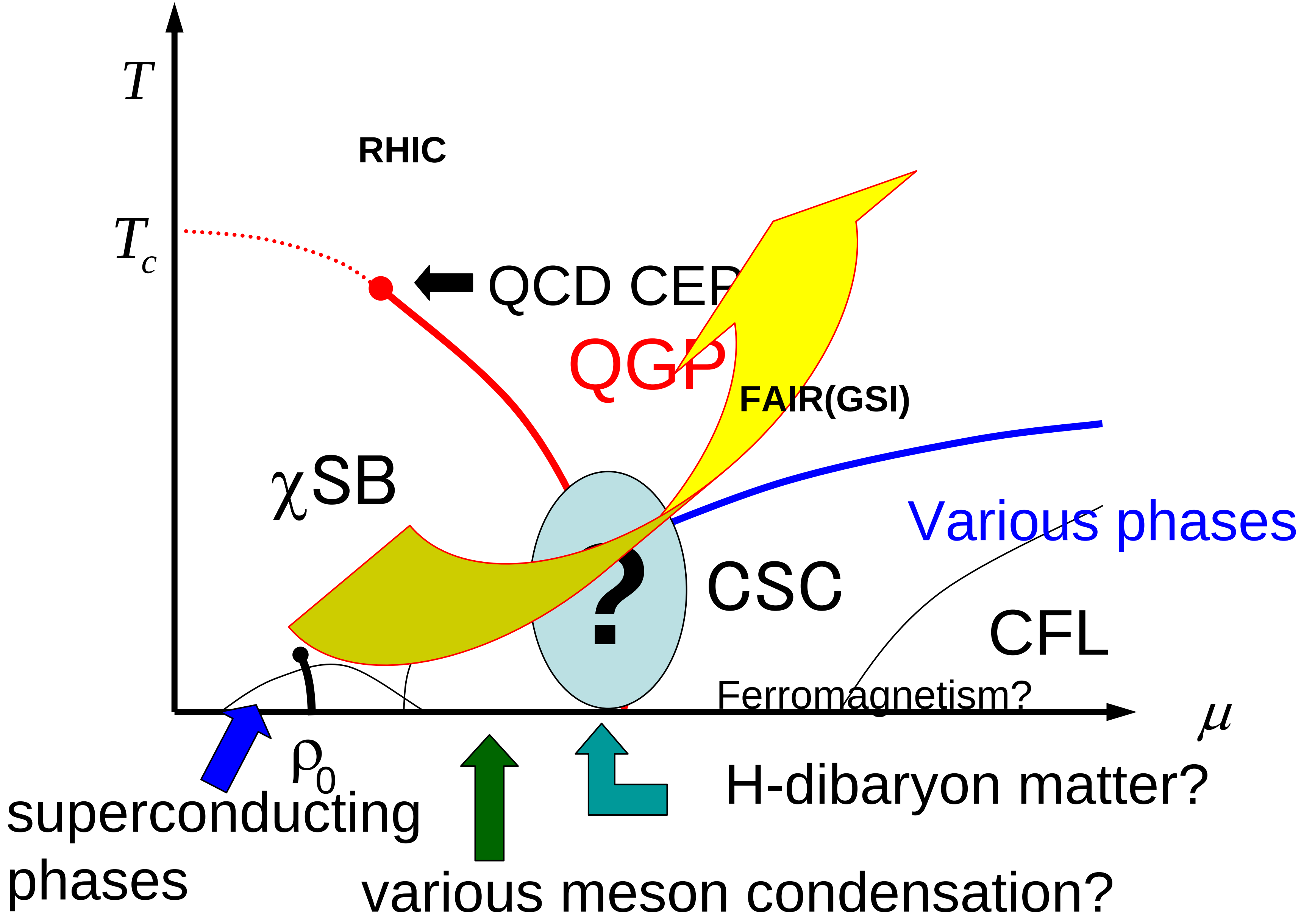
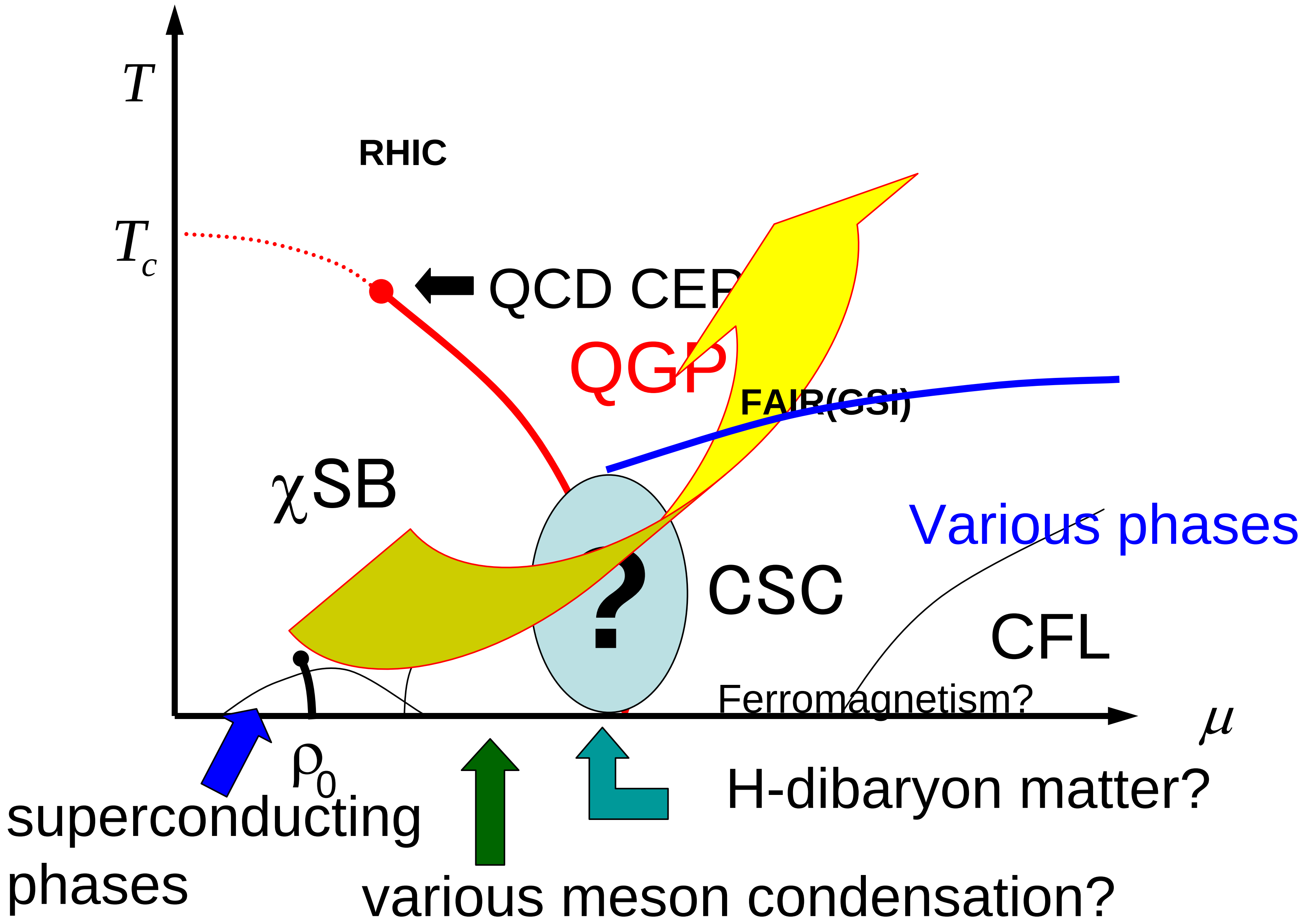
in collaboration with M. Kitazawa and Y. Nemoto

A conjectured QCD phase diagram



A conjectured QCD phase diagram



Contents

- Part 1 The soft mode of CSC above Tc and lepton-pair production
- Part 2 The sigma mode above Tc at finite density and lepton-pair production

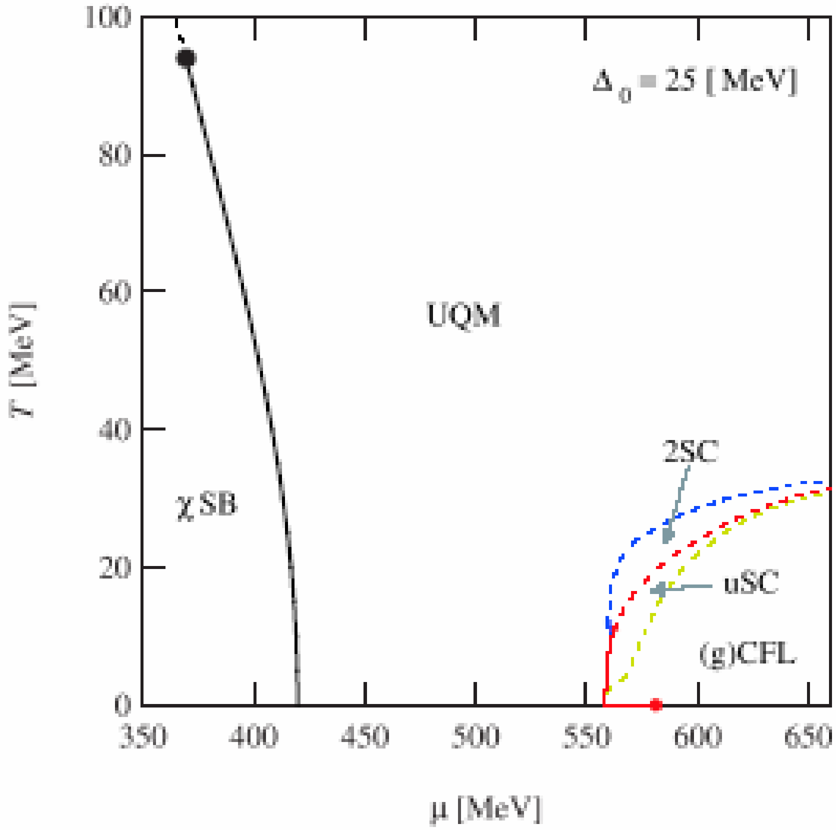
PART I

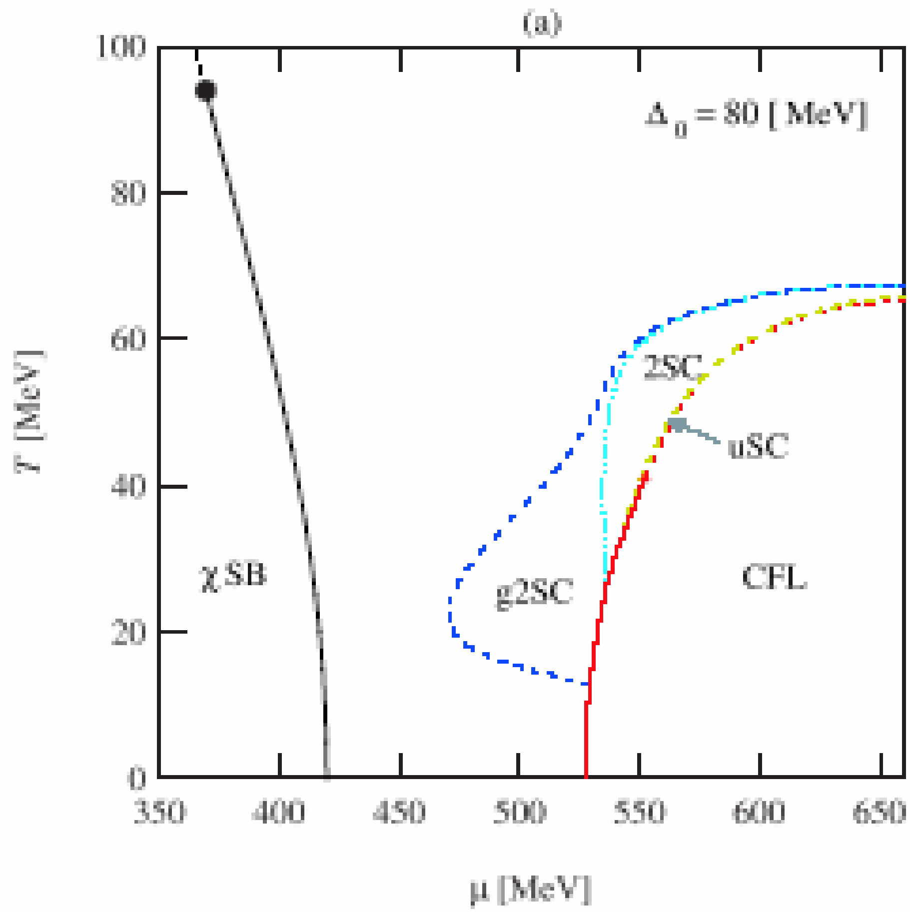
Precursory Phenomena of Color Superconductivity in Heated Quark Matter

Ref. M. Kitazawa, T. Koide, T. K. and Y. Nemoto
Phys. Rev. D70, 956003(2004);
Prog. Theor. Phys. 114, 205(2005),
M. Kitazawa, T.K. and Y. Nemoto,
Phys. Lett.B 631(2005),157
M. Kitazawa and T. K., in preparation

Various CSC phases in $T\!-\!\mu$ plane

H .Abuki and T.K.
Nucl. Phys. A, 768 (2006),118;
with charge and color neutrality





The phase in the highest temperature is 2SC or g2SC.

