A novel spectral broadening from vector - axial-vector mixing in dense matter

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based on
M.H. and C.Sasaki, arXiv:0902.3608

see also
M.H., C.Sasaki and W.Weise, Phys. Rev. D 78, 114003 (2008)
M.H. and C.Sasaki, PRD74, 114006 (2006)

of Hadrons

Origin of Mass ?

of Us

=

One of the Interesting problems of QCD

Origin of Mass = quark condensate ?

$$\langle \bar{q}q \rangle \neq 0$$

⇕

Spontaneous Chiral Symmetry Breaking

☆ QCD under extreme conditions

- Hot and/or Dense QCD
- large flavor QCD

◎ Chiral symmetry restoration

$$\langle \bar{q}q \rangle \neq 0 \Rightarrow \langle \bar{q}q \rangle = 0$$

$T_{critical}$ ∼ 170 – 200 MeV

$\rho_{critical}$ ∼ a few times of normal nuclear matter density

$Nf_{critical}$ ∼ 5 – 12 (still asymptotically free)

Change of Hadron masses ?

☆ Dropping mass of hadrons

Masses of mesons become lighter due to chiral restoration

◎ NJL model — T.Hatsuda and T.Kunihiro, PLB185, 304 (1987)

$$\frac{m_\sigma^*}{m_\sigma} \xrightarrow[T \to T_c]{} 0$$

◎ Brown-Rho scaling — G.E.Brown and M.Rho, PRL 66, 2720 (1991)

$$\frac{m_\sigma^*}{m_\sigma} \sim \frac{m_N^*}{m_N} \sim \frac{m_\rho^*}{m_\rho} \sim \frac{m_\omega^*}{m_\omega} \sim \frac{\langle \bar{q}q \rangle^*}{\langle \bar{q}q \rangle} \to 0$$

for $T \to T_{critical}$
and/or $\rho \to \rho_{critical}$

◎ QCD sum rule :

T.Hatsuda, Quark Matter 91 [NPA544, 27 (1992)]
T.Hatsuda and S.H.Lee, PRC46, R34 (1992)

$$\frac{m_\rho^*}{m_\rho} \sim \left(\frac{\langle \bar{q}q \rangle_T^*}{\langle \bar{q}q \rangle} \right)^{1/3} \xrightarrow[T \to T_c]{} 0 \qquad \frac{m_\rho^*}{m_\rho} \sim \frac{\langle \bar{q}q \rangle_\rho^*}{\langle \bar{q}q \rangle} \xrightarrow[\rho \to \rho_c]{} 0$$

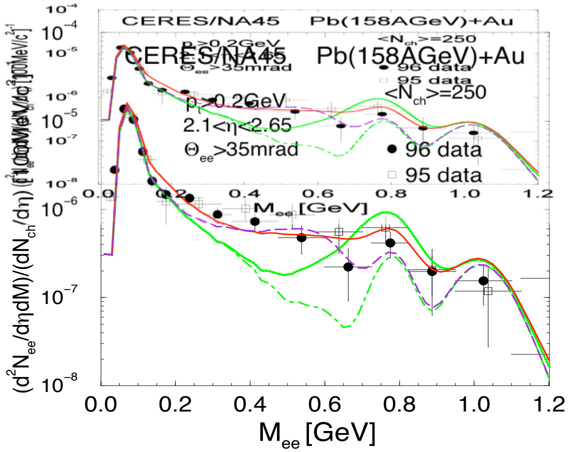
◎ Vector Manifestation

M.H. and K.Yamawaki, PRL**86**, 757 (2001)
M.H. and C.Sasaki, PLB**537**, 280 (2002)
M.H., Y.Kim and M.Rho, PRD**66**, 016003 (2002)

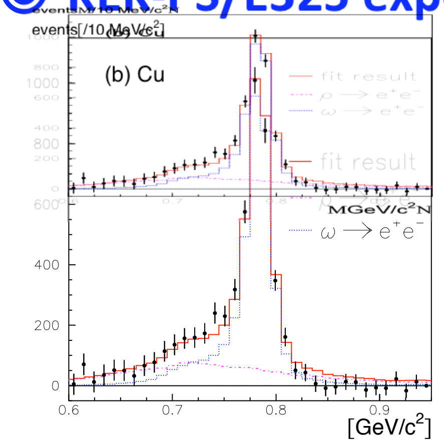
$$m_\rho \sim \langle \bar{q}q \rangle^\alpha \to 0$$

☆ Di-lepton data consistent with dropping mass

Analysis : R.Rapp and J.Wambach, ANP **25**,1 (2000)
Exp: G.Agakishiev et al. [CERES], PRL75, 1272 (1995)

