

Progress in Chiral Thermodynamics

-- Chiral Mixing in Dense Matter --

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Why chiral mixing?

Q. Do we see any signal of chiral symmetry restoration in dilepton measurement?

- ❑ Light vector mesons change their properties in hot/dense matter --- χ -sym. restoration?
- ❑ The best way: V spectrum vs. A spectrum
- ❑ Axial-vector mesons can show up in vector spectrum in a medium!

$\langle VV \rangle \leftarrow \text{chiral mixing} \rightarrow \langle AA \rangle$

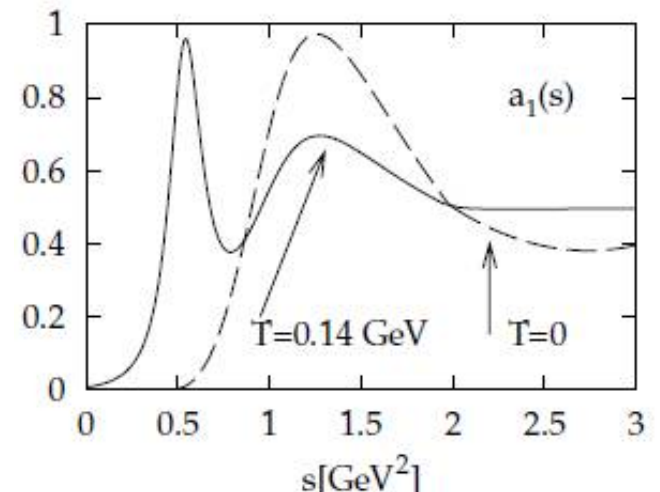
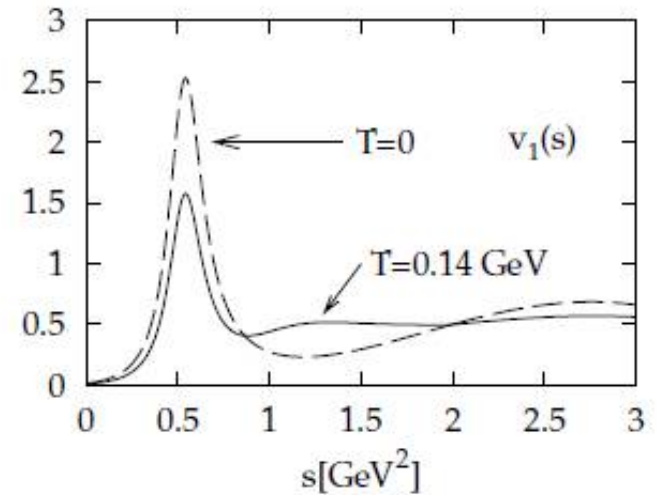
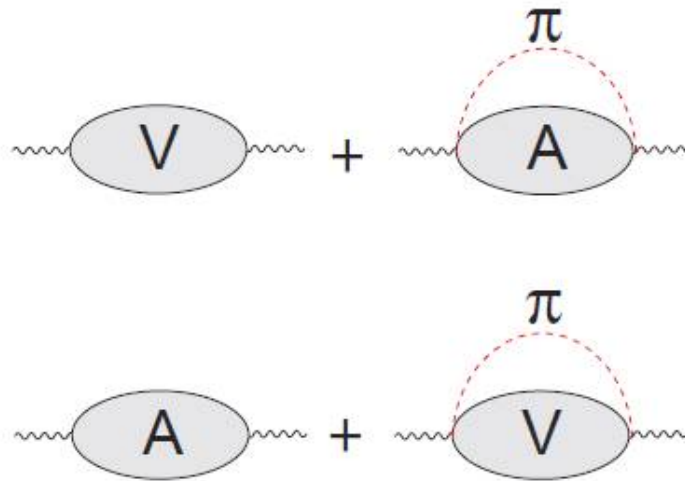
Low-energy theorem

for low $T \lesssim m_\pi$: [Dey, Eletsky and Ioffe (90)]

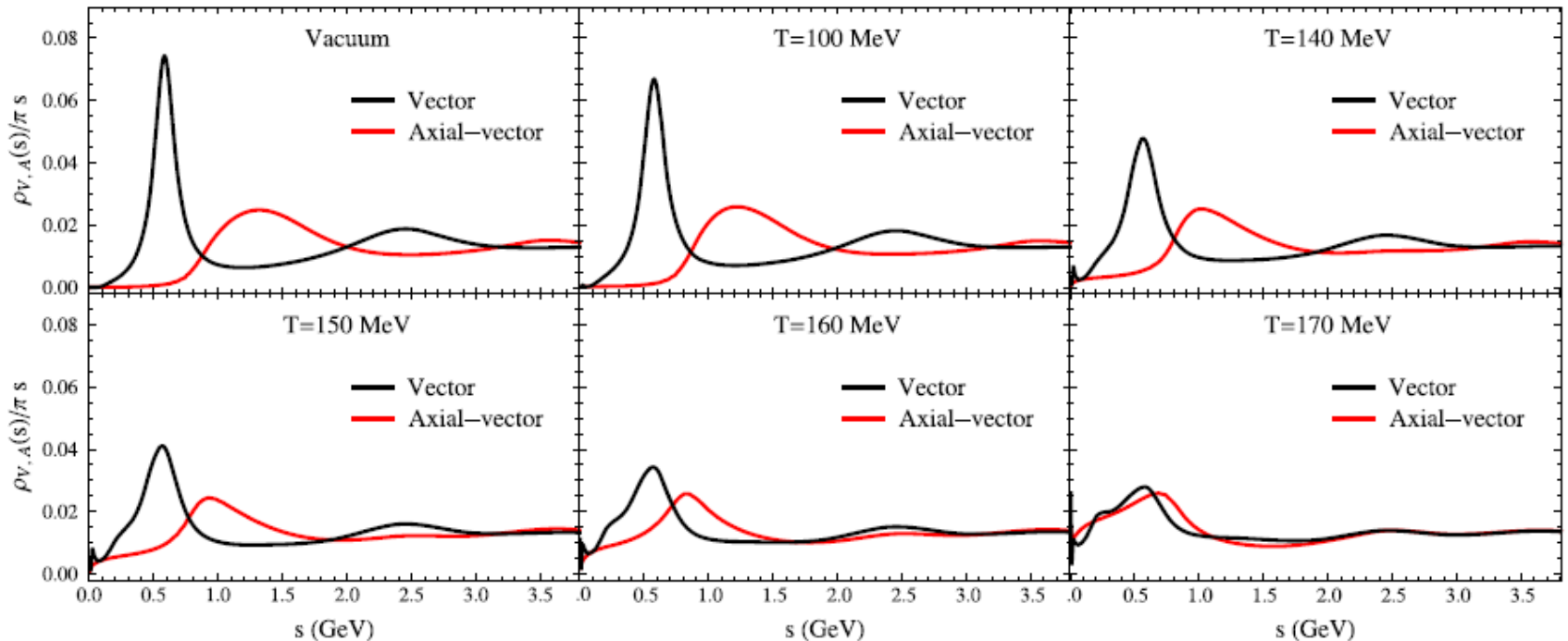
$$G_V^{\mu\nu}(T) = (1 - \epsilon)G_V^{\mu\nu}(0) + \epsilon G_A^{\mu\nu}(0)$$

$$G_A^{\mu\nu}(T) = (1 - \epsilon)G_A^{\mu\nu}(0) + \epsilon G_V^{\mu\nu}(0)$$

$$\epsilon = \frac{T^2}{6F_\pi^2}$$



From low T to high T



□ Weinberg SRs [Weinberg ('67); Kapusta, Shuryak ('94)]

