Chiral Symmetry Restoration at High Baryon Density

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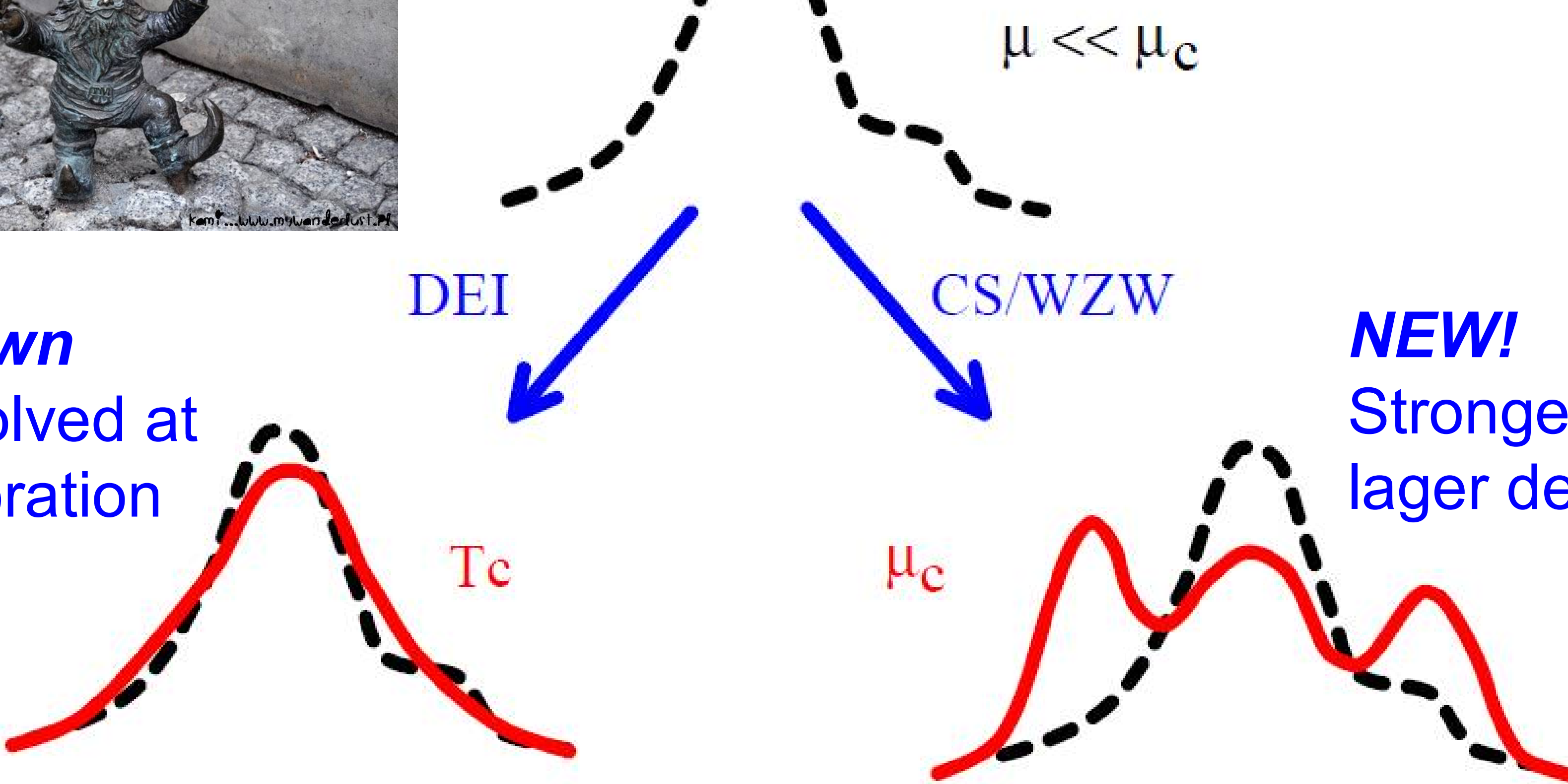
Why chiral mixing?

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?
- ❑ Strategy: vector and axial-vector states
- ❑ Axial-vector mesons can show up in vector spectrum in a medium!

<VV> ← chiral mixing → <AA>

My fingers crossed, FAIR/NICA/J-PARC/RHIC-BES!



Known
Resolved at restoration

NEW!
Stronger at lager density

Hot dilute matter