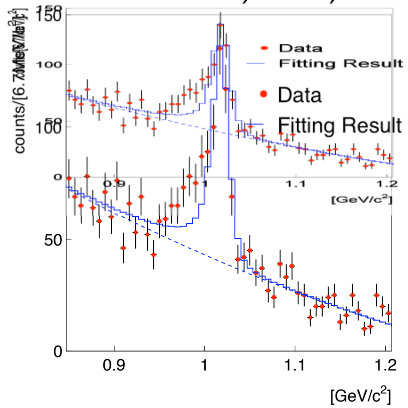


◎ KEK-PS/E325 experiment



$$m_\rho = m_0 (1 - \alpha\, \rho/\rho_0)$$
for $\alpha = 0.09$

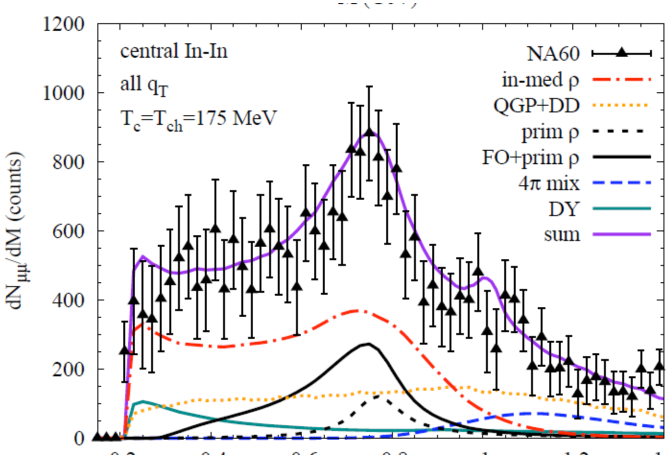
K.Ozawa et al., PRL86, 5019 (2001)
M.Naruki et al., PRL96, 092301 (2006)
R.Muto et al., PRL98, 042501 (2007)
F.Sakuma et al., PRL98, 152302 (2007)



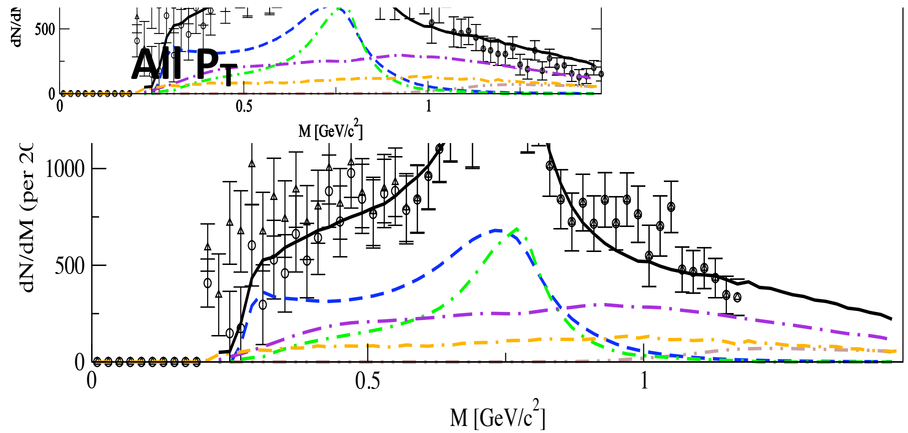
$$m_\phi = m_0 (1 - \alpha\, \rho/\rho_0)$$
for $\alpha = 0.03$

☆ Di-lepton data (NA60) consistent with NO dropping mass

H.v.Hees and R.Rapp, NPA806, 339 (2008)



J.Ruppert, C.Gale, T.Renk, P.Lichard and J.I.Kapusta,
PRL100, 162301 (2008)



☆ In this talk

・ **Effect of the Axial-vector Meson on the vector spectrum in dense baryonic matter**

[M.H. and C.Sasaki, arXiv:0902.3608]

・・・ **a background (many body effects of hadrons) needed for the determination of mass shift**