□ Vector SF & ansatz for a_1 mass and width

✓ Reduction of a_1 mass, width broadening

✓ Role of higher-lying states: ρ' , a_1' , ...

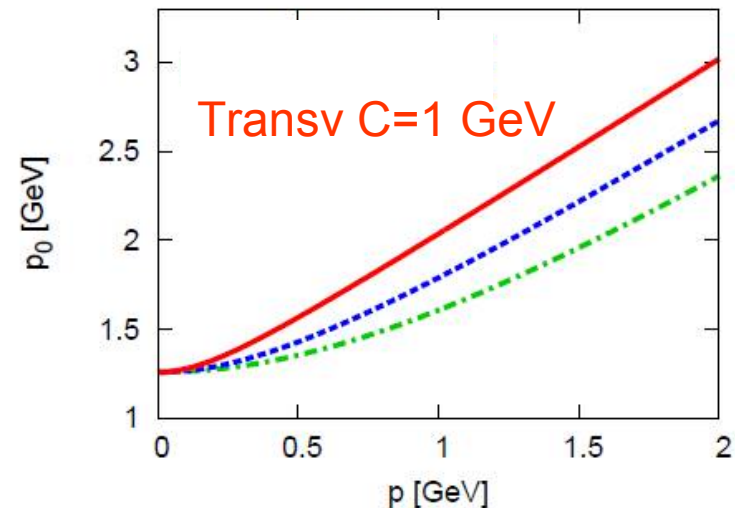
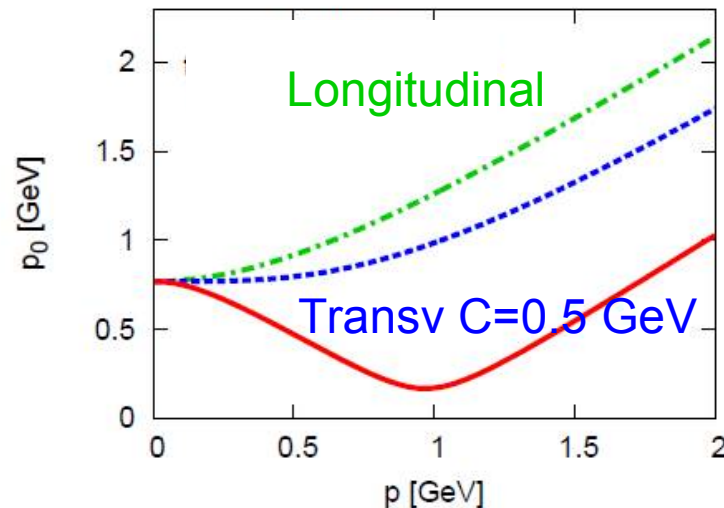
Holographic approach

$$S_{4\text{dim}} = \int d^4x \left[\frac{1}{2} (\partial_\mu \pi)^2 - \frac{1}{2} m_\pi^2 \pi^2 - \frac{1}{4} (\rho_{\mu\nu})^2 - \frac{1}{4} (a_{\mu\nu})^2 \right. \\ \left. + \frac{1}{2} m_\rho^2 \rho_\nu^2 + \frac{1}{2} m_a^2 a_\mu^2 + C \epsilon^{ijk} (\rho_i \partial_j a_k + a_i \partial_j \rho_k) \right]$$

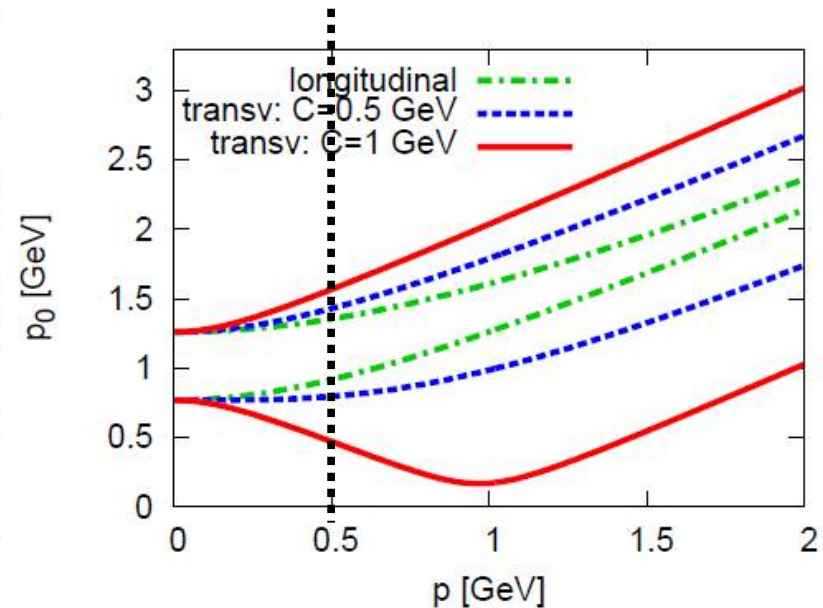
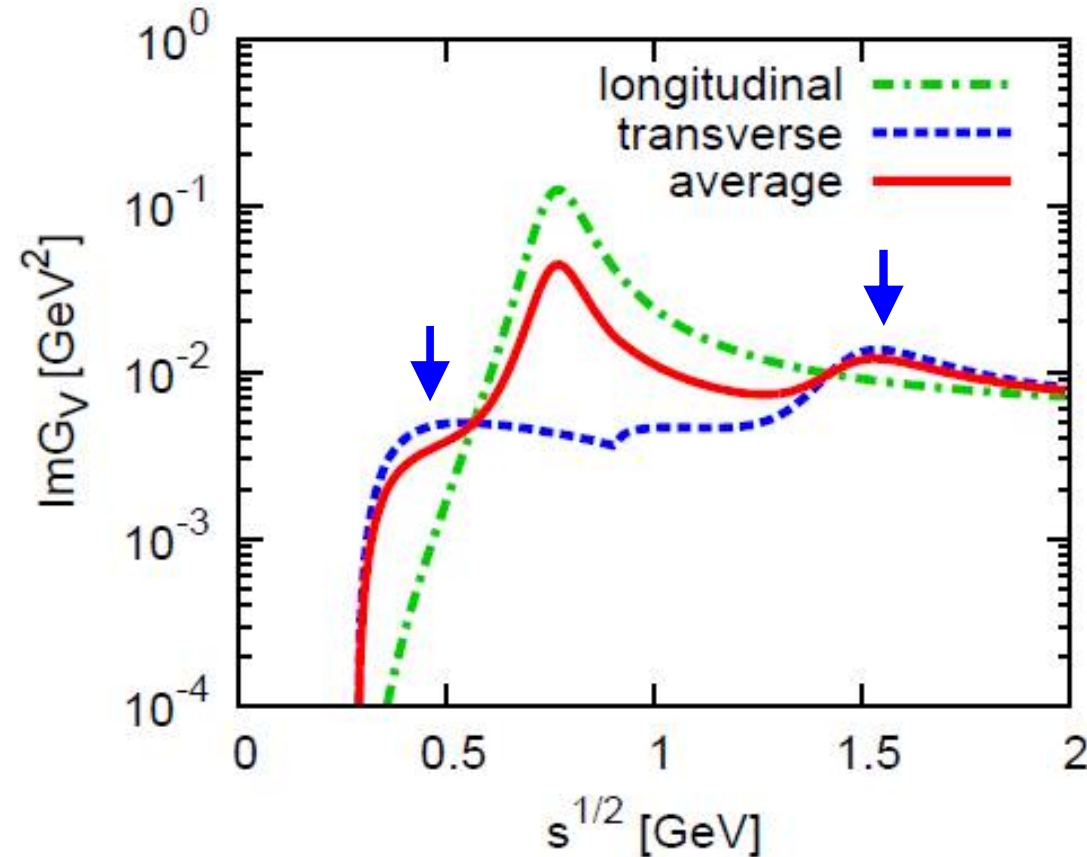
$$p_0^2 - |\vec{p}|^2 = \frac{1}{2} \left[m_\rho^2 + m_{a_1}^2 \pm \sqrt{(m_{a_1}^2 - m_\rho^2)^2 + 16C^2 |\vec{p}|^2} \right]$$