Various CSC phases in $T-\mu$ plane

H .Abuki and T.K.
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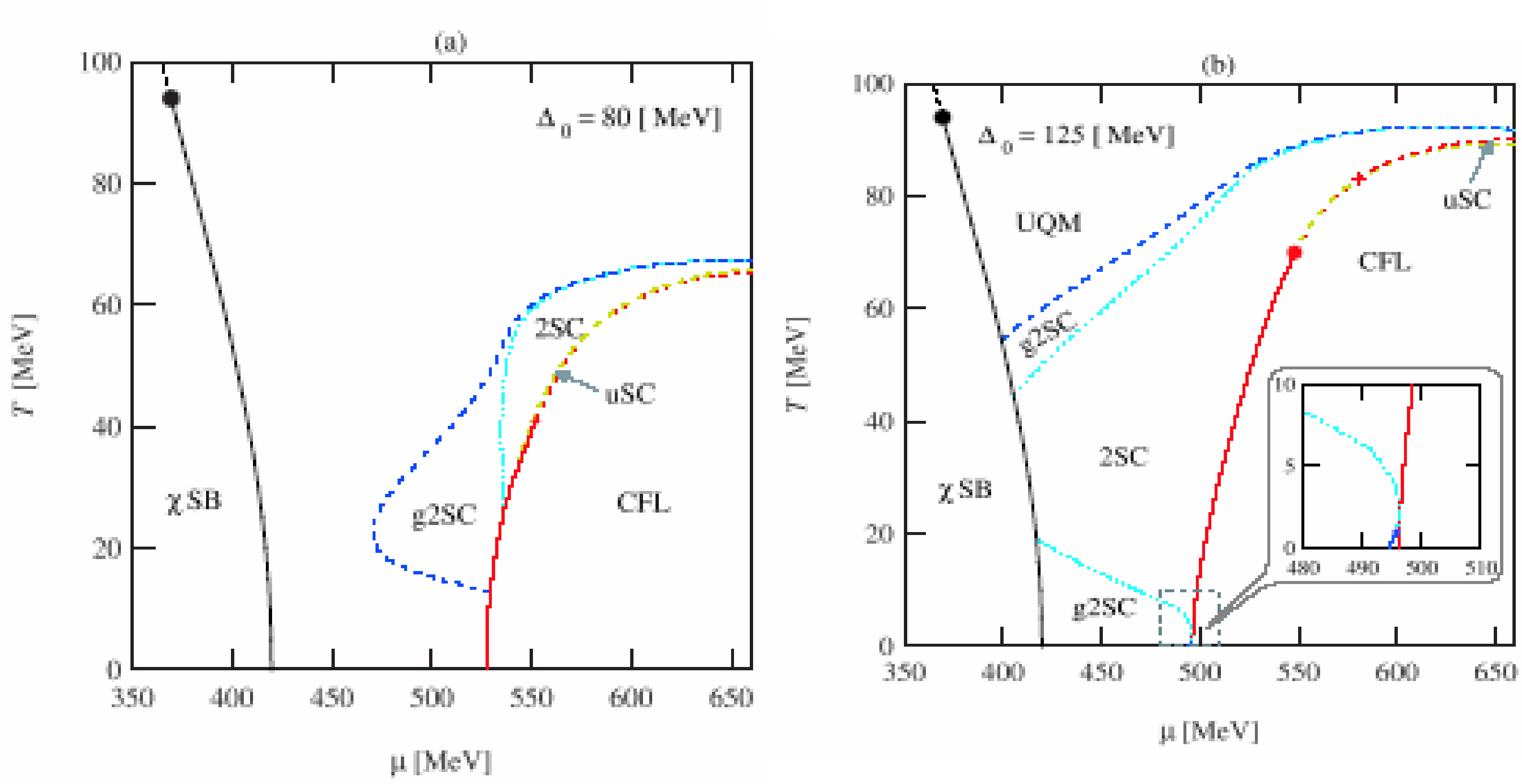
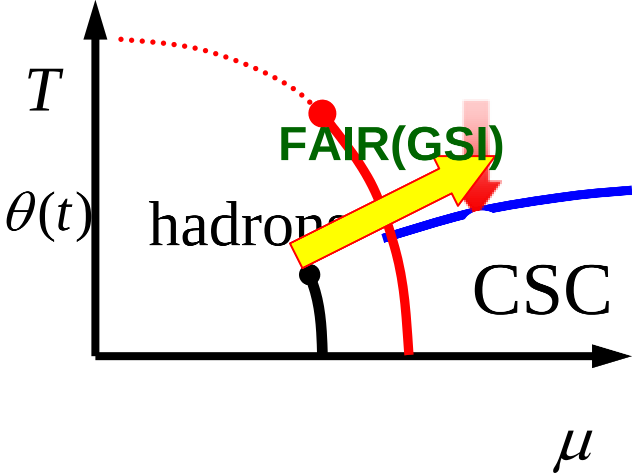


The phase in the highest temperature is 2SC or g2SC.

Pair Fluctuations in CSC

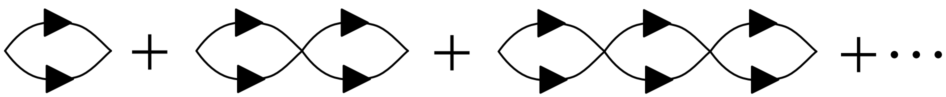


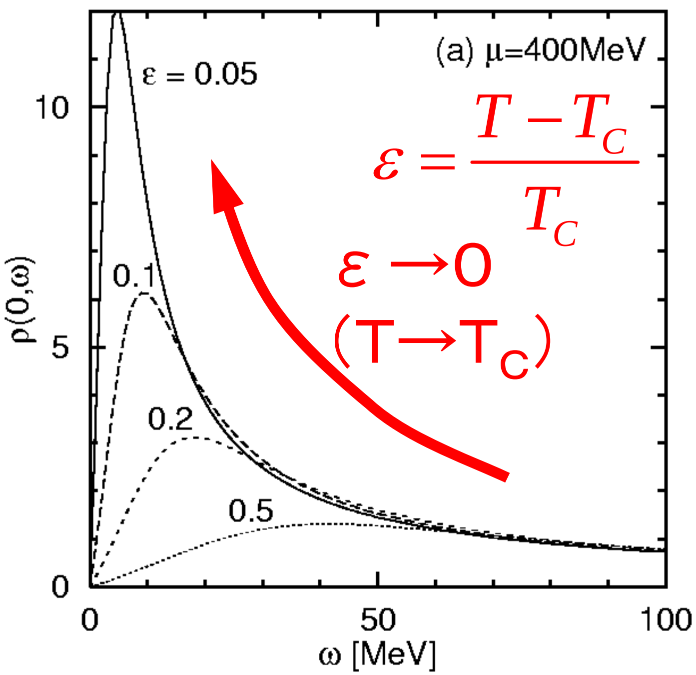
$$D^R(\mathbf{x},t) = -2G_C\left\langle\left[\bar\psi(x)i\gamma_5\tau_2\lambda_2\psi^C(x), \bar\psi(0)i\gamma_5\tau_2\lambda_2\psi^C(0)\right]\right\rangle\theta(t)$$

Spectral Function of the diquark excitations

$$\rho(\mathbf{k},\omega) = -\frac{1}{\pi}\mathrm{Im}\, D^R(\mathbf{k},\omega)$$

$$D^R(\mathbf{k},\omega) =$$





- Sharp peak from ε **~ 0.2**

electric SC: ε **~ 0.005**

even in 2d-SC

Existence of large pair fluctuations

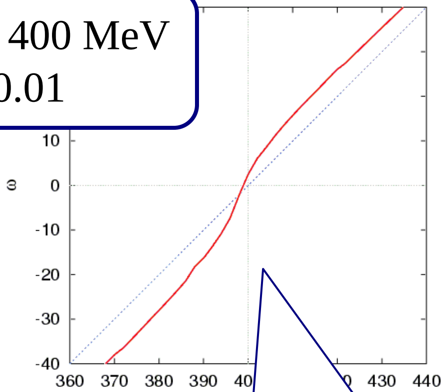
M.Kitazawa, T. Koide, T. K., Y. Nemoto, PRD **65**, 091504 (2002)

It may affect various observables even well above T_c.

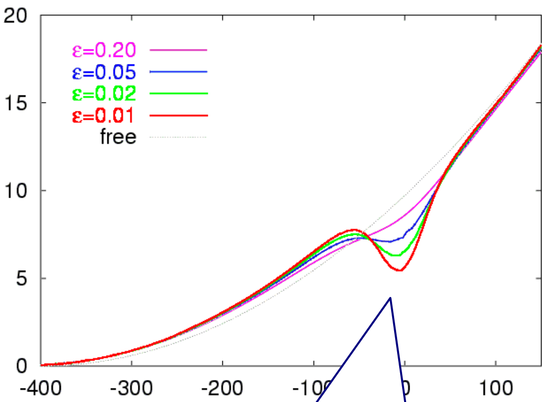
Precursory Phenomena

- quark dispersion
- density of states
- specific heat

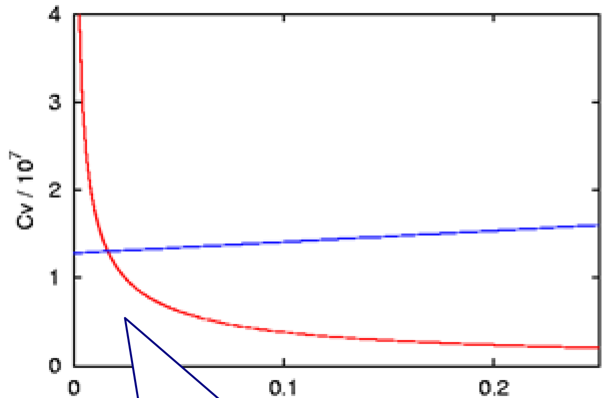
μ= 400 MeV
ε=0.01



rapid increase around p_F



formation of the **pseudogap**



anomalous enhancement as $T \to T_c$

M.Kitazawa, T.Koide, T.K., Y. Nemoto, PRD**70**,056003('04)

QM~ High Tc SC

maybe relevant to the cooling process of **newly-born neutron star**

- More accessible observables?

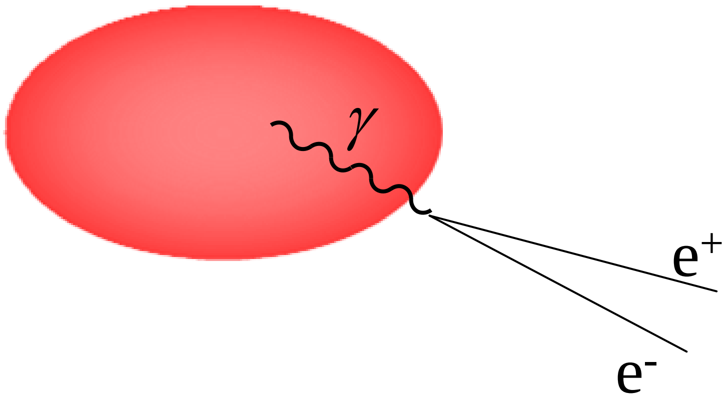
→ dilepton-pair production. in H-I collisions.

But **how?**

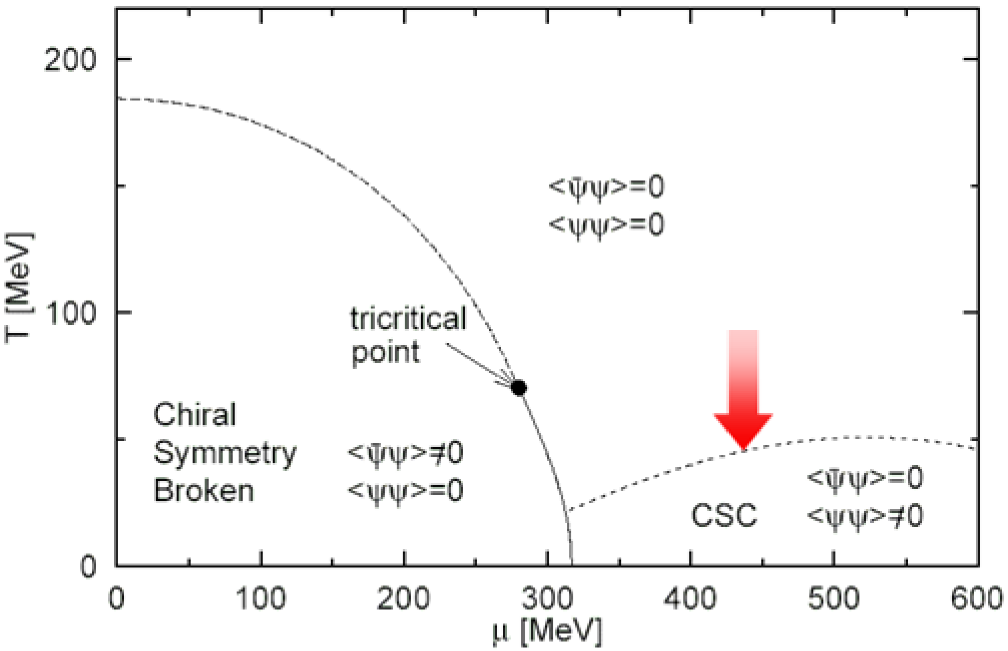
Dilepton-pair Production Rate

$$\frac{dR_{ee}}{d^4q} = -\frac{\alpha}{12\pi^4 Q^2}\,\mathrm{Im}\,\Pi^{R\mu}_{\mu}\,\frac{1}{e^{q^0/T}-1}$$

Photon Self-Energy



How do the diquark fluctuations affect the photon self-energy?

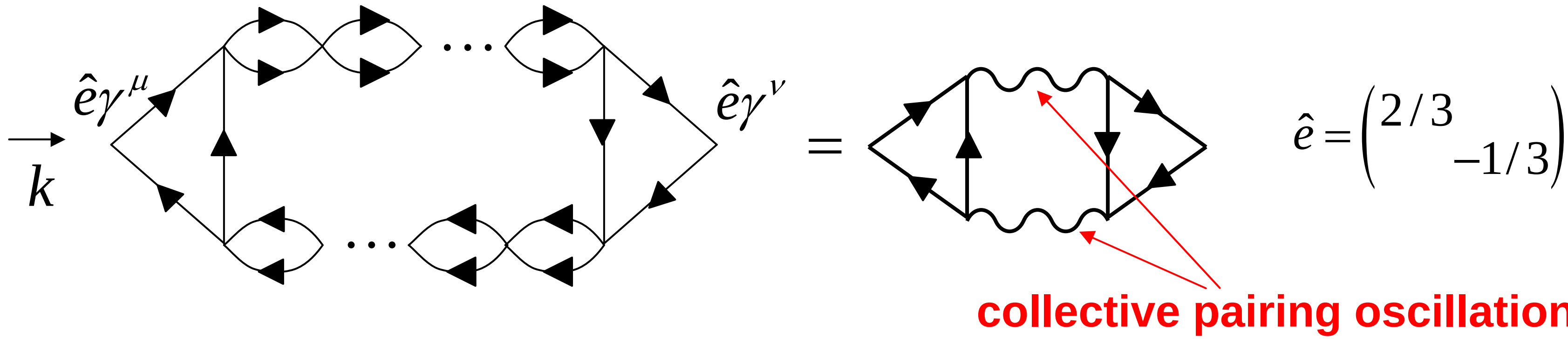


Anomalous Self-energy of Photon; Aslamasov-Larkin term

Sov. Phys. SS **10**,875('68)

Photon Self-Energy Π

$\Pi^{\mu\nu}_{AL} =$



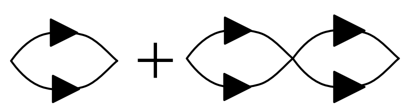
$$\hat{e} = \begin{pmatrix} 2/3 & \\ & -1/3 \end{pmatrix}_f$$

$$= 3\int d^4q\,\Gamma^{\mu}(q, q+k)\,\Xi(q+k)\,\Gamma^{\nu}(q+k, q)\,\Xi(q)$$

factor **3** due to color degrees of freedom

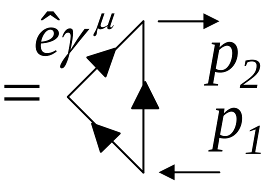
- Pair field (T-matrix):

$\Xi(q) =$

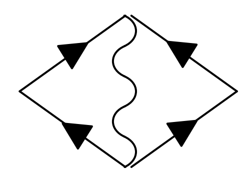
$1 +$  $+ \cdots$

$=$ 

- Vertex:

$\Gamma^{\mu}(p_1, p_2) =$ 

cf) Maki-Thompson term



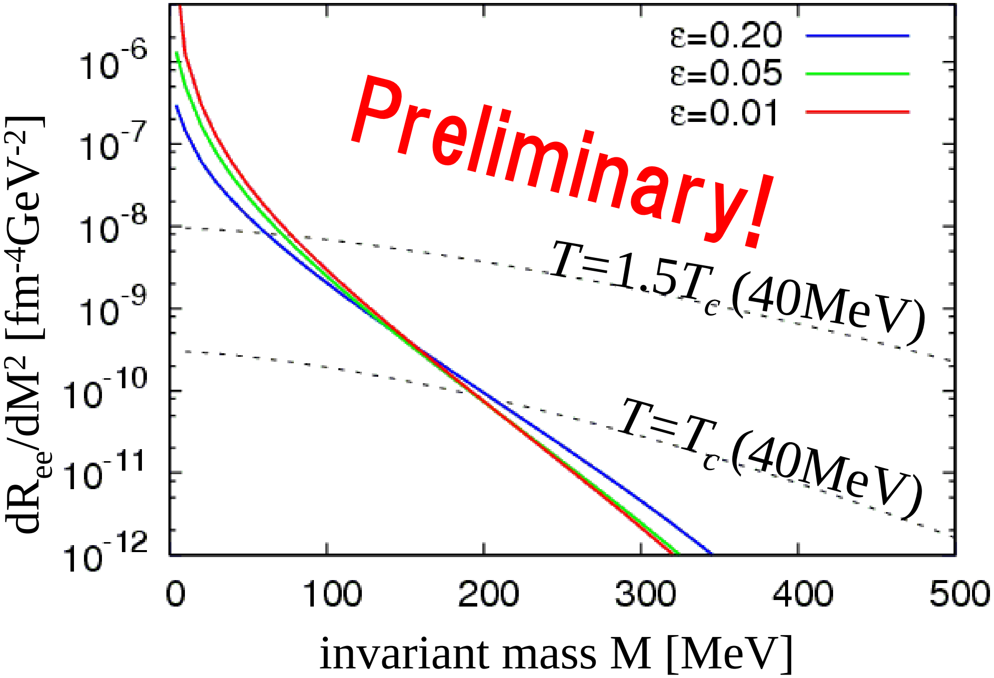
Dilepton-pair Production

$$\frac{dR_{ee}}{d^4q} = -\frac{\alpha}{12\pi^4 Q^2}\,\mathrm{Im}\,\Pi^{R\mu}_{\mu}\,\frac{1}{e^{q^0/T}-1}$$

-per invariant mass

$$\frac{dR_{ee}}{dM^2} = \int \frac{d^3q}{2q^0}\frac{dR_{ee}}{d^4q}$$

—— from AL-term
------ from free quarks



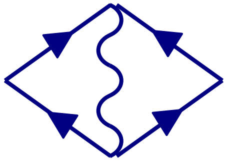
M. Kitazawa and T.K., (2005),unpublished

- Prominent enhancement at M<150MeV.
- The peak becomes sharp as $\varepsilon \to 0$.

Possible experimental observable for the CSC to be seen in FAIR(GSI)?
Maybe difficult, unfortunately, because of the too-low mass enhancement.

Remarks:

* Effects of the Maki-Thompson term

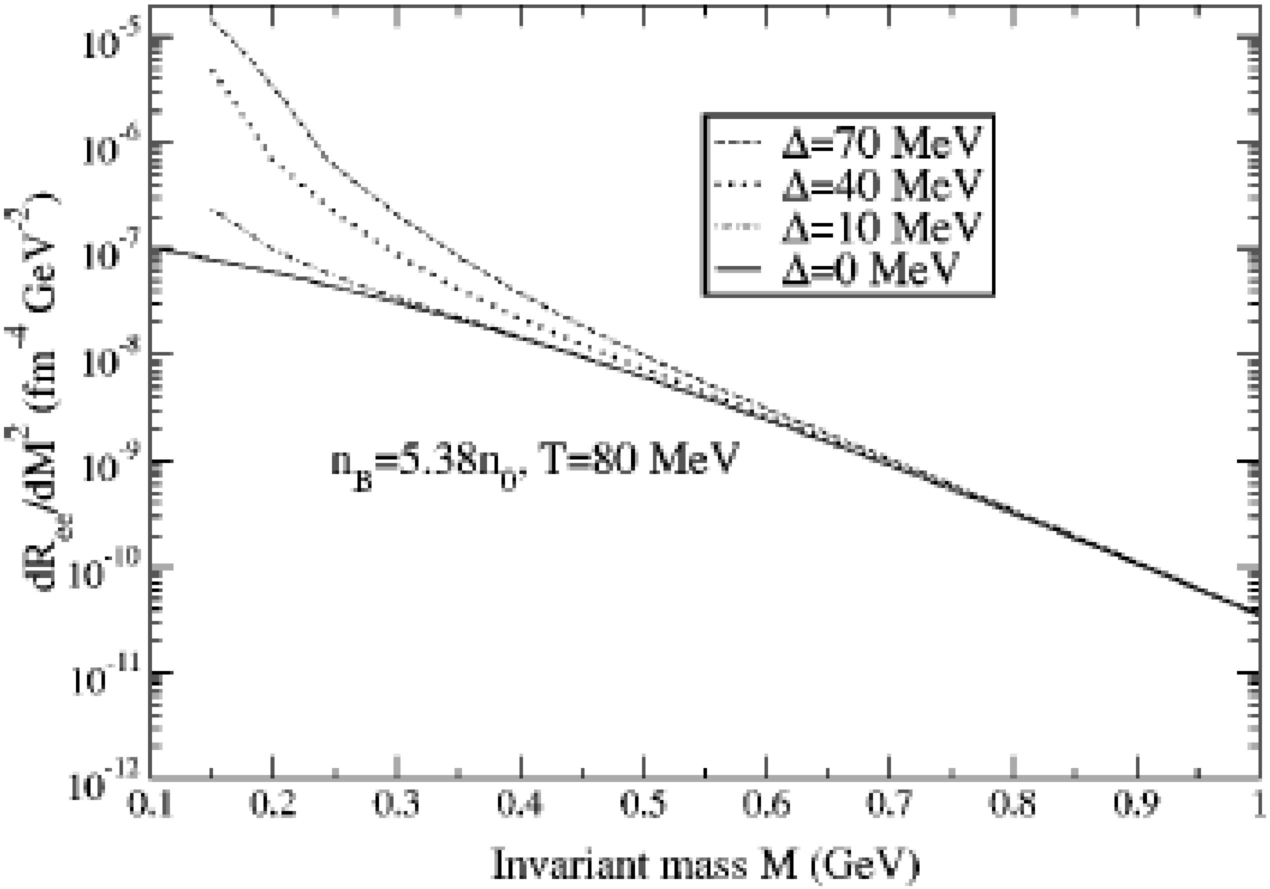


*If Tc is higher, say, 100 MeV or higher, the enhancement is more prominent.

How about, the lepton pair emission from the color-counducting phase?

Dilepton emission rate from the CFL phase

P. Jaikumar R. Rapp and I. Zahed('02)

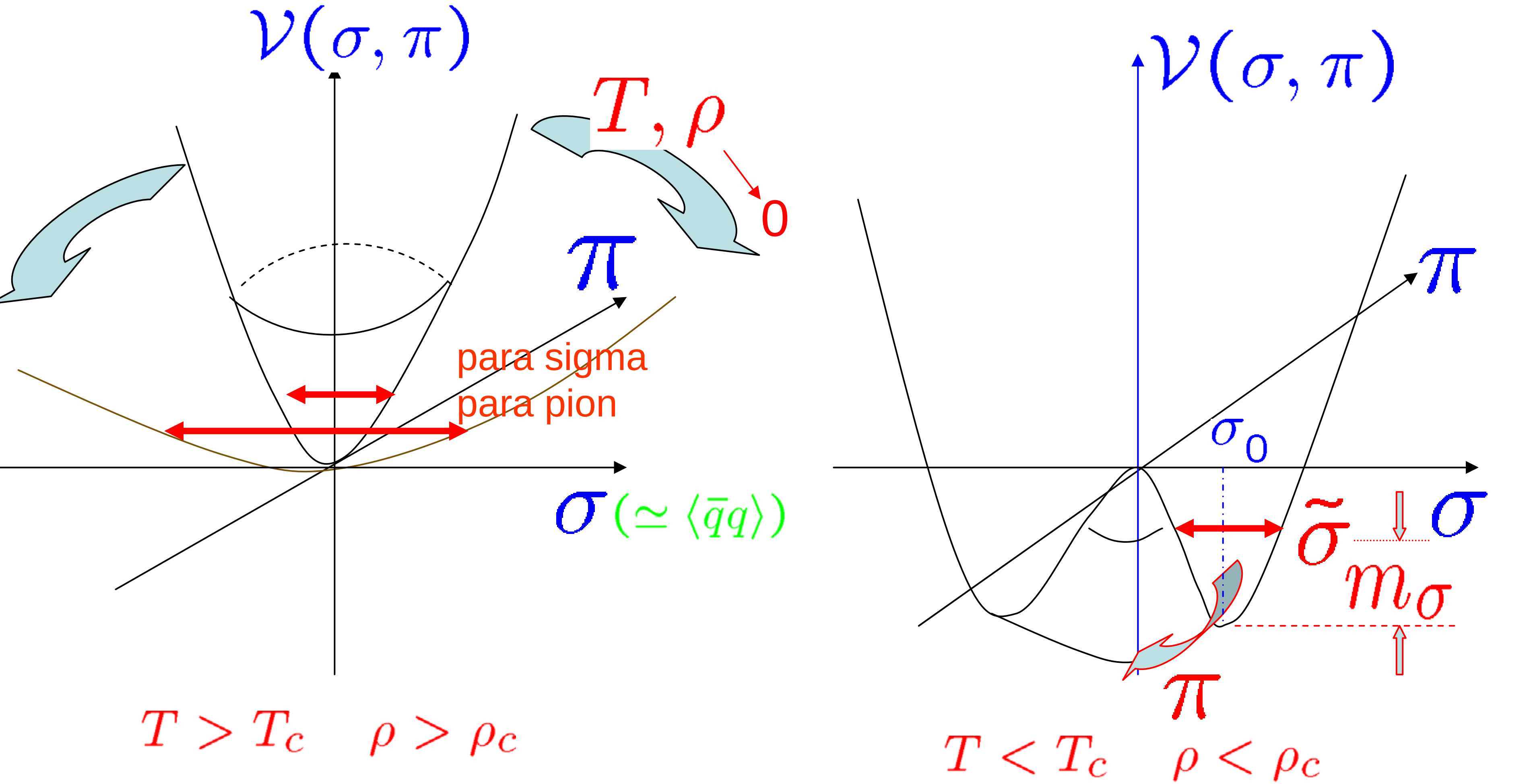


Enhancement due to phton-gluon mixing in the CFL phase、
and from the generalized rho meson.(not shown here)

PART II

The Case of the Chiral Transition

Chiral Transition and the sigma mode (meson)



$$\sigma = \sigma_0 + \tilde{\sigma}$$

c.f. Higgs particle in WS model

ϕ ; Higgs field ➡ $\phi = \langle \phi \rangle + \tilde{\phi}$

Higgs particle

Confinement and chiral transion in Lattice QCD

(F.Karsch, Lect. Notes 583 (2002), 209)

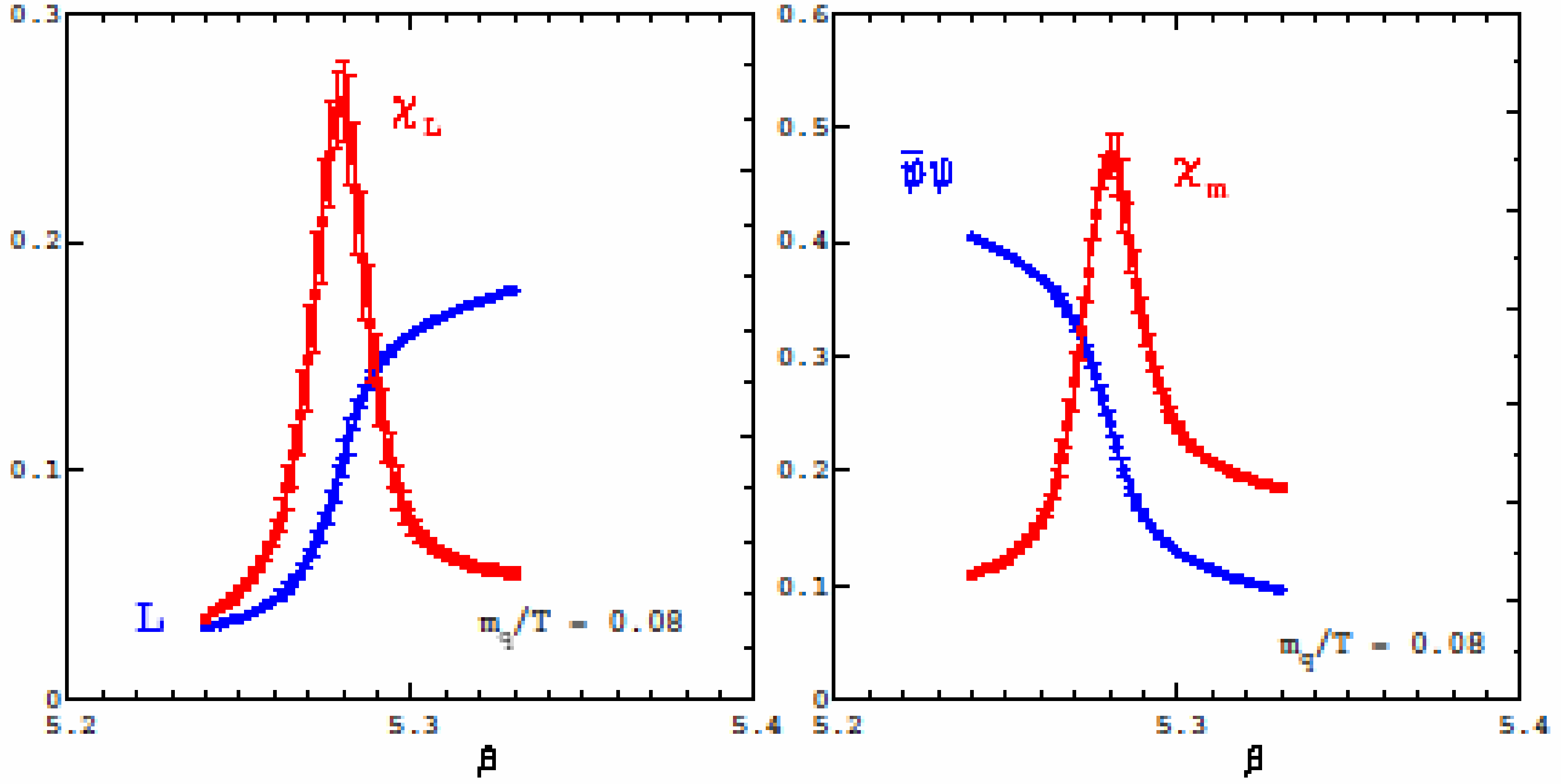
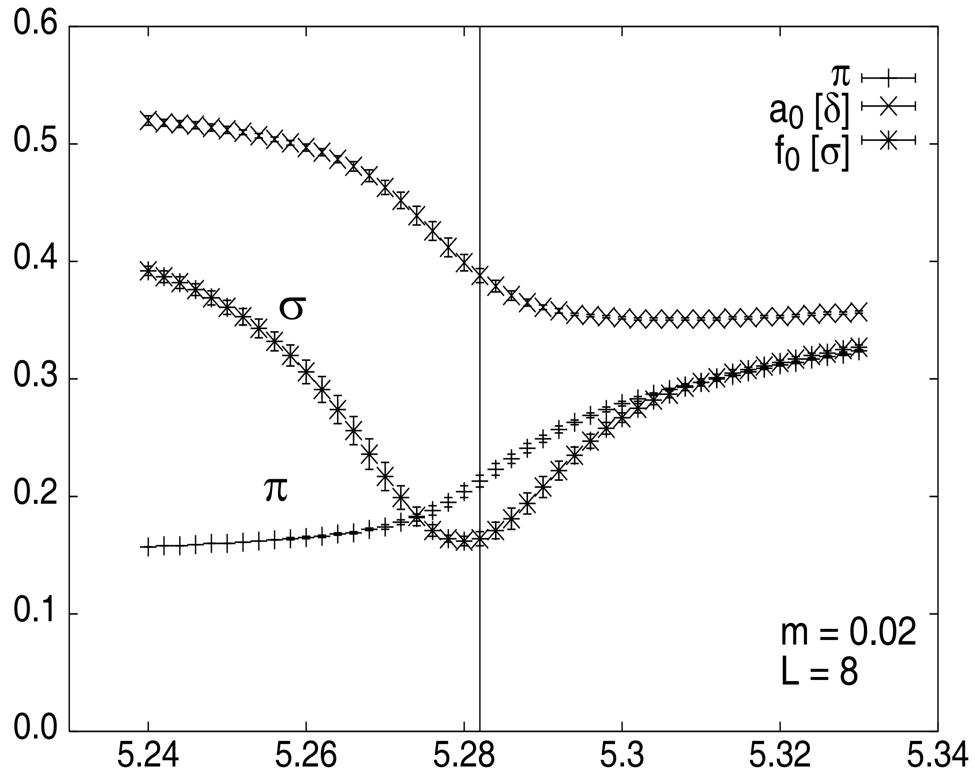