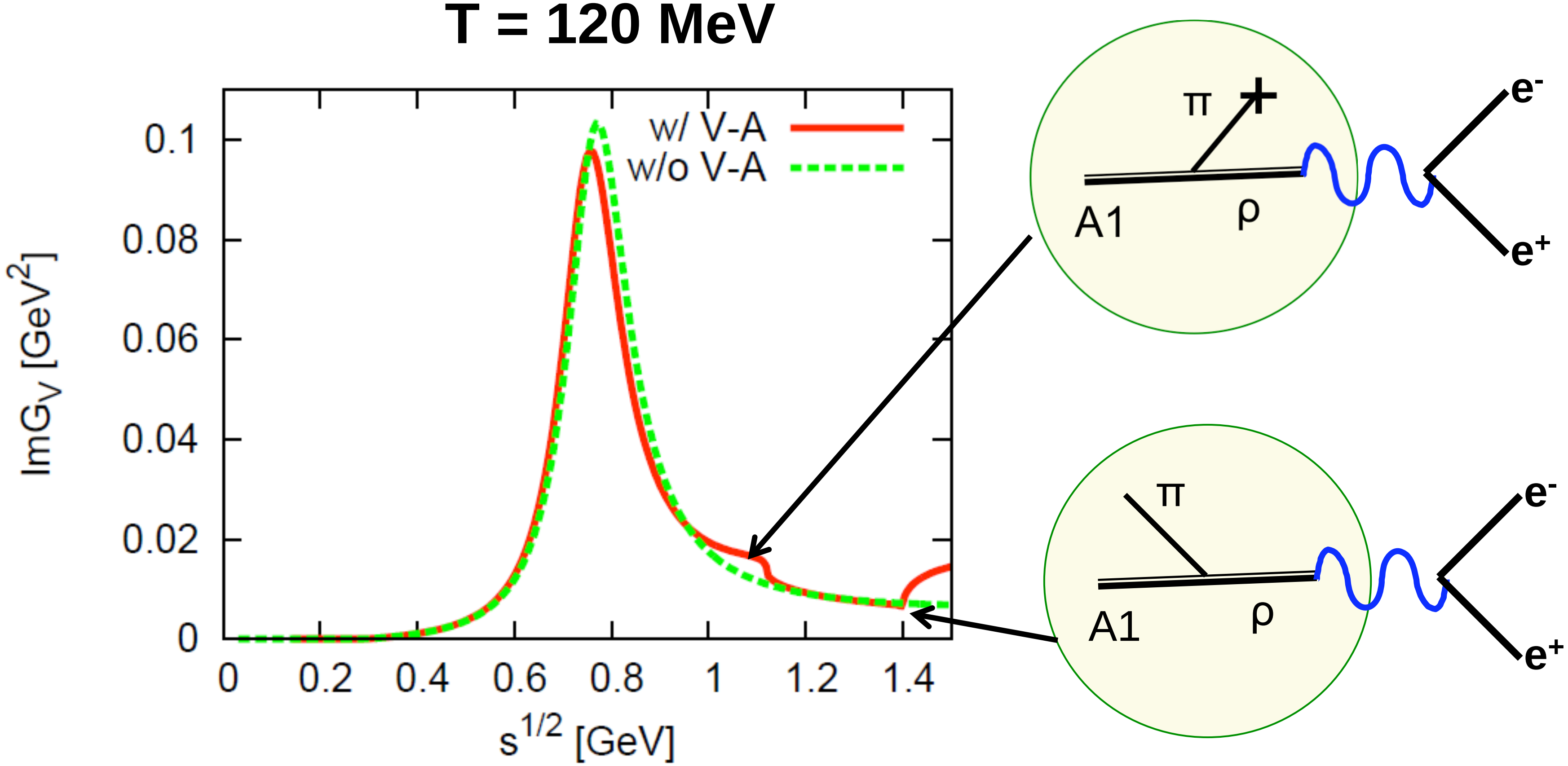
☆ Outline

1. Introduction
2. V-A mixing in hot matter (as a comparison)
3. V-A mixing in dense baryonic matter
4. Summary

2. V-A mixing in hot medium
→ modification of the vector spectral function

[M.H., C.Sasaki and W.Weise, Phys. Rev. D 78, 114003 (2008)]

T = 120 MeV



enhancement at $s^{1/2} = m_a - m_\pi$
cusp structure at $s^{1/2} = m_a + m_\pi$

3. V-A mixing in dense baryonic matter

[M.H. and C.Sasaki, arXiv:0902.3608]

◎ V-A mixing from the current algebra analysis in the low density region

B.Krippa, PLB427 (1998)

$$G_V^{\mu\nu}(n_B) = (1-\varepsilon)\, G_V^{\mu\nu}(0) + \varepsilon\, G_A^{\mu\nu}(0)$$

$$G_A^{\mu\nu}(n_B) = (1-\varepsilon)\, G_A^{\mu\nu}(0) + \varepsilon\, G_V^{\mu\nu}(0)$$

$$\varepsilon = 4 n_B \frac{\sigma_{\pi N}}{3 f_\pi^2 m_\pi^2}$$

- This is obtained at loop level in a field theoretic sense.
- Is there more direct V-A mixing at Lagrangian level ?

  such as $\mathcal{L} \sim V_\mu A^\mu$?