ρ meson

a_1 meson



Spectral function: Not BW



□ $C = 1 \text{ GeV}$, 3-momentum $p = 0.5 \text{ GeV}$

□ 1 bump of shifted ρ , 1 bump of shifted a_1

Chiral mixing induced by WZW

□ Wess-Zumino-Witten term [Kaiser, Meissner ('90)]

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

$$\langle \omega_0 \rangle = g_{\omega NN} \cdot n_B / m_\omega^2 \quad C = g_{\omega\rho a_1} \cdot g_{\omega NN} \cdot \frac{n_B}{m_\omega^2}$$

□ Mixing strength: $C = 0.1 \text{ GeV}$ at ρ_0

- AdS/QCD $\rightarrow C = 1 \text{ GeV}$ at $\rho_0 \rightarrow$ vector cond.!?
- Why so large? --- higher-lying states in large N_c

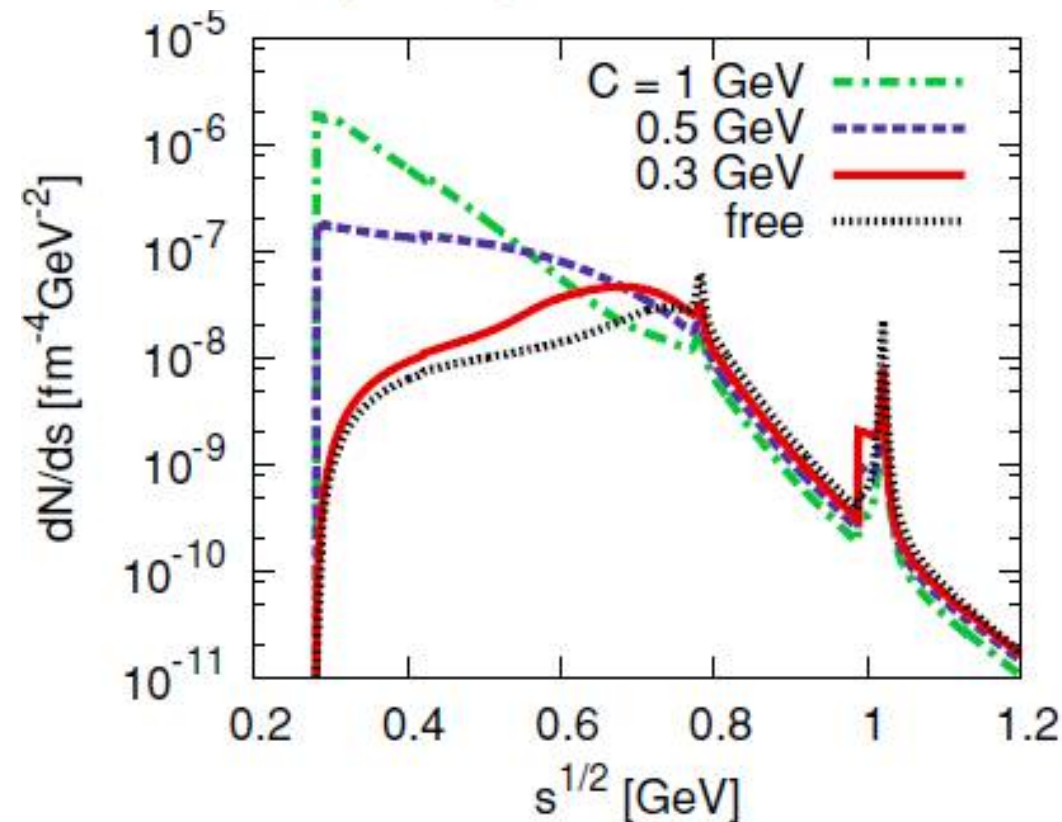
cf. VMD

$$C_{\text{hQCD}} \sim C_{\omega\rho a_1} + \sum_n C_{\omega^n \rho a_1}$$

Dilepton rates at T = 100 MeV

□ Propagator using $D_{V,A} = s - m_{\rho,a_1}^2 + im_{\rho,a_1}\Gamma_{\rho,a_1}(s)$

$$G_V^L = \left(\frac{g_V}{m_V}\right)^2 \frac{-s}{D_V}, \quad G_V^T = \left(\frac{g_V}{m_V}\right)^2 \frac{-sD_A + 4c^2\vec{p}^2}{D_V D_A - 4c^2\vec{p}^2}$$



$$\begin{aligned} \frac{dN}{d^4p}(p_0, \vec{p}; T, n_B) \\ = \frac{\alpha^2}{\pi^3 s} \frac{1}{e^{p_0/T} - 1} \text{Im} G_V \end{aligned}$$

$$\frac{dN}{ds}(s; T, n_B) = \int \frac{d^3\vec{p}}{2p_0} \frac{dN}{d^4p}$$

A missing piece: χ sym. restoration

$$\langle AA \rangle \rightarrow \langle VV \rangle$$

Chiral restoration vs. mixing

□ Dispersion relations for small 3-momenta

$$p_0^2 \simeq m_{a_1, \rho}^2 + \left(1 \pm \frac{4C^2}{m_{a_1}^2 - m_\rho^2} \right) \vec{p}^2$$

□ The mixing effect will be enhanced as δm decreases!