Fig. 2. Deconfinement and chiral symmetry restoration in 2-flavour QCD: Shown is $\langle L \rangle$ (left), which is the order parameter for deconfinement in the pure gauge limit ($m_q \to \infty$), and $\langle \bar{\psi}\psi \rangle$ (right), which is the order parameter for chiral symmetry breaking in the chiral limit ($m_q \to 0$). Also shown are the corresponding susceptibilities as a function of the coupling $\beta = 6/g^2$.

Cf. Lattice Calculation of the *generalized masses*

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

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



the softening of the σ with increasing T

and

a degeneracy of the σ and π at high T

What is the significance of the σ in hadron physics?

How about above T_c?

Interest in the nature of elementary modes in ‘QGP’ phase

RHIC experiments

robust collective flow

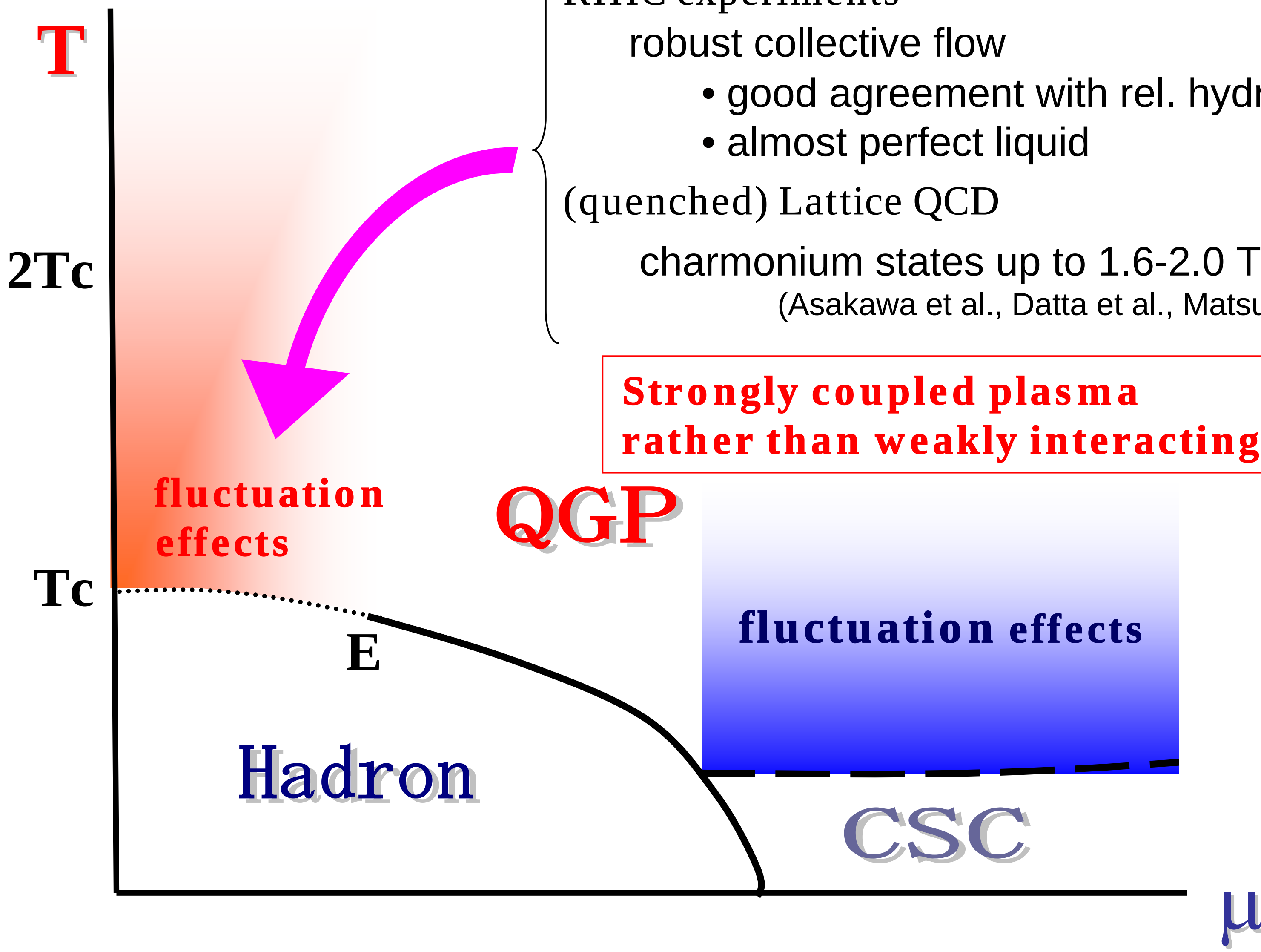
- good agreement with rel. hydro models
- almost perfect liquid

(quenched) Lattice QCD

charmonium states up to 1.6-2.0 Tc

(Asakawa et al., Datta et al., Matsufuru et al. 2004)

Strongly coupled plasma rather than weakly interacting gas

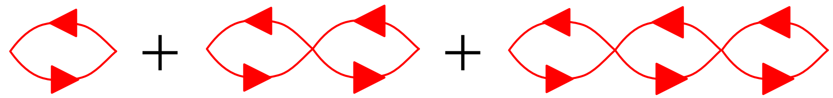


The spectral function of the degenerate hadronic ``para-pion” and the ``para-sigma” at T>Tc for the chiral transition: Tc=164 MeV

T. Hatsuda and T.K. (1985)

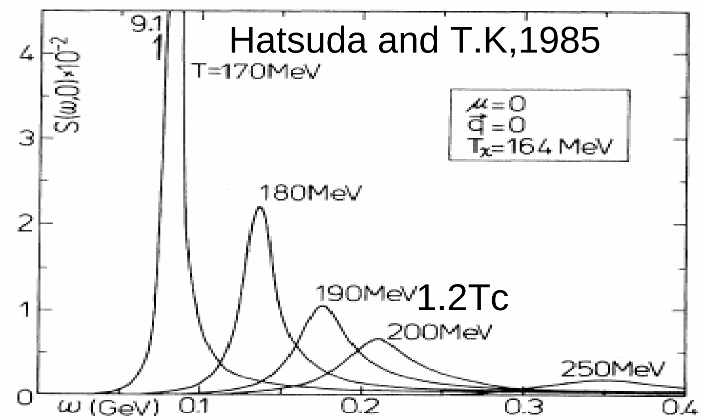
- response function in RPA

$D(\mathbf{k},\omega) =$



- spectral function

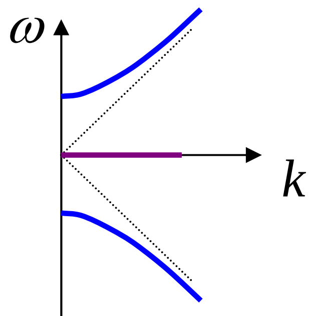
$$A(\mathbf{k}\omega) = -\frac{1}{\pi}\,\mathrm{Im}\,D(\mathbf{k}\omega)$$

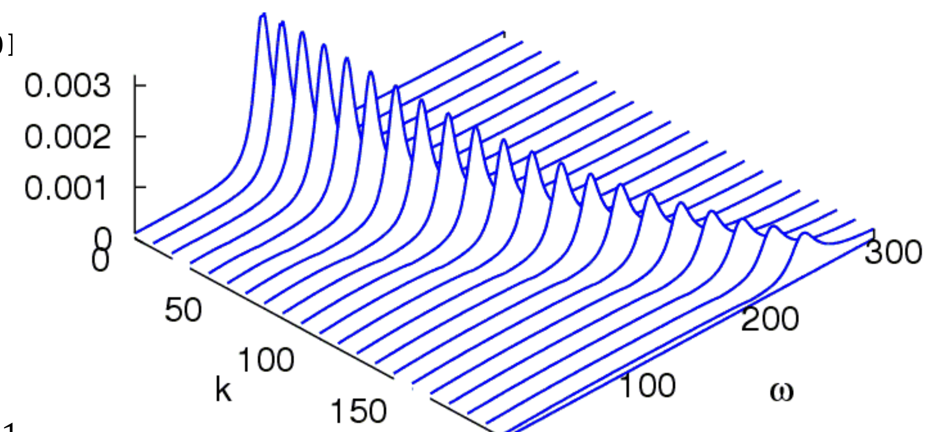


$T \to T_c$, they become elementary modes with small width!

1.two γ decay
2. modified quark spectrum

sharp peak in time-like regio



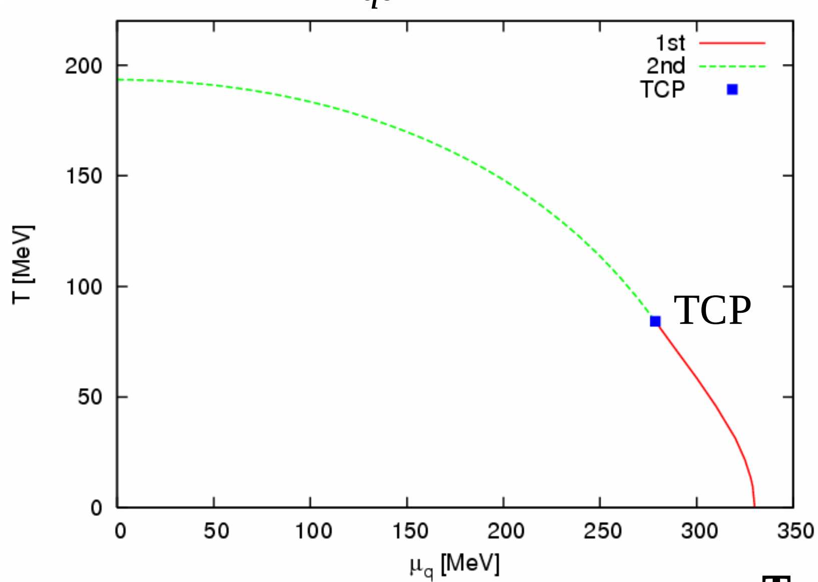


M.Kitazawa, Y.Nemoto and T.K. (05)