  ・・・ impossible in hot matter

  due to parity and charge conjugation invariance

  ・・・ possible in dense baryonic matter

  since charge conjugation is violated

  but be careful since parity is not violated

☆ **A possible V-A mixing term**

violates charge conjugation but conserves parity

S.K.Domokos, J.A.Harvey, PRL99 (2007)

$$\mathcal{L}_{\rm mix} = C\epsilon^{0\nu\lambda\sigma}\left[\partial_\nu V_\lambda \cdot A_\sigma + \partial_\nu A_\lambda \cdot V_\sigma\right]$$

generates a mixing between transverse ρ and A_1

ex : for $p^\mu = (p_0, 0, 0, p)$

no mixing between $V_{0,3}$ and $A_{0,3}$ (longitudinal modes)

mixing between V_1 and A_2, V_2 and A_1 (transverse modes)

◎ Dispersion relations for transverse ρ and A_1

$$p_0^2 - \bar{p}^2 = \frac{1}{2}\left[m_\rho^2 + m_{a_1}^2 \pm \sqrt{(m_{a_1}^2 - m_\rho^2)^2 + 16C^2\bar{p}^2}\right]$$

+ sign ･･･ transverse A_1 [$p_0 = m_{a1}$ at rest ($p = 0$)]

- sign ･･･ transverse ρ [$p_0 = m_\rho$ at rest ($p = 0$)]

☆ Determination of mixing strength *C*

◎ An estimation from ω dominance

- ρ A_1 ω interaction term

$$\mathcal{L}_{\omega\rho a_1} = g_{\omega\rho a_1}\, \varepsilon^{\mu\nu\lambda\sigma}\, \omega_\mu \left[\partial_\nu V_\lambda \cdot A_\sigma + \partial_\nu A_\lambda \cdot V_\sigma\right]$$

an empirical value : $g_{\omega\rho a_1} \simeq 3$ (cf: N.Kaiser,U.G.Meissner, NPA519,671(1990))

- ωNN interaction provides the ω condensation in dense baryonic matter

$$\mathcal{L}_{\omega NN} = -g_{\omega NN}\, \omega_\mu \bar{N}\gamma^\mu N \quad \Rightarrow \quad \langle \omega_0 \rangle = \frac{g_{\omega NN}}{m_\omega^2} n_B$$

an empirical value : $g_{\omega NN} \simeq 18$

- Mixing term from ω dominance

$$\mathcal{L}_{\rm mix} = g_{\omega\rho a_1} \langle \omega_0 \rangle\, \varepsilon^{0\nu\lambda\sigma} \left[\partial_\nu V_\lambda \cdot A_\sigma + \partial_\nu A_\lambda \cdot V_\sigma\right]$$

$$C_\omega = g_{\omega\rho a_1} \langle \omega_0 \rangle = \frac{g_{\omega\rho a_1} g_{\omega NN}}{m_\omega^2} n_B \simeq 0.1\,\text{GeV}$$

at $n_B = n_0$ (normal nuclear matter)

◎ An estimation in a holographic QCD (AdS/QCD) model

- Infinite tower of vector mesons in AdS/QCD models

  ω, ω', ω", ...

- These infinite ω mesons can generate V-A mixing

$$C_{\mathrm{AdS/QCD}} = C_{\omega} + C_{\omega'} + C_{\omega''} + \cdots$$

- This summation was done in an AdS/QCD model

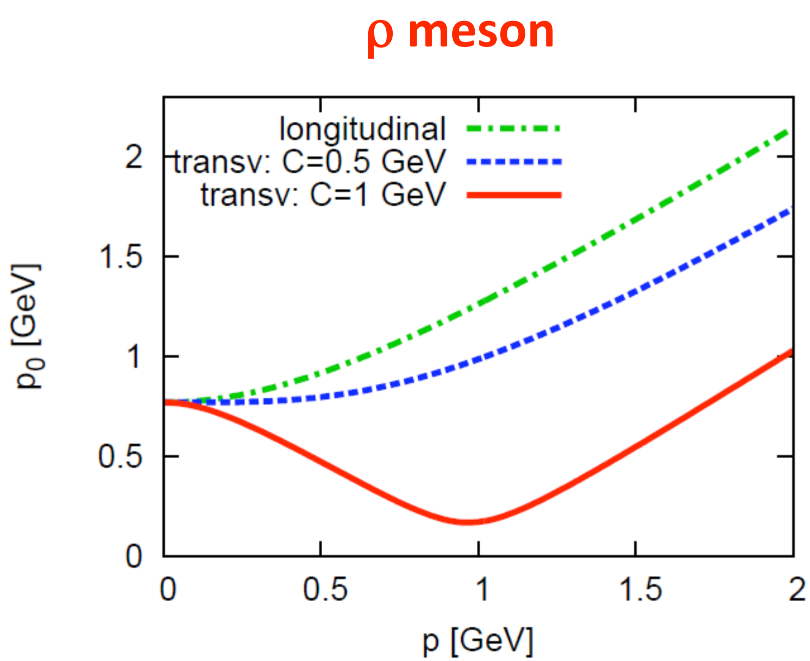
S.K.Domokos, J.A.Harvey, PRL99 (2007)