➤ In-medium δm

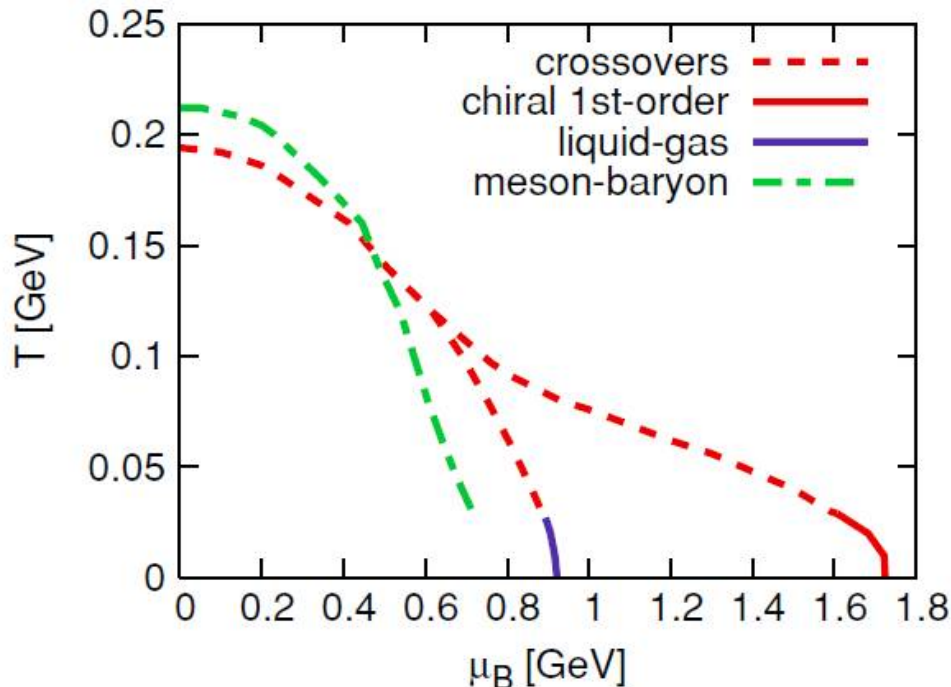
➤ In-medium mixing C

Set-up: rho/omega

□ Mass difference = order parameter

- Chiral restoration $\rightarrow \langle \sigma \rangle$
 - Density effect $\rightarrow \langle \omega_0 \rangle$
- } Chiral MF models

□ Nucleon parity-doublet model [Zschesche et al.]