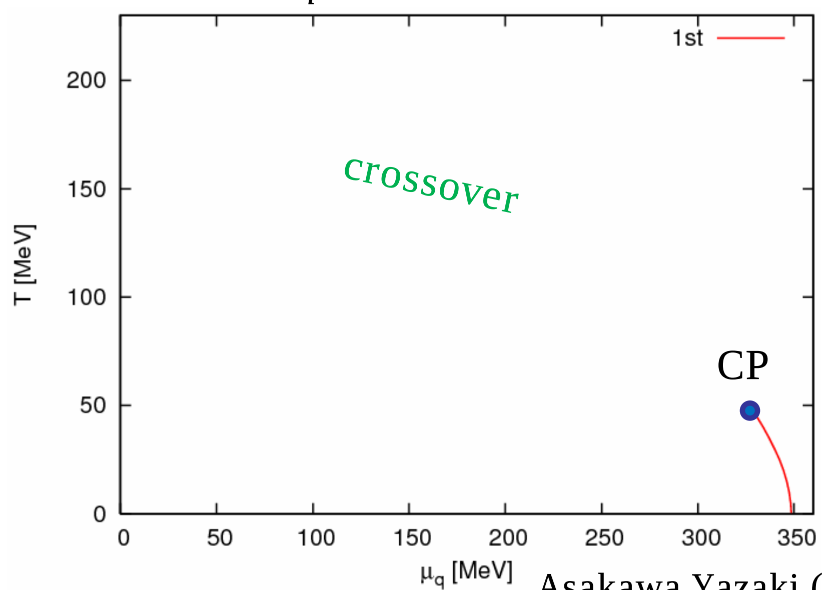
Finite T and μ with finite quark mass

Phase diagram

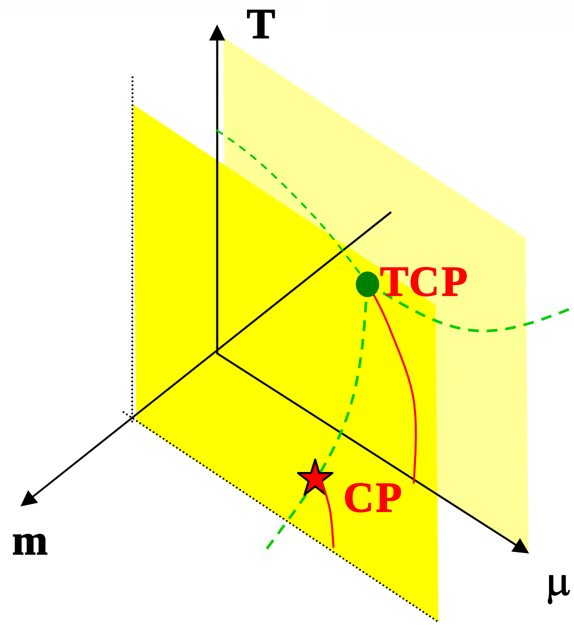
$m_{q0} = 0$



$m_{q0} = 5.5$ MeV

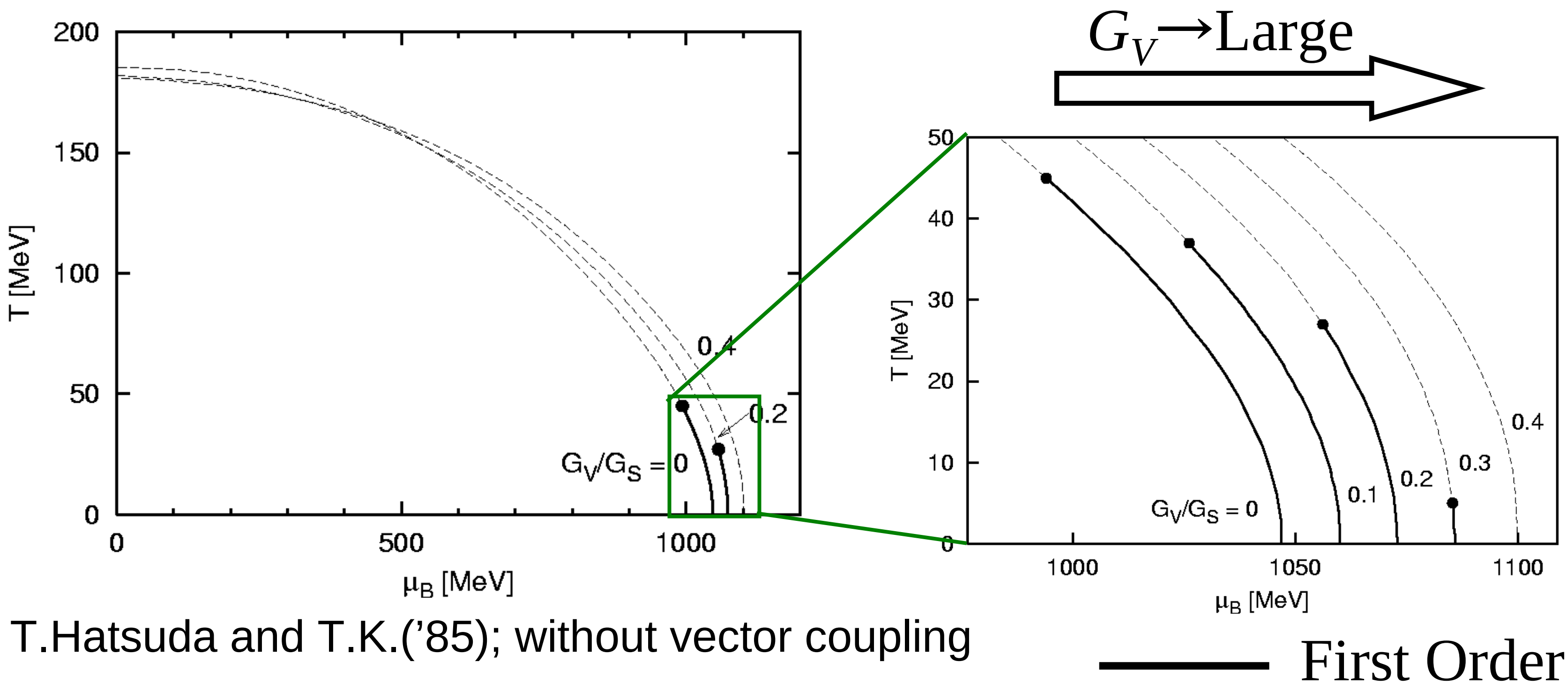


Asakawa,Yazaki,(1989)



Caveats

★ Effects of G_V on Chiral Restoration



T.Hatsuda and T.K.('85); without vector coupling

As G_V is increased,

- Chiral restoration is shifted to higher densities.
- The phase transition is weakened.

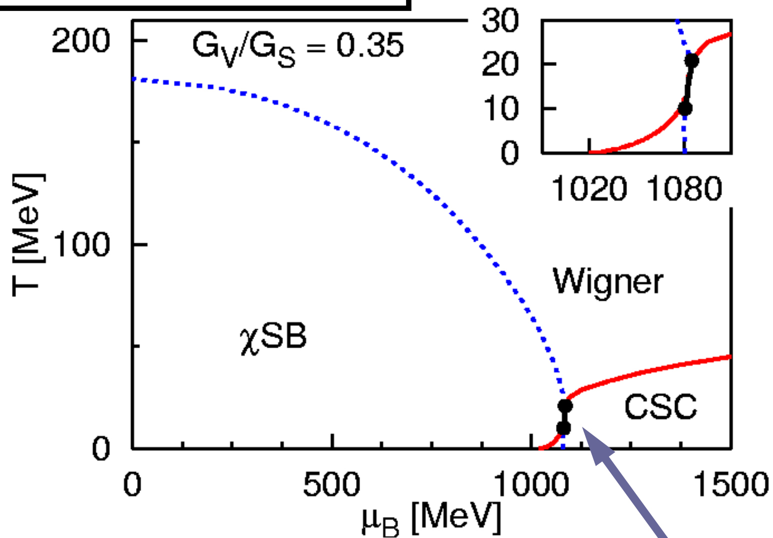
Asakawa,Yazaki '89 /Klimt,Lutz,&Weise '90 /T.K. '90/ Buballa,Oertel '96

What would happen when the CSC joins the game?

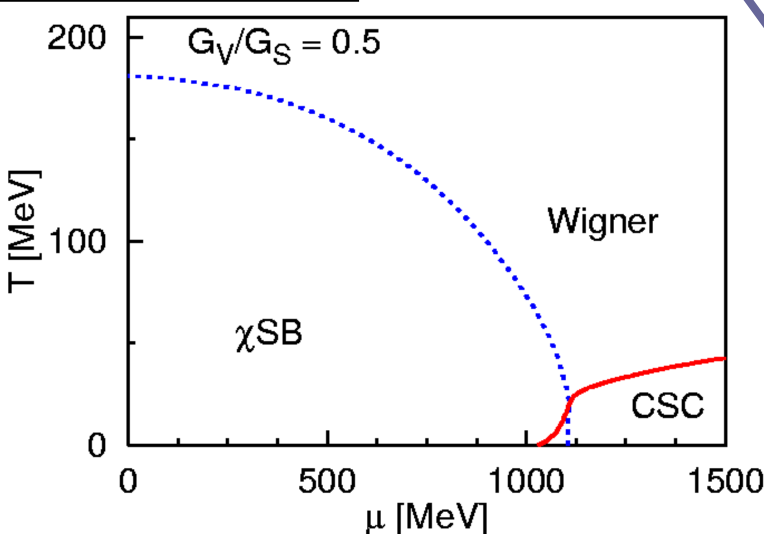
With color superconductivity transition incorporated

M. Kitazawa et al ('02)

$G_V / G_S = 0.35$



$G_V / G_S = 0.5$



(2) The **first order transition** between χSB and CSC phases **is weakened** and eventually **disappears**.

(3) The region of **the coexisting phase becomes broader**.

Appearance of the coexisting phase becomes robust.

(4) Another end point appears from lower temperature, and hence **there can exist <u>two end points</u>** in some range of G_V**!** $0.33 \sim G_V \sim 0.38$

Smooth variation of the quark condensate with baryon density?

S. Klimt, M. Lutz and W. Weise, PLB249 ('90)

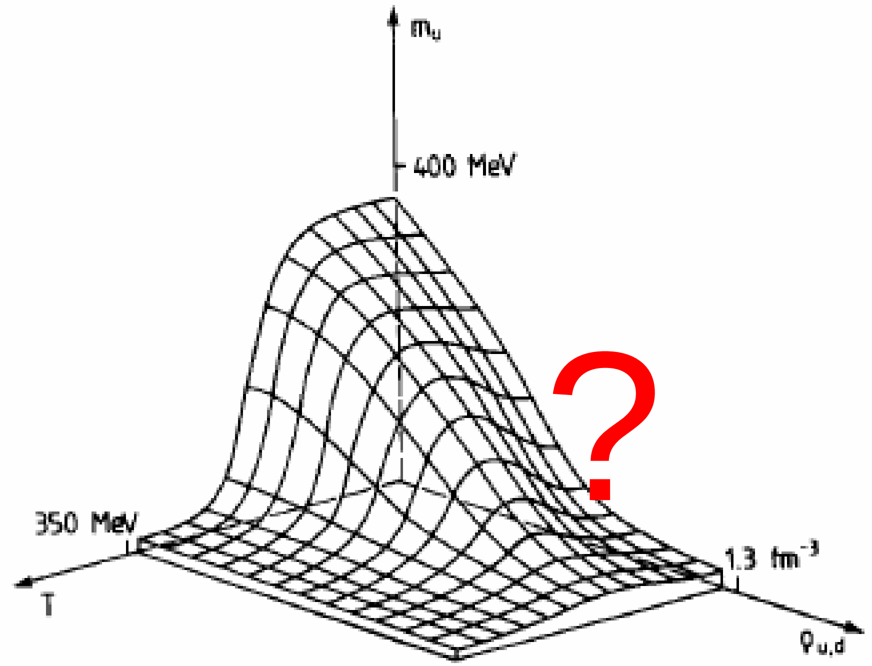
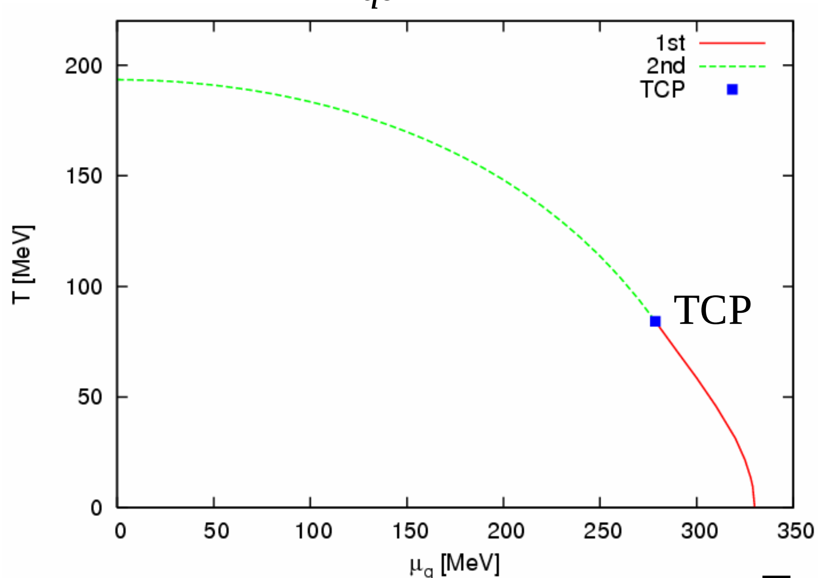


Fig. 1. Quark mass m_u as a function of temperature T and quark density ρ_u at $\rho_s = 0$.

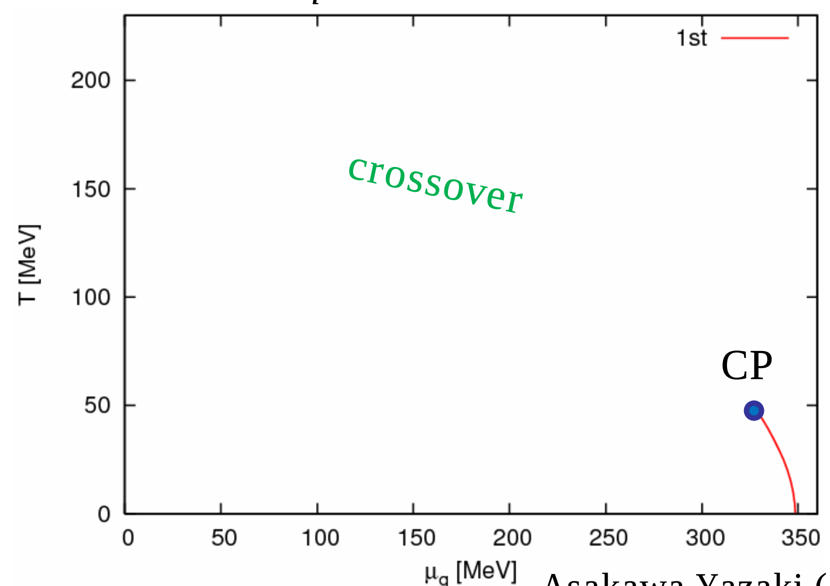
So strong vector coupling making the chiral transition crossover at finite density!

Phase diagram

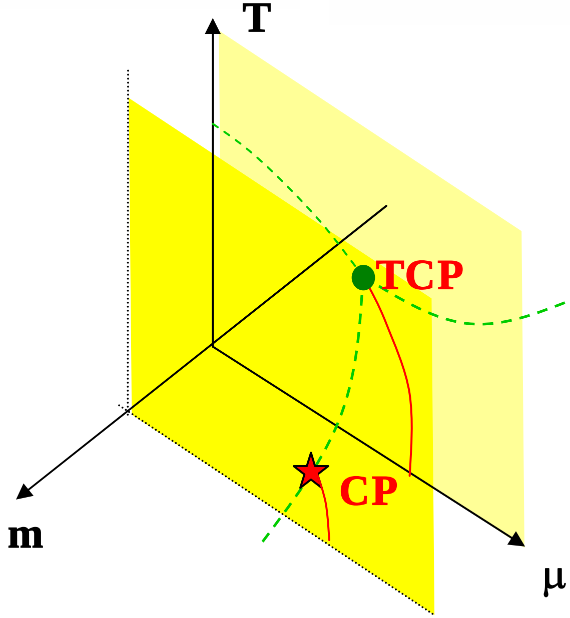
$m_{q0}=0$



$m_{q0}=5.5$ MeV



Asakawa,Yazaki,(1989)



What is the soft mode at CP?

Sigma meson has still a non-zero mass at CP.
This is because the chiral symmetry is explicitly broken.

What is the soft mode at CP?

Phonon mode in the space-like region softens at CP.

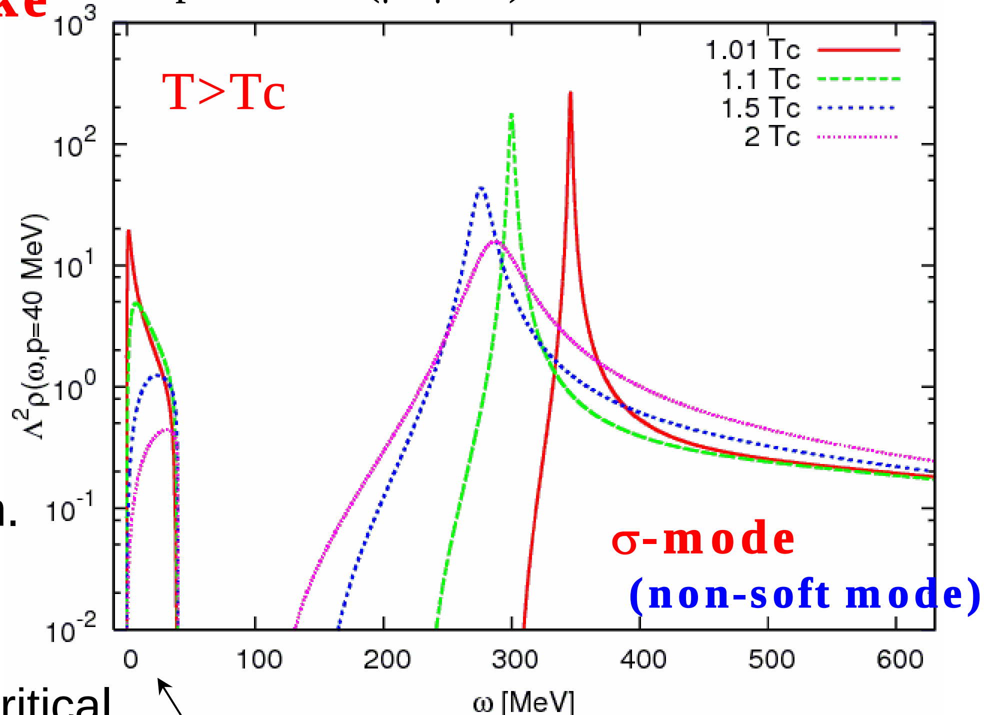
H. Fujii (2003)
H. Fujii and M.Ohtani(2004)

See also, D. T. Son and M. Stephanov (2004)

does not affect particle creation in the time-like region.