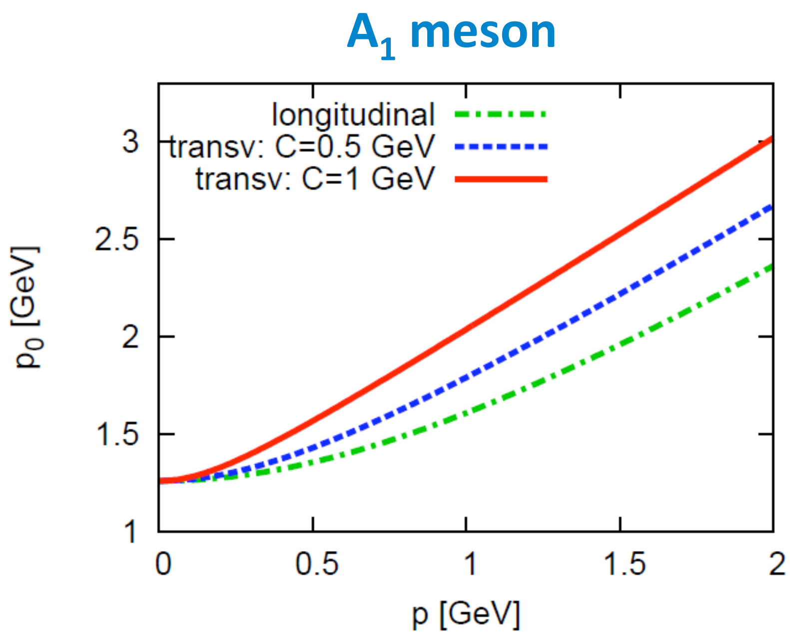
$$C_{\mathrm{AdS/QCD}} \simeq 1\,\mathrm{GeV} \times \frac{n_B}{n_0}$$

n_0 : normal nuclear matter density

☆ Dispersion relations

$$p_0^2 - \bar{p}^2 = \frac{1}{2}\left[m_\rho^2 + m_{a_1}^2 \pm \sqrt{(m_{a_1}^2 - m_\rho^2)^2 + 16C^2\bar{p}^2}\right]$$

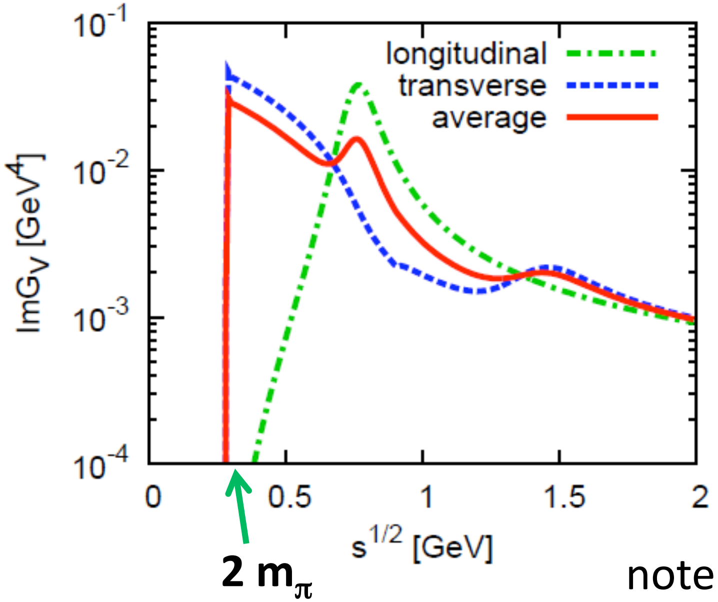




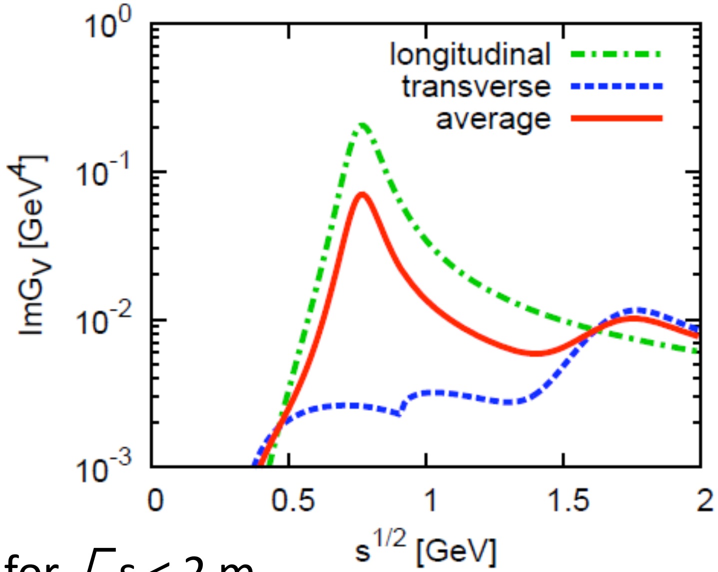
- **C = 0.5 GeV** : small changes for ρ and A_1 mesons
- **C = 1 GeV** : small change for A_1 meson
  substantial change in ρ meson
- C ∼ 1.1 GeV : $p_0^2 < 0$ for ρ → vector meson condensation ?
  [S.K.Domokos, J.A.Harvey, PRL99 (2007)]