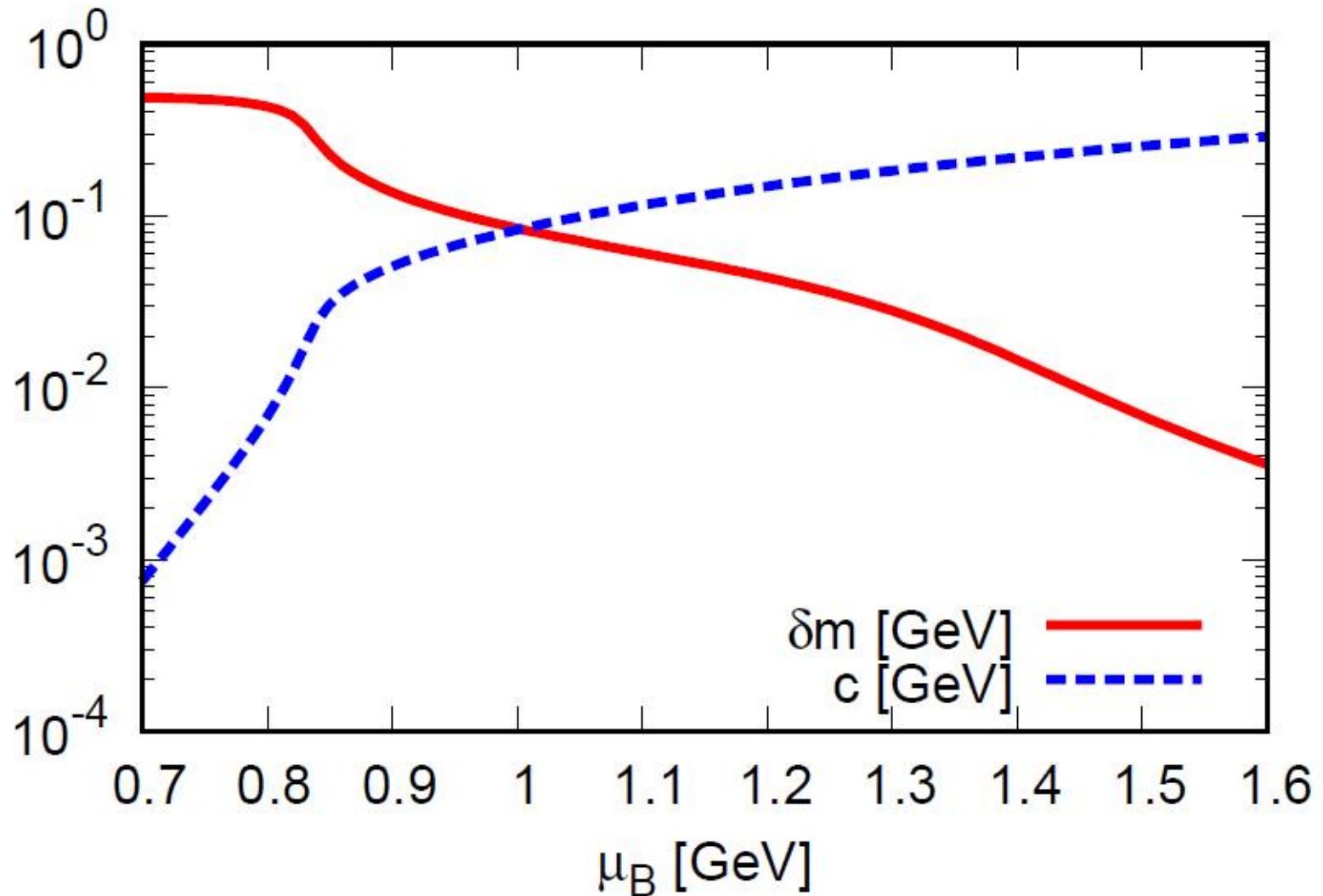


✓ T_c at $\mu = 0$

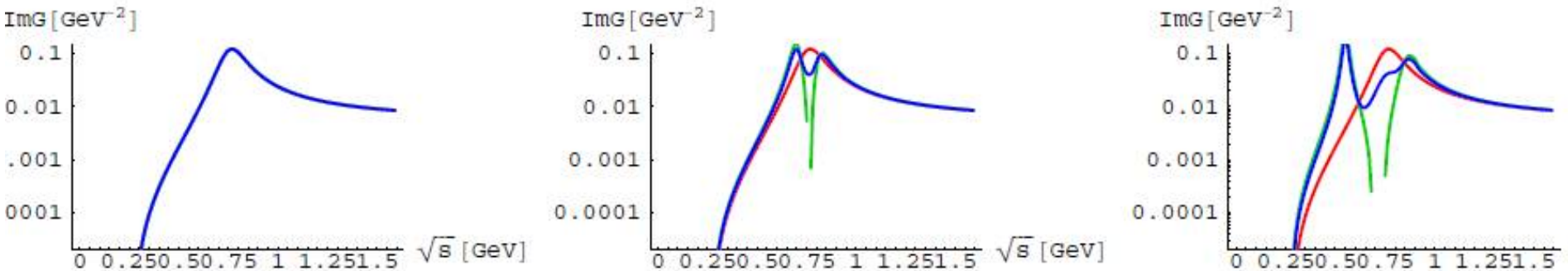
✓ Nuclear ground state
[CS, Mishustin ('10)]

→ **Masses & mixing**

Mass difference vs. mixing : $T=50$ MeV



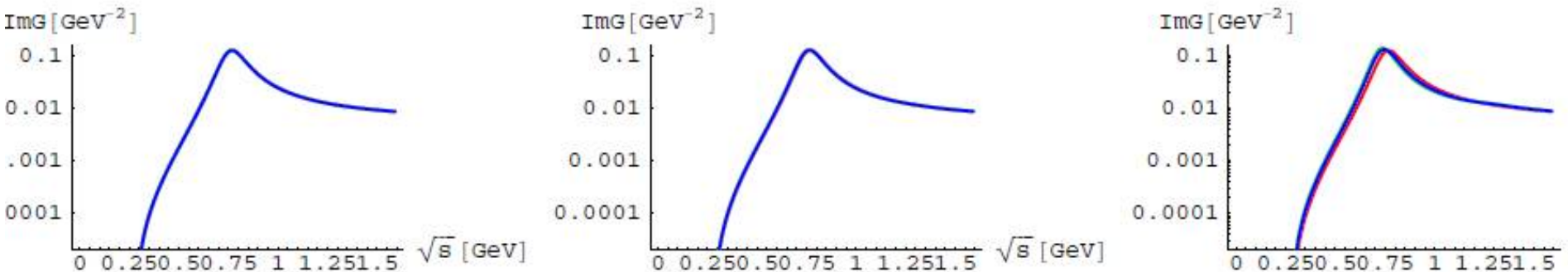
Spectral function at $T = 50$ MeV



Low μ_B



High μ_B



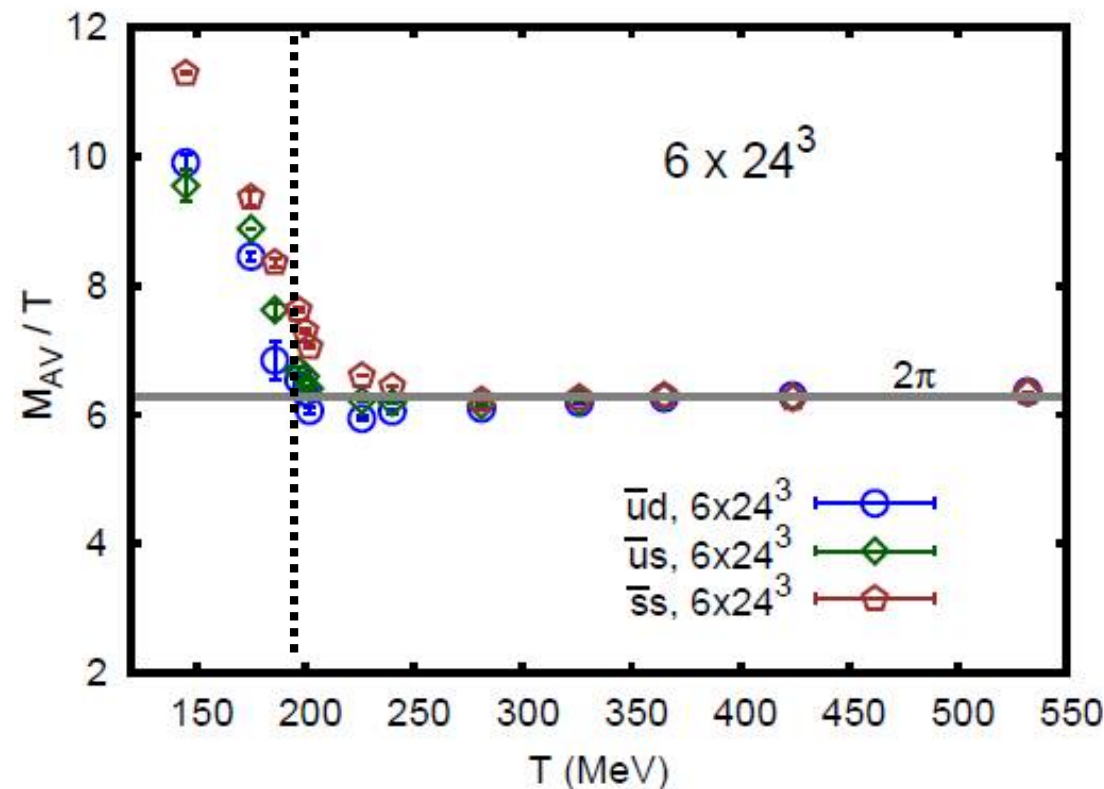
(top) chiral restoration (bottom) no restoration

--- longitudinal --- transverse --- average

Set-up: phi

□ Masses of Φ meson and $f_1(1420)$?