It couples to hydrodynamical modes,
leading to interesting dynamical critical phenomena.

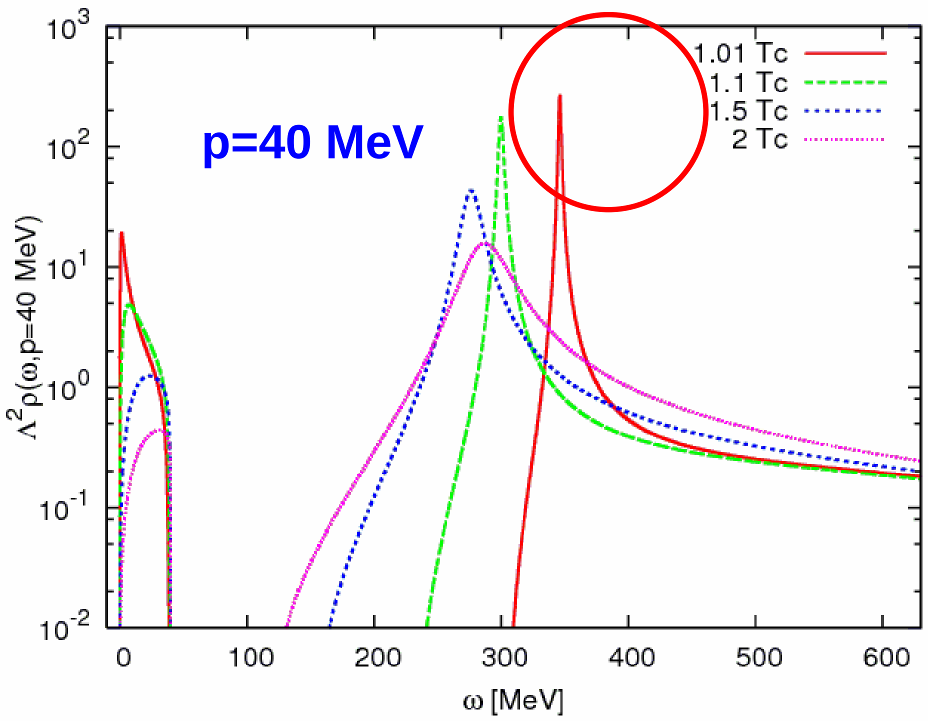
Spectral function of the chiral condensate
T-dependence ($\mu=\mu_{CP}$)



Space-like region
(the soft modes)

Dilepton production rate from the sigma mode at T>Tc

s
p



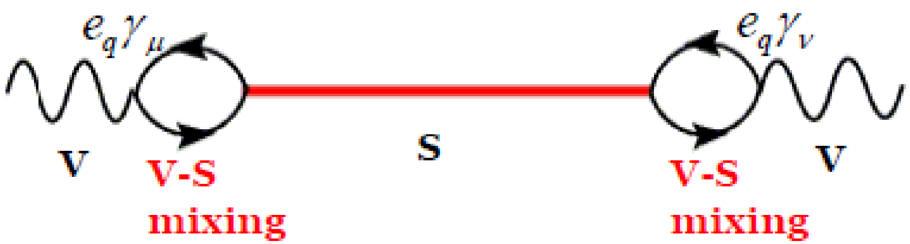
Spectral function of the sigma mode

What is contributions of the sigma mode?

Enhancement around

$m_\sigma \approx 2M_q$.

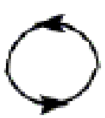
Vector-scalar mixing

$\Pi_{\mu\nu}(q_0, \vec{q}) =$ 

The above vector-scalar mixing exists if

$$\begin{cases} \mu \neq 0 \\ m_q \neq 0 \\ q \neq 0 \\ \textbf{Not SU(3) limit } (m_u = m_d = m_s) \end{cases}$$

ex: SU(2) symmetry $(m_q = m_u = m_d)$

 $\propto N_C(e_u + e_d)m_q \int d^3k F(q_\mu, \vec{k})[f(E_k - \mu) - f(E_k + \mu)]$

cf: quark number susceptibility through the vs-mixing
Kunihiro,1991

cf: dilepton production due to σ–ω and σ–γ mixings in hadronic matter
Weldon,1992
Wolf, Friman, Soyeur,1998

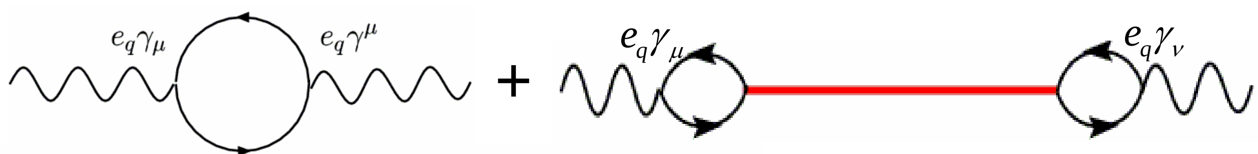
without the notion of chiral transition, nor softening of the sigam

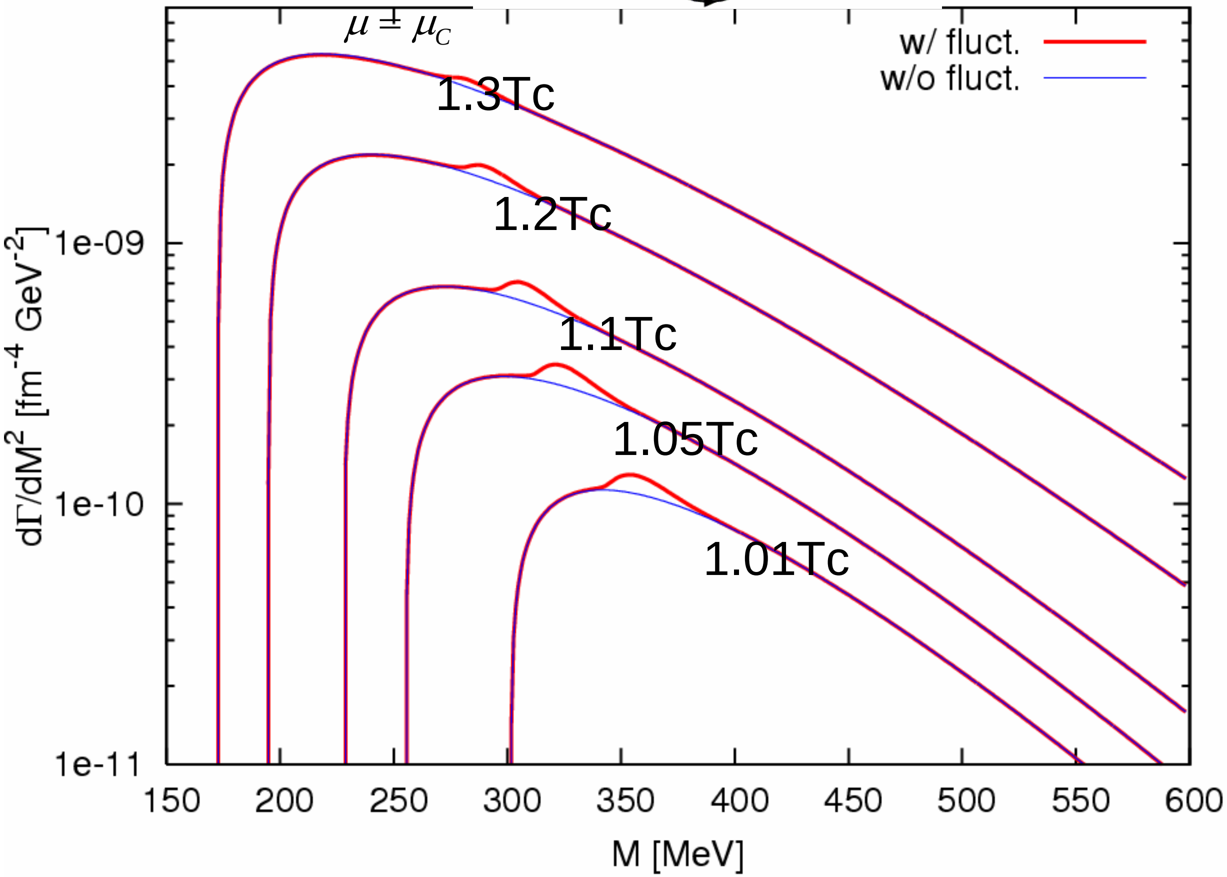
Di-electron Production Rate

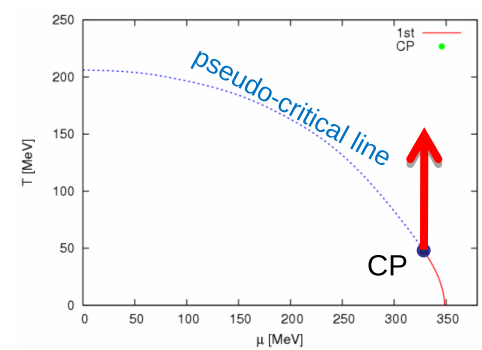
along T-axis

$$\frac{d\Gamma}{dM^2} = \int \frac{d^3q}{2q_0} \frac{d\Gamma}{d^4q} \qquad \frac{d\Gamma}{d^4q} = \frac{-\alpha \, \mathrm{Im}\, \Pi^{R\mu}_{\mu}(q_0, q)}{12\pi^4 q^2 (\exp[q_0/T]-1)}$$

$$\Pi^{R\mu}_{\mu}(q_0, q) =$$







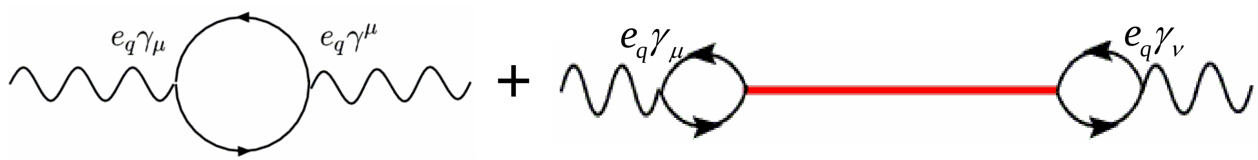
Enhancement around

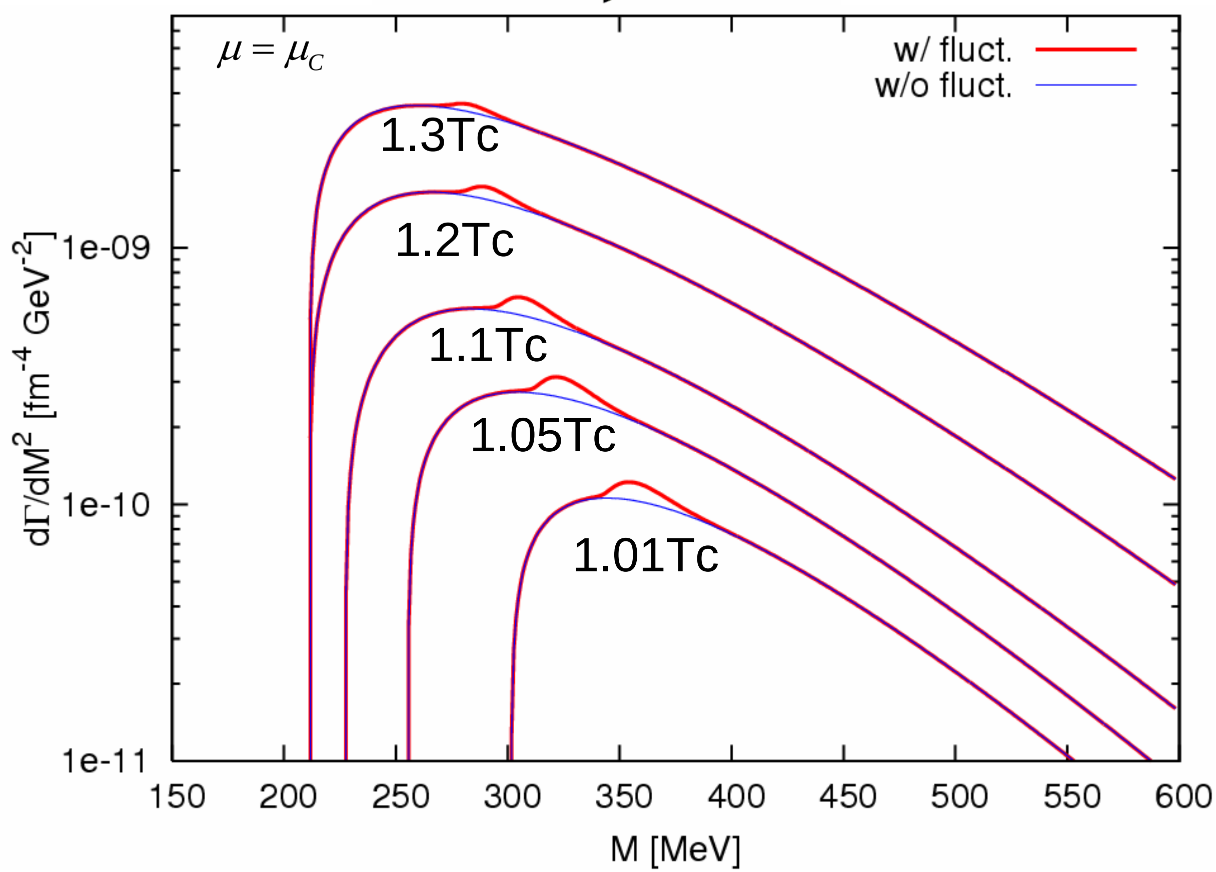
$m_\sigma \approx 2M_q$ at $T > T_c$

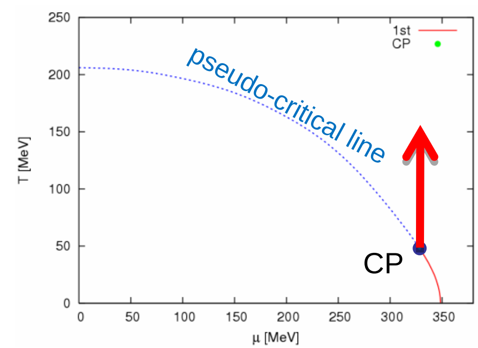
Di-muon Production Rate

along T-axis

$$\frac{d\Gamma}{dM^2} = \int \frac{d^3q}{2q_0}\frac{d\Gamma}{d^4q} \qquad \frac{d\Gamma}{d^4q} = \frac{-\alpha\,\mathrm{Im}\,\Pi^{R\mu}_{\mu}(q_0,q)}{12\pi^4 q^2(\exp[q_0/T]-1)}\left(1+\frac{2m_\mu^2}{q^2}\right)\left(1-\frac{4m_\mu^2}{q^2}\right)^{1/2}$$

$\Pi^{R\mu}_{\mu}(q_0,\vec{q}) =$ 



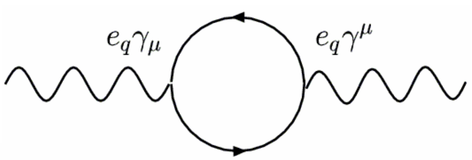


Di-electron Production Rate

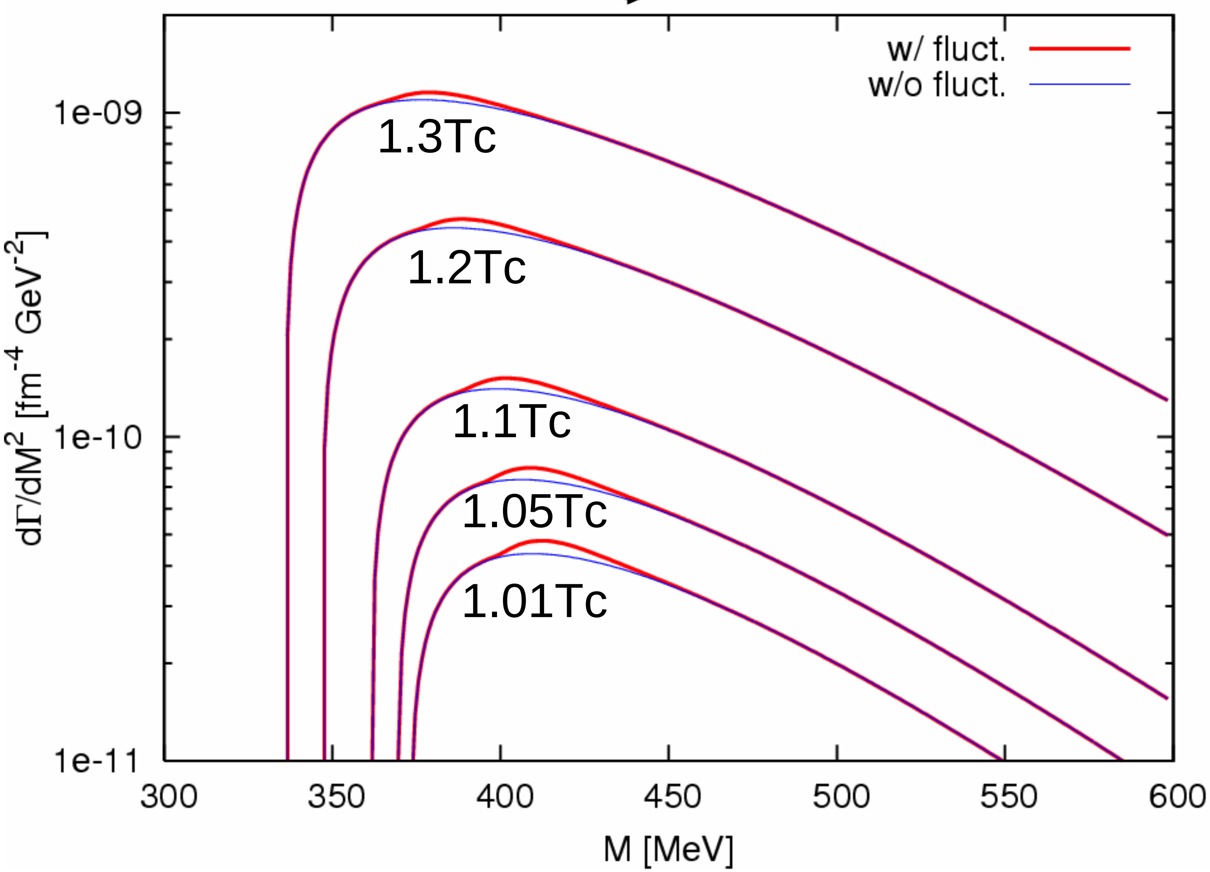
along a pseudo-critical li

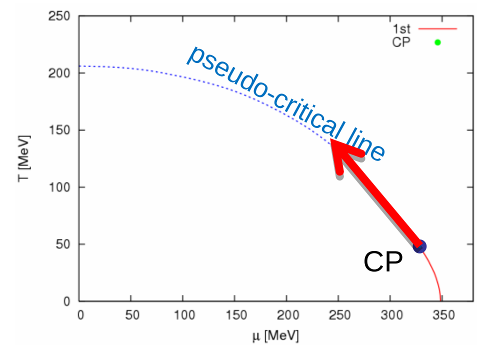
$$\frac{d\Gamma}{dM^2} = \int \frac{d^3q}{2q_0} \frac{d\Gamma}{d^4q} \qquad \frac{d\Gamma}{d^4q} = \frac{-\alpha \,\mathrm{Im}\,\Pi^{R\mu}_{\mu}(q_0, q)}{12\pi^4 q^2 (\exp[q_0/T]-1)}$$

$$\Pi^{R\mu}_{\mu}(q_0, q) =$$



$+$



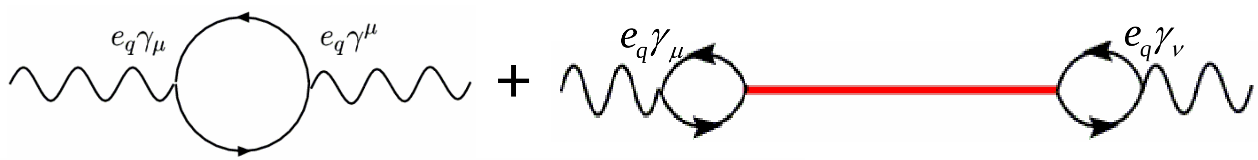


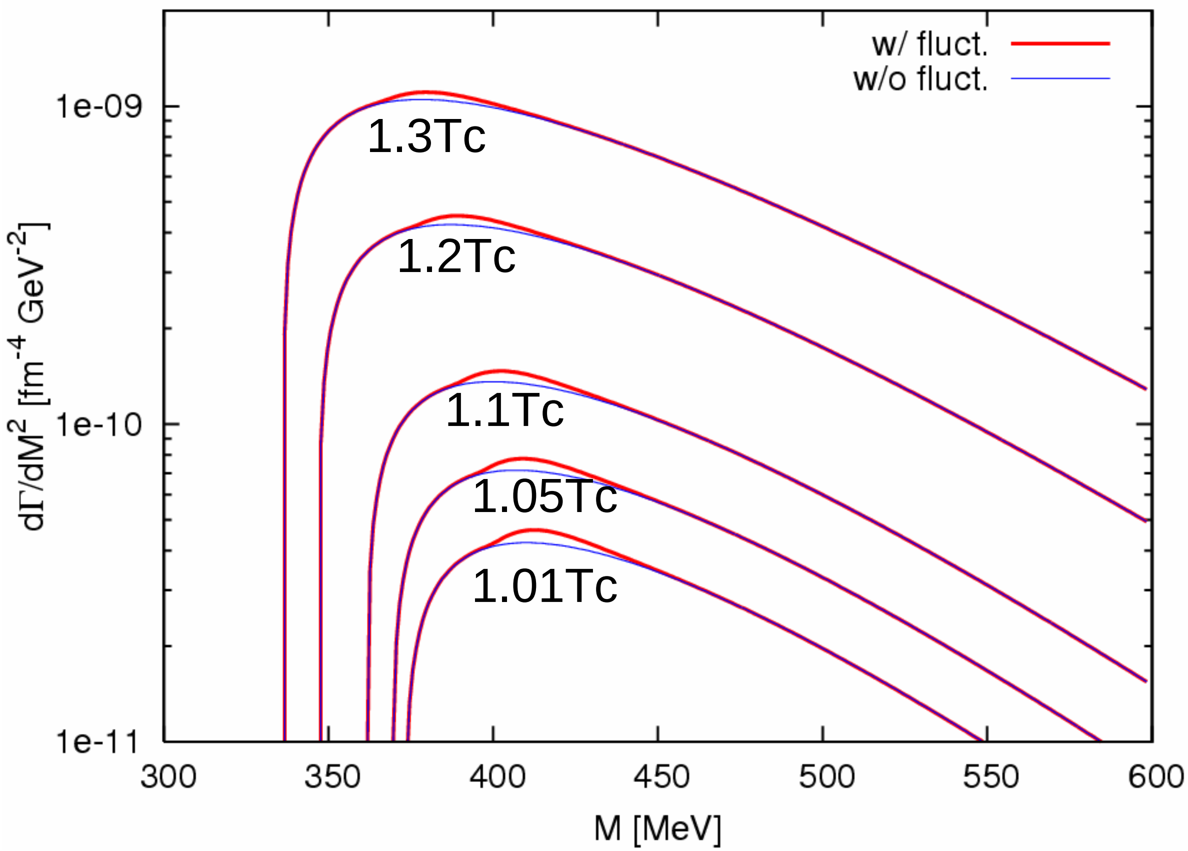
Di-muon Production Rate

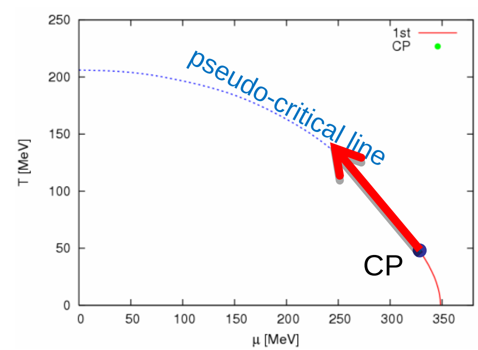
along a pseudo-critical li

$$\frac{d\Gamma}{dM^2} = \int \frac{d^3q}{2q_0}\frac{d\Gamma}{d^4q} \qquad \frac{d\Gamma}{d^4q} = \frac{-\alpha\,\mathrm{Im}\,\Pi^{R\mu}_{\mu}(q_0,q)}{12\pi^4 q^2(\exp[q_0/T]-1)}\left(1+\frac{2m_\mu^2}{q^2}\right)\left(1-\frac{4m_\mu^2}{q^2}\right)^{1/2}$$