☆ Integrated vector spectrum for C = 1 GeV

$0 < \bar{p} < 0.5$ GeV



$0.5 < \bar{p} < 1$ GeV



note : $\Gamma_\rho = 0$ for $\sqrt{s} < 2\, m_\pi$

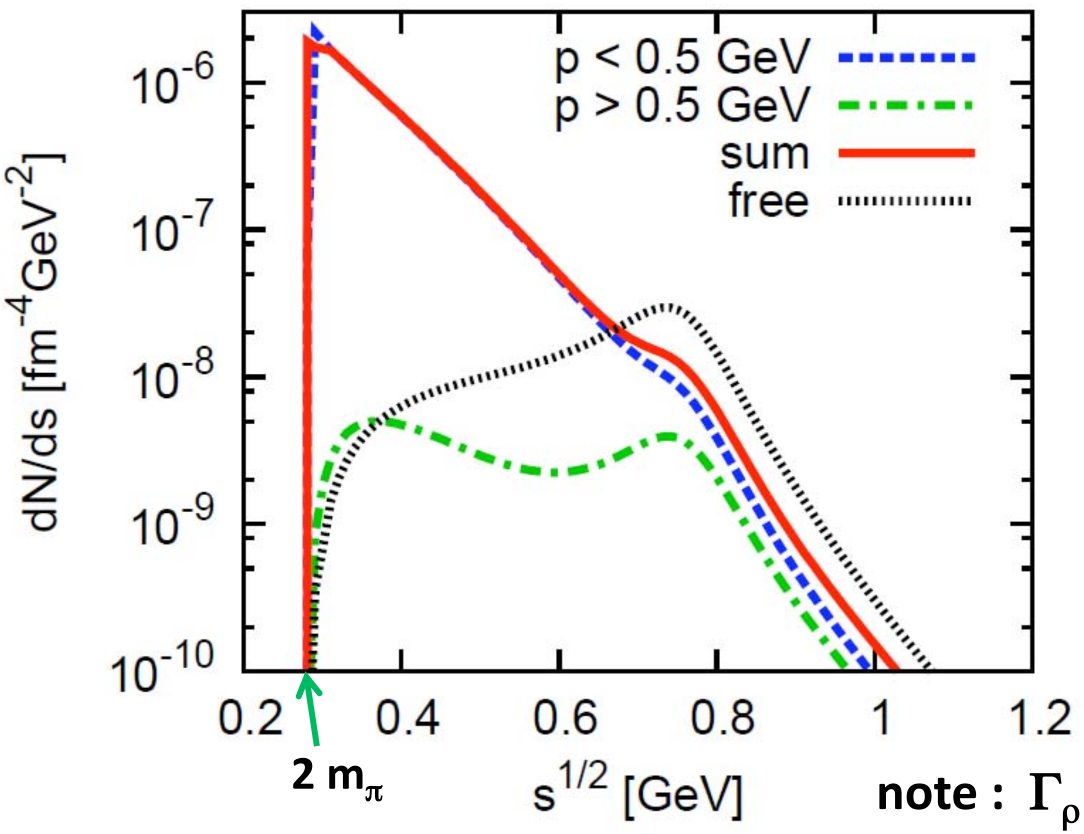
◎ low p region

- longitudinal mode : ordinary ρ peak
- transverse mode : an enhancement for $\sqrt{s} < m_\rho$ and no clear ρ peak
  a gentle peak corresponding to A_1 meson
- spin average $(\mathrm{Im}\, G_L + 2\, \mathrm{Im}\, G_T)/3$: 2 peaks corresponding to ρ and A_1

◎ high p region

- longitudinal mode : ordinary ρ peak
- transverse mode : 2 small bumps and a gentle A_1 peak
- spin averaged : 2 peaks for ρ and A_1 ; Broadening of ρ peak

☆ Di-lepton spectrum at *T* = 0.1 GeV with *C* = 1 GeV



note : $\Gamma_\rho = 0$ for $\sqrt{s} < 2\,m_\pi$

- A large enhancement in low $\sqrt{s}$ region
  → result in a strong spectral broadening

・・・ might be observed in with low-momentum binning at J-PARC, GSI/FAIR and RHIC low-energy running