- Screening mass in LQCD: modification sets in at T_c

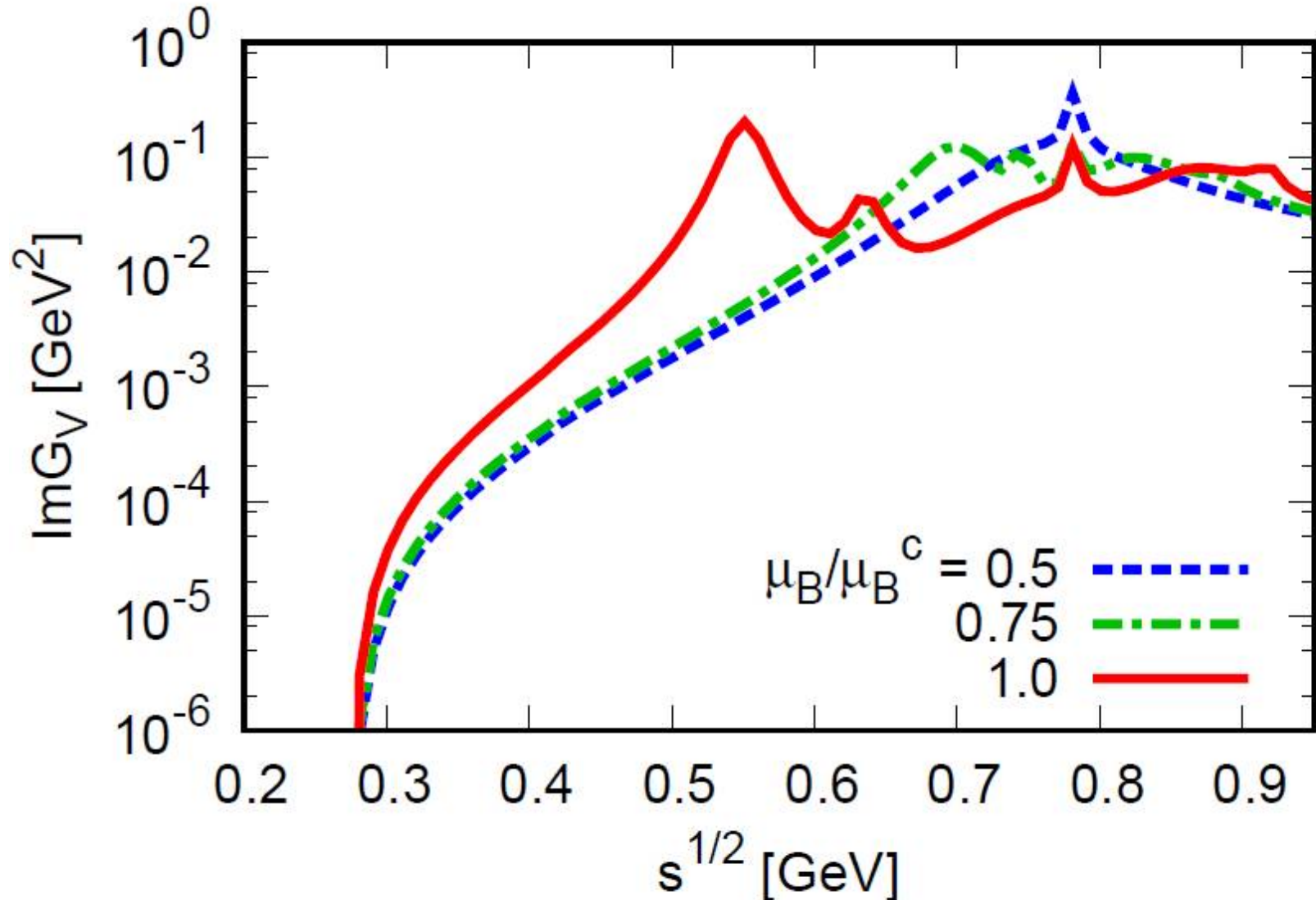


Assumptions:

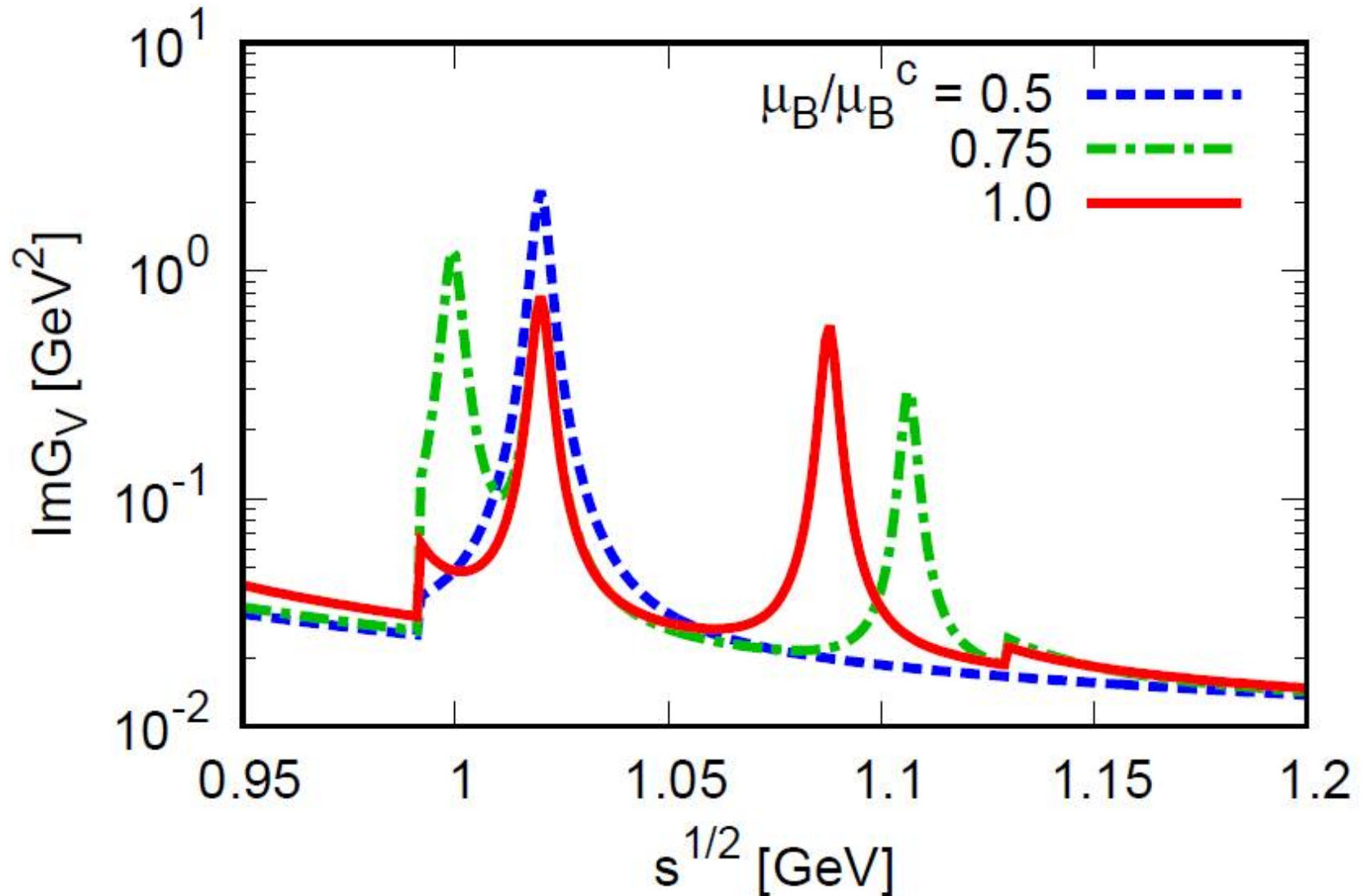
- $\delta m(q) \approx 0$ at T_c
- $\delta m(s) \approx 0$ at $1.2 T_c$
- Constant mass of vector states