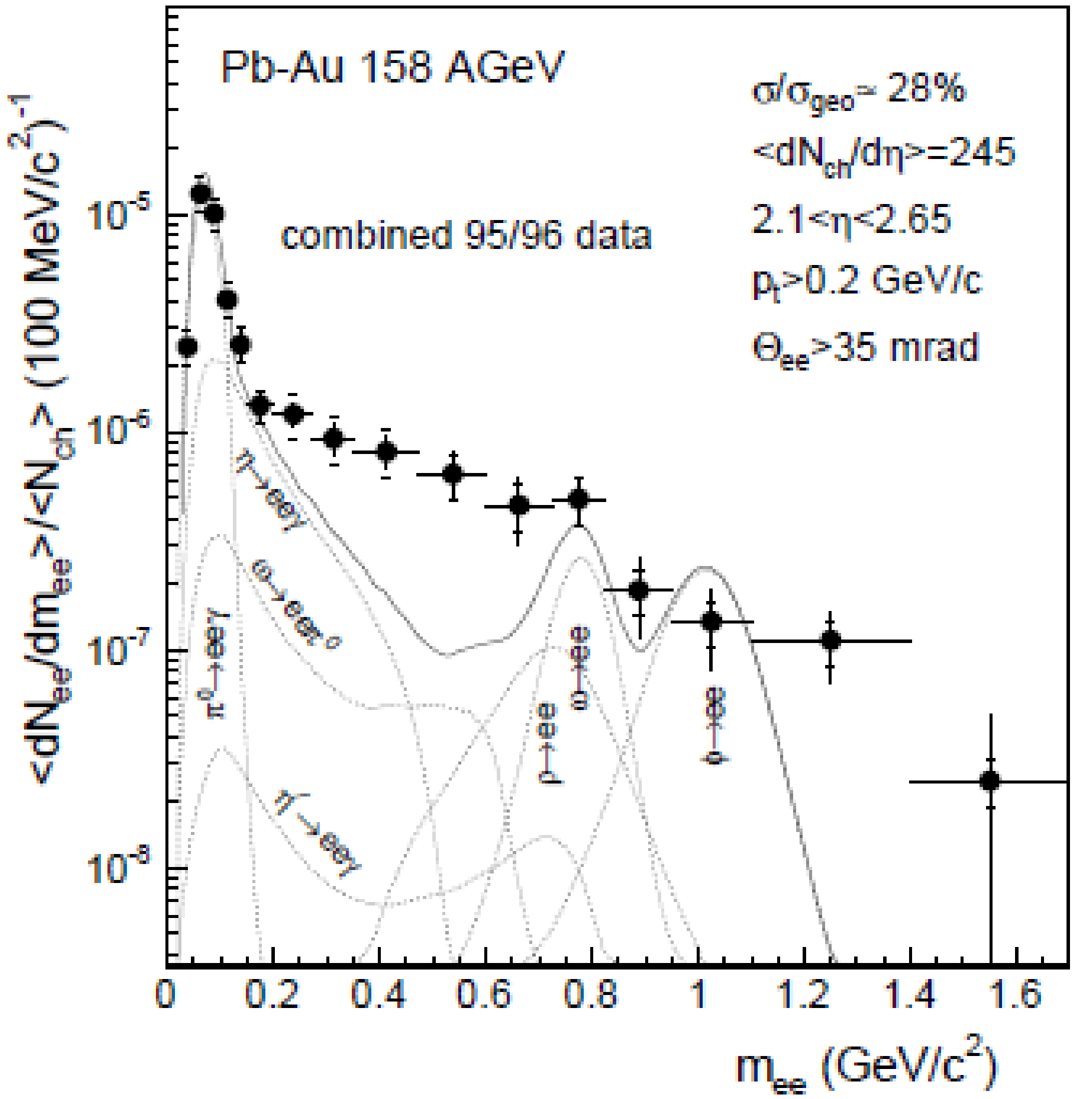
$$\Pi^{R\mu}_{\mu}(q_0,\vec{q}) =$$







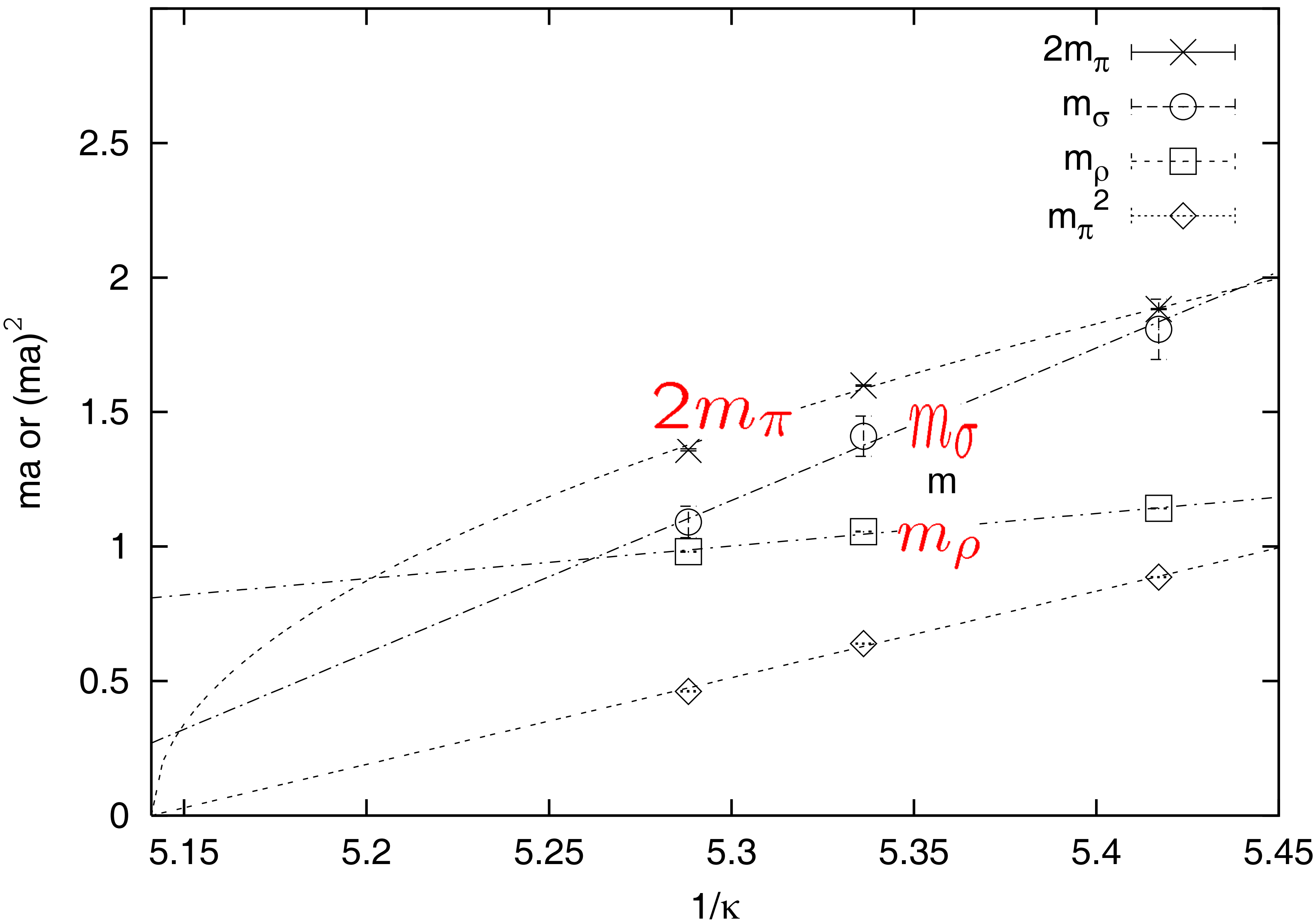
CERES ('05)



What is the origin of an enhancement around .0.3 GeV?

Remarks on the sigma mode in the hadronic phase at finite T and density.

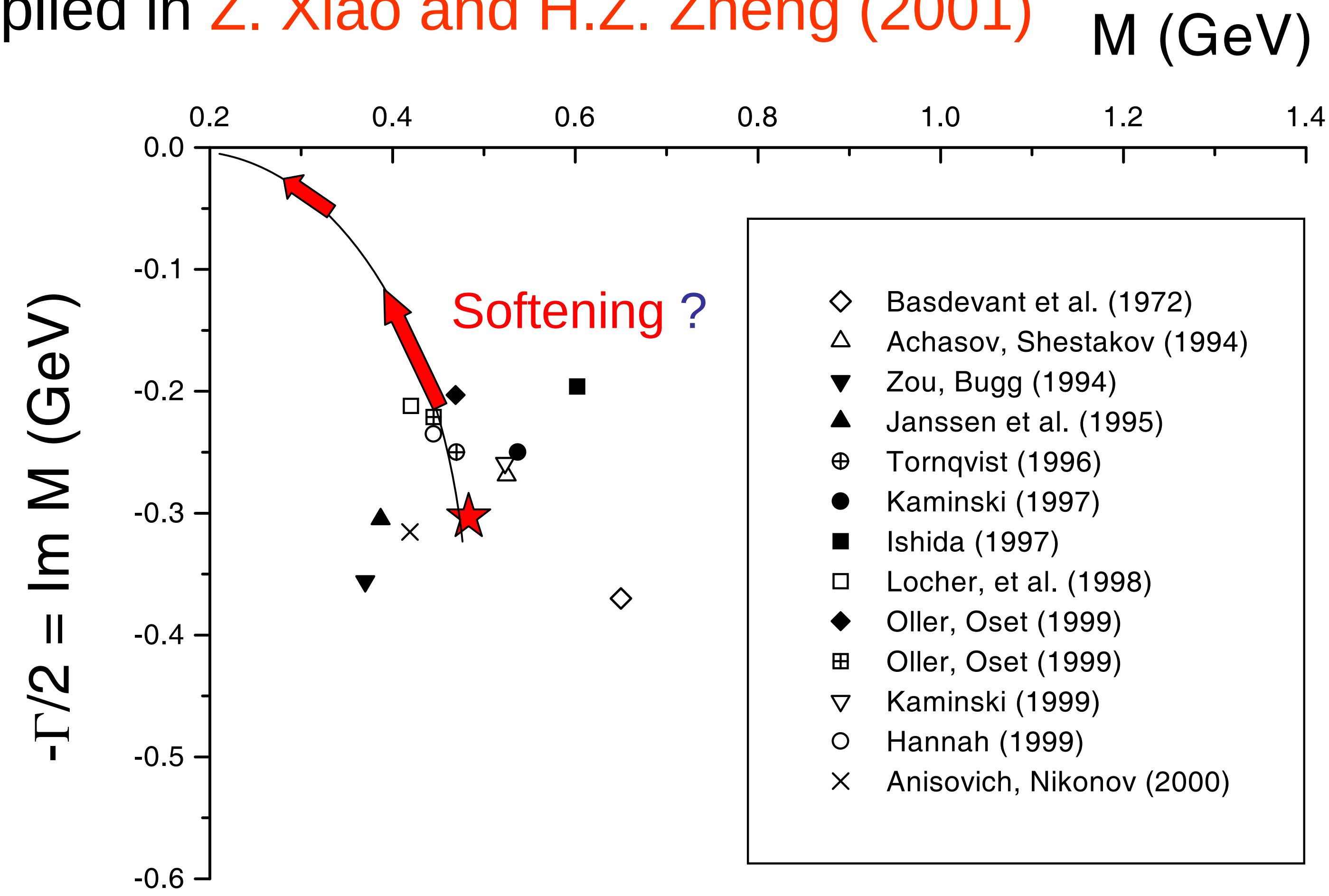
Lattice Calculations in full QCD of the sigma mass



The SCALAR collaboration, PRD70, 034504(2004)

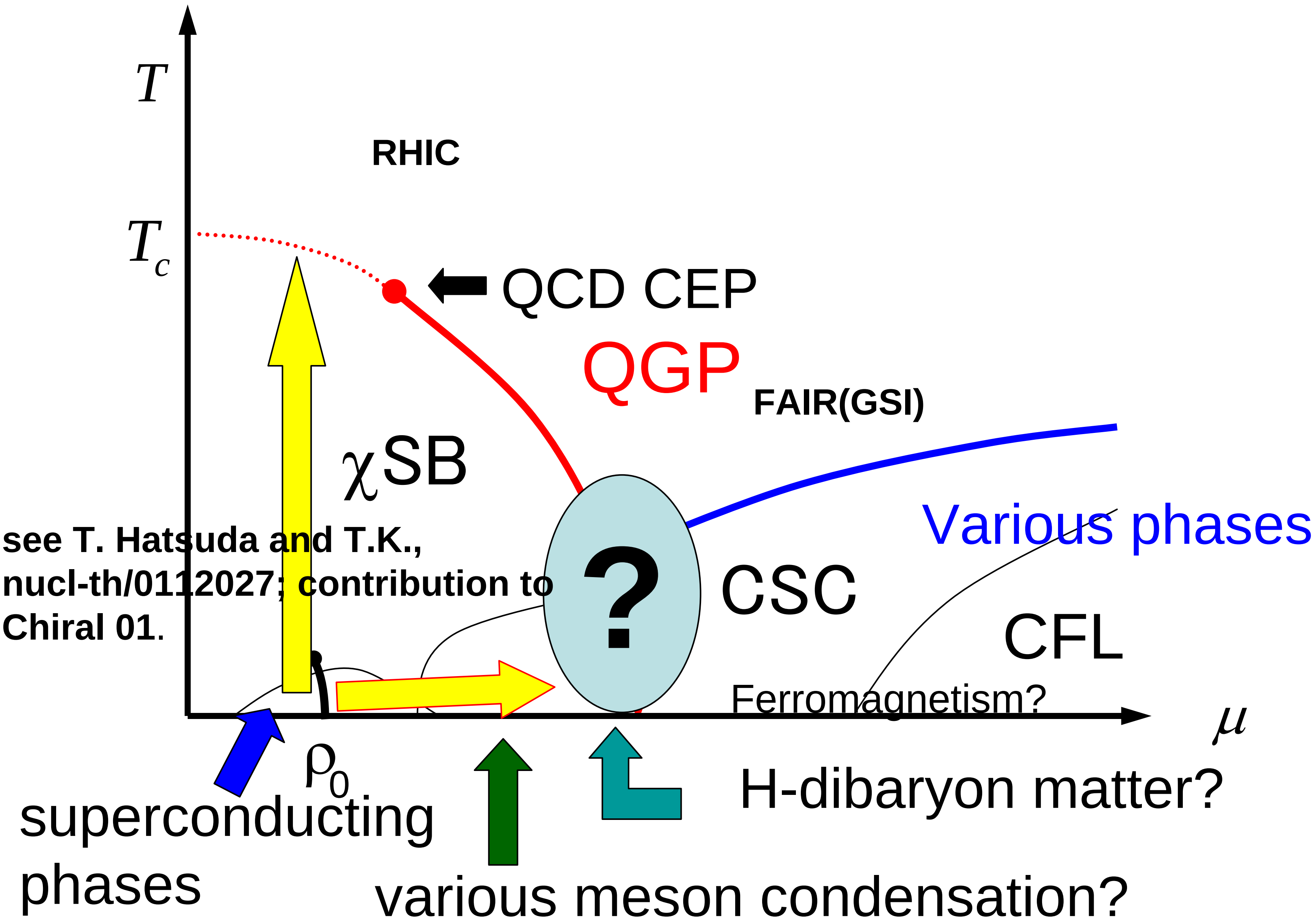
The poles of the S matrix in the complex mass plane for the sigma meson channel:

complied in Z. Xiao and H.Z. Zheng (2001)



See also, I. Caprini, G. Colangero and H. Leutwyler, PRL(2006);
H. Leutwyler, hep-ph/0608218 ; M_sigma=441 – i 272 MeV

A conjectured QCD phase diagram



K. Saito et al (1998)

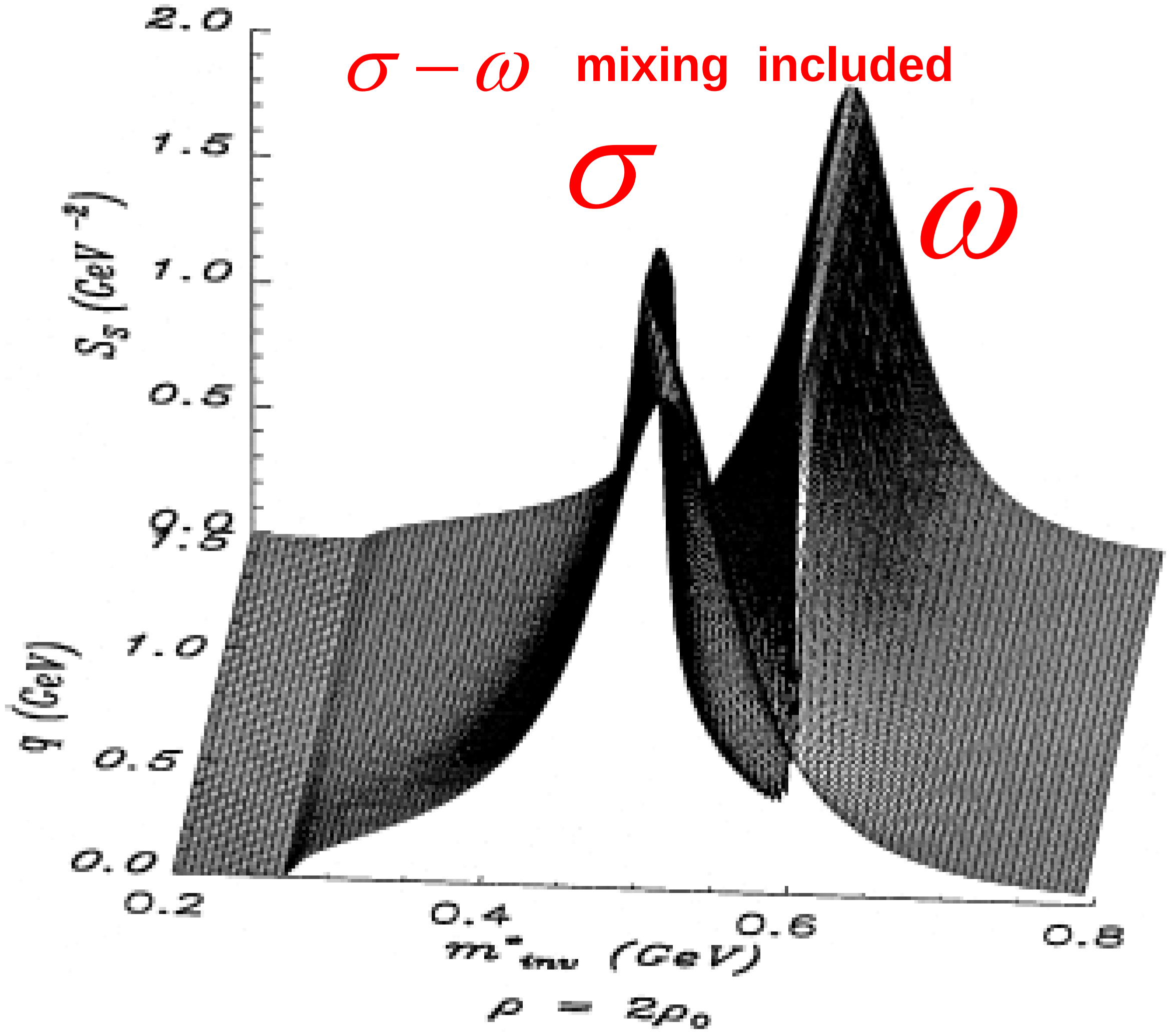


Fig. 6. Spectral function for the σ at $\rho_B / \rho_0 = 2$.

see also, G. Wolf et al(1998);
O. Teodorescu et al (2001)

Summary and concluding remarks

- The notion of the soft modes of QCD phase transitions was emphasized; they may be hadronic excitations above Tc.
- The soft modes of color-superconductivity above Tc may cause an enhancement of the electron-pair production in very-low mass region.
- Off the chiral limit, the lepton-pair production due to the specific mode around the QCD critical point is enhanced around 2 Mq ~ 300-400MeV, which might account (at least partly) for the excess of lepton pairs seen in CERES experiment.