☆ Effects of V-A mixing for ω and ϕ mesons

- Assumption of nonet structure
  → common mixing strength *C*
  for ρ-A_1, ω-f_1(1285) and ϕ-f_1(1420)

$$\mathcal{L}_{\rm mix} = C\epsilon^{0\nu\lambda\sigma}\left[\partial_\nu V_\lambda \cdot A_\sigma + \partial_\nu A_\lambda \cdot V_\sigma\right]$$

- **Vector current correlator**

$$G_V^L = \sum_{V=\rho,\omega,\phi} \frac{-s(g_V/m_V)^2}{D_V}, \quad G_V^T = \sum_{V=\rho,\omega,\phi} \frac{(g_V/m_V^2)(-sD_A + 4C^2\bar{p}^2)}{D_V D_A - 4C^2\bar{p}^2}$$

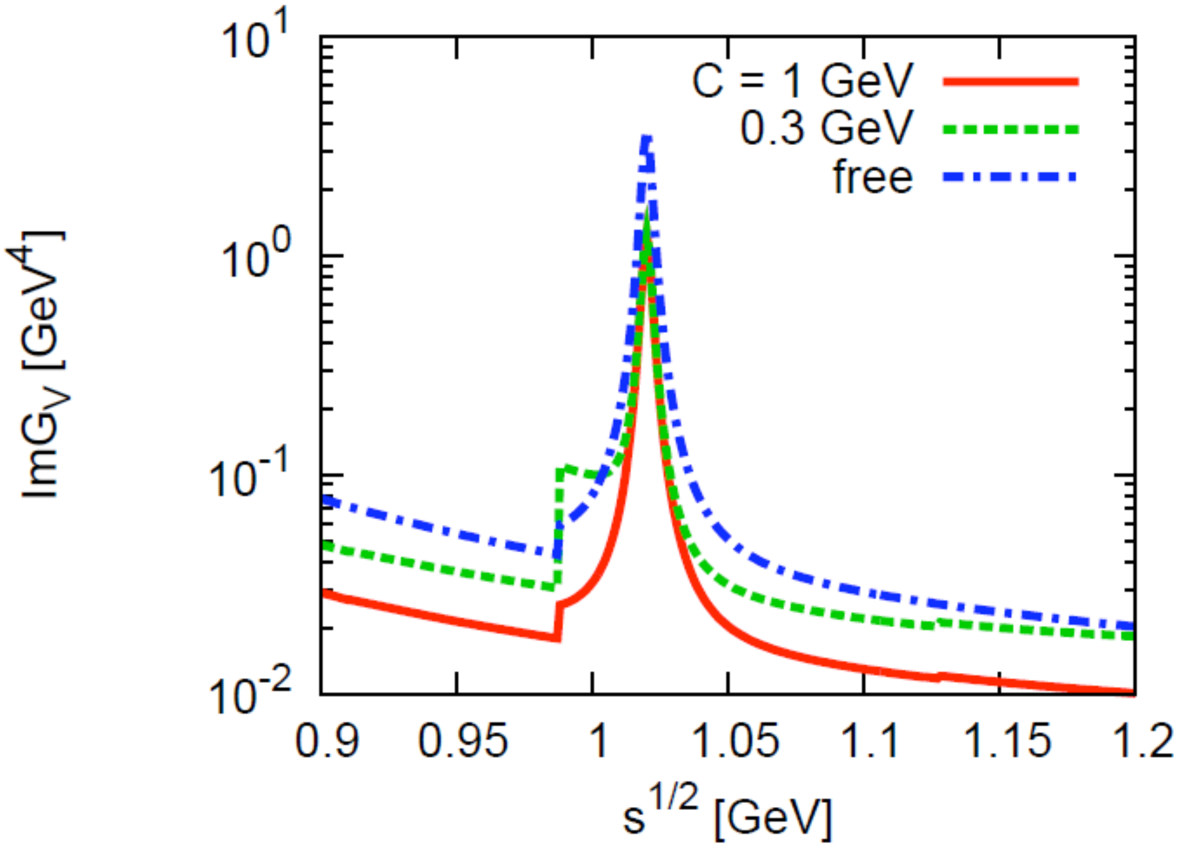
note : we used the following meson widths

$$\Gamma_\omega = \Theta(s-(3m_\pi)^2)\,8.49\ \text{MeV}, \quad \Gamma_{f_1(1285)} = \Theta(s-(4m_\pi)^2)\,24.3\ \text{MeV}$$

$$\Gamma_\phi = \Theta(s-(2m_K)^2)\,4.26\ \text{MeV}, \quad \Gamma_{f_1(1420)} = \Theta(s-(m_\pi+2m_K)^2)\,54.9\ \text{MeV}$$