[Cheng et al., ('11)]

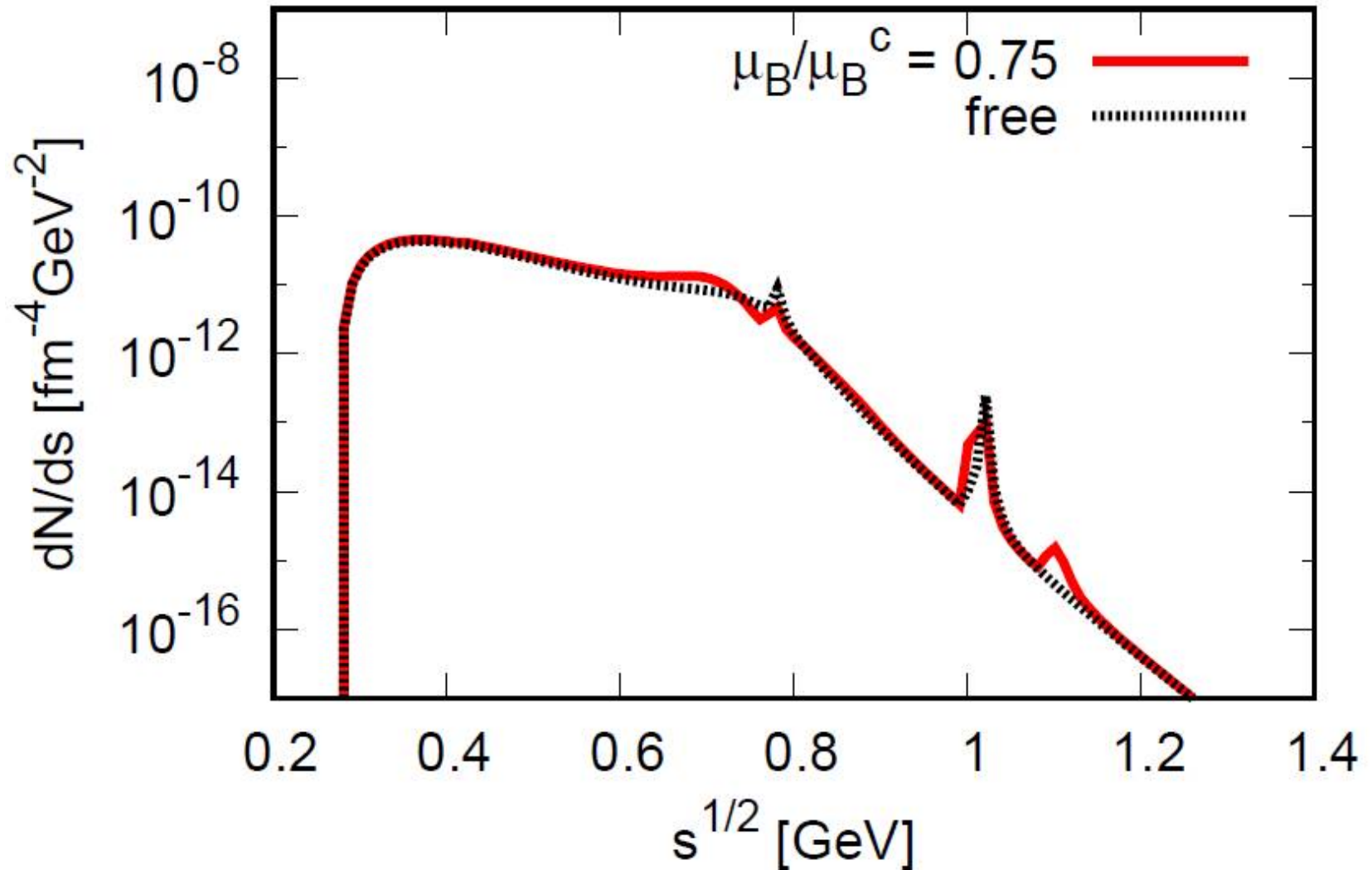
Rho/omega spectrum at $T = 50$ MeV



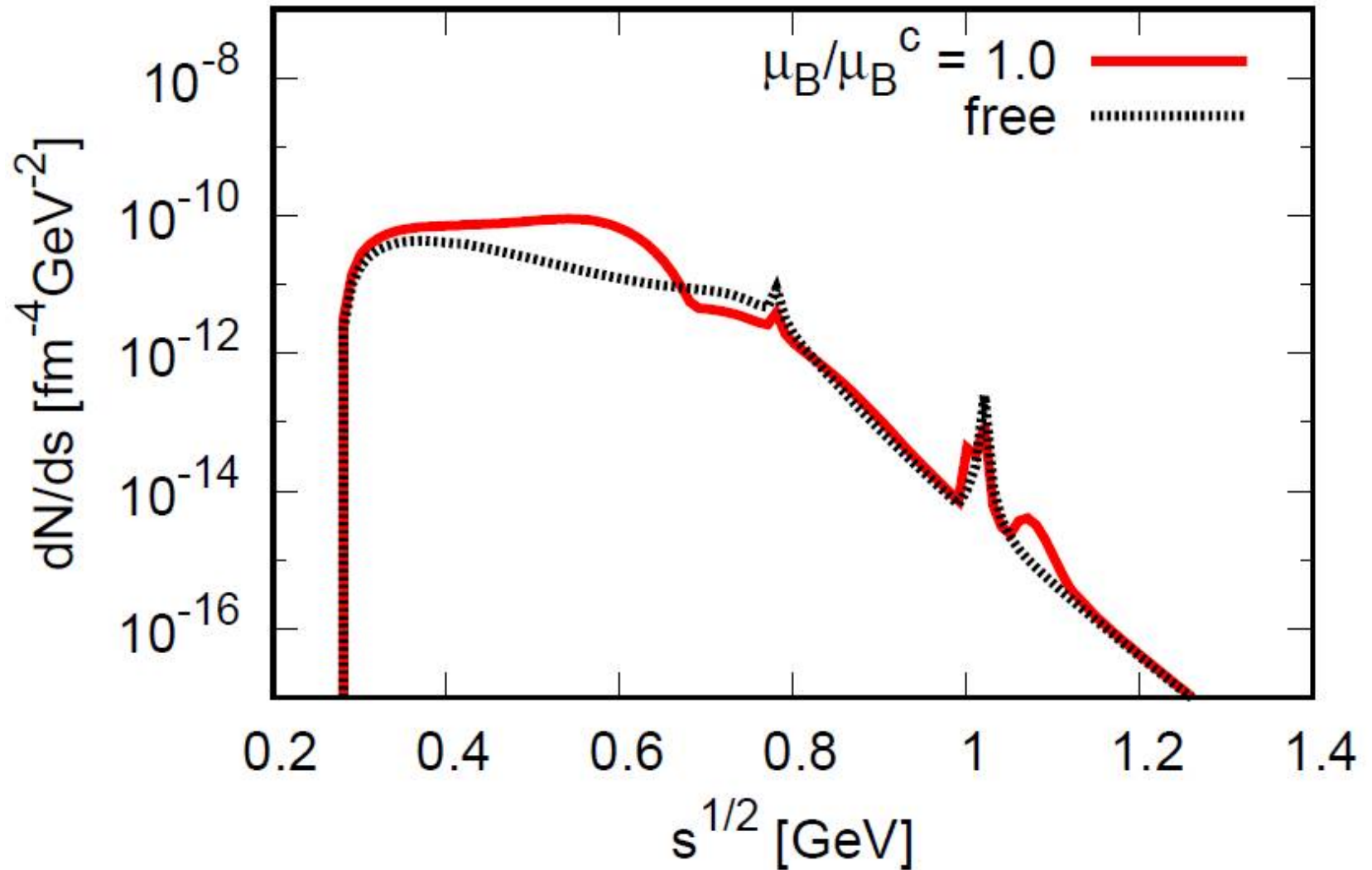
Phi spectra at $T = 50$ MeV



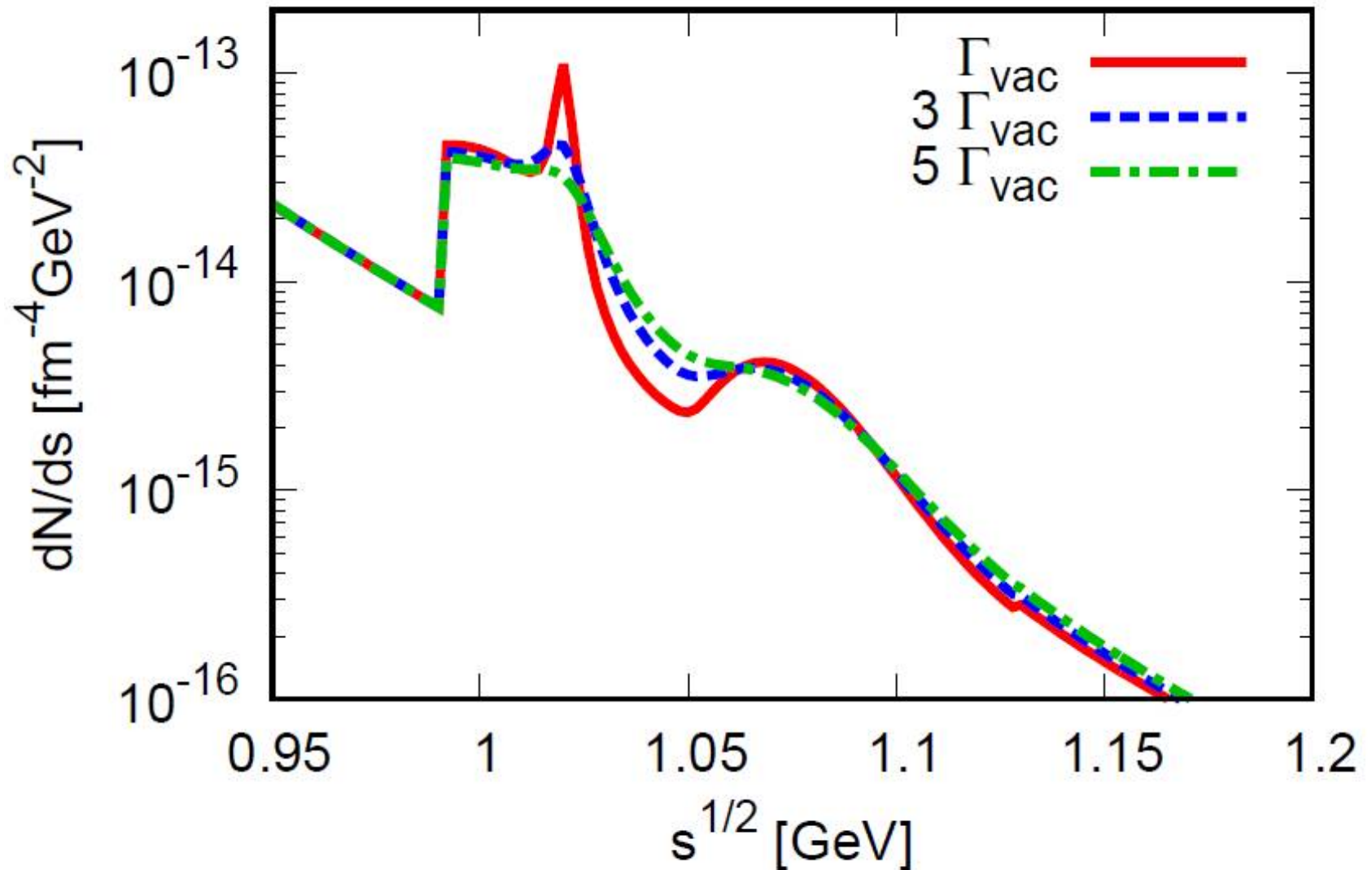
Dilepton rates at $T = 50$ MeV



Dilepton rates at $T = 50$ MeV



ϕ width broadening



Summary

□ Parity doubling of vector mesons

- Chiral mixing: pion-induced vs. **density-induced**
(decreases) (increases)

[Harada, CS, Weise ('08)]

□ Chiral symmetry restoration

- ρ , ω sector: enhancement below vac mass, screened by many-body effects?
- ϕ sector: bumps below/above m_ϕ
- Relevant to the physics at FAIR, NICA, J-PARC!