◎ ϕ meson spectral function

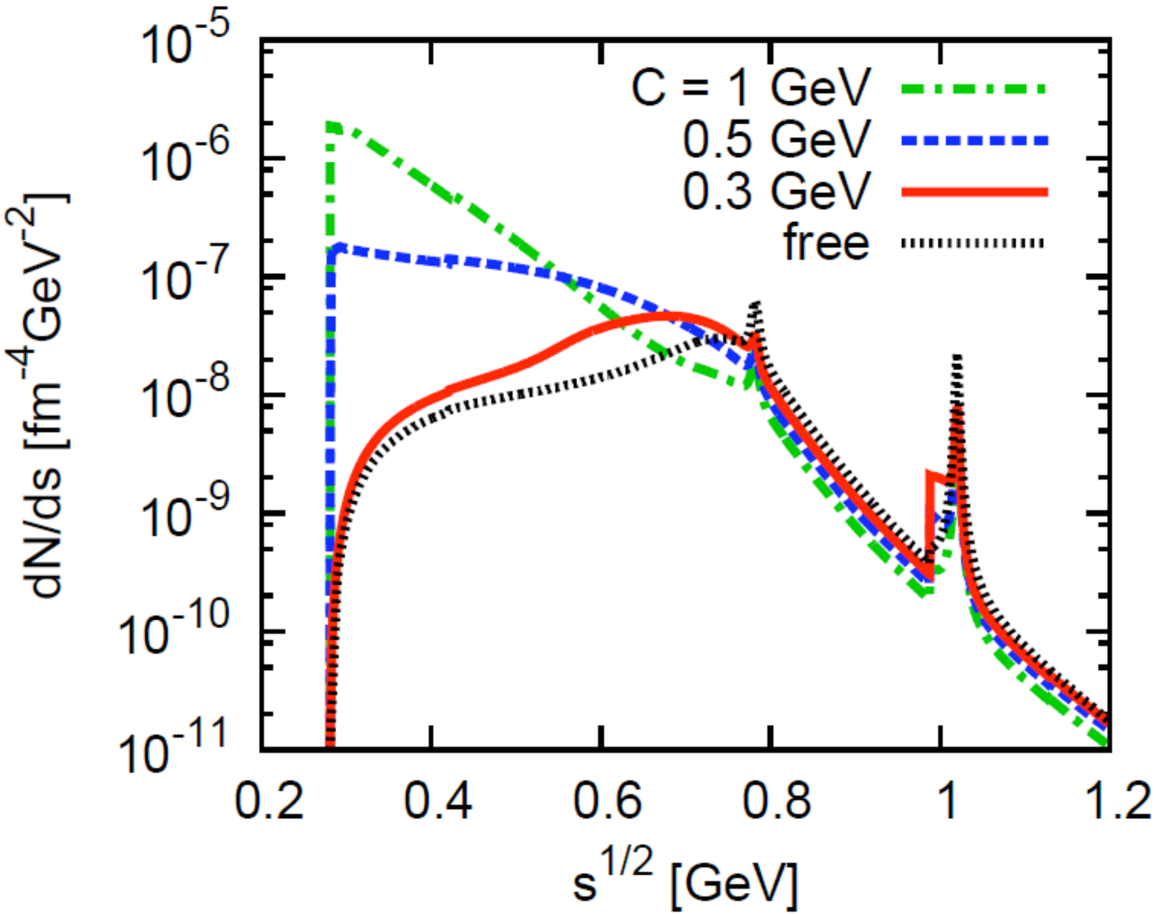
spin averaged, integrated over $0 < p < 1$ GeV



- C = 1 GeV : suppression of ϕ peak (broadening)
- C = 0.3 GeV : suppression for $\sqrt{s} > m_\phi$

  enhancement for $\sqrt{s} < m_\phi$

☆ Integrated rate with ρ, ω and ϕ mesons for C = 0.3, 0.5, 1 GeV



(at T = 0.1GeV)

- An enhancement for $\sqrt{s} < m_\rho$, m_ω (reduced for decreasing C)
- An enhancement for $\sqrt{s} < m_\phi$ from ϕ-f_1(1420) mixing
  → a broadening of ϕ width

4. Summary

◎ V-A mixing (violating charge conjugation) can exist in dense baryonic matter

$$\mathcal{L}_{\rm mix} = C\epsilon^{0\nu\lambda\sigma}\left[\partial_\nu V_\lambda \cdot A_\sigma + \partial_\nu A_\lambda \cdot V_\sigma\right]$$

for ρ-A_1, ω-$f_1(1285)$ and ϕ-$f_1(1420)$

→ ・ modification of dispersion relations

・ change in vector spectral function (broadening)

◎ Large *C* ? : $C_\omega \simeq 0.1\,\text{GeV}$ or $C_{\text{AdS/QCD}} \simeq 1\,\text{GeV}$?

- If C = 0.1GeV, then this mixing will be irrelevant.
- If C > 0.3GeV, then this mixing will be important.
- We need more analysis for estimation.

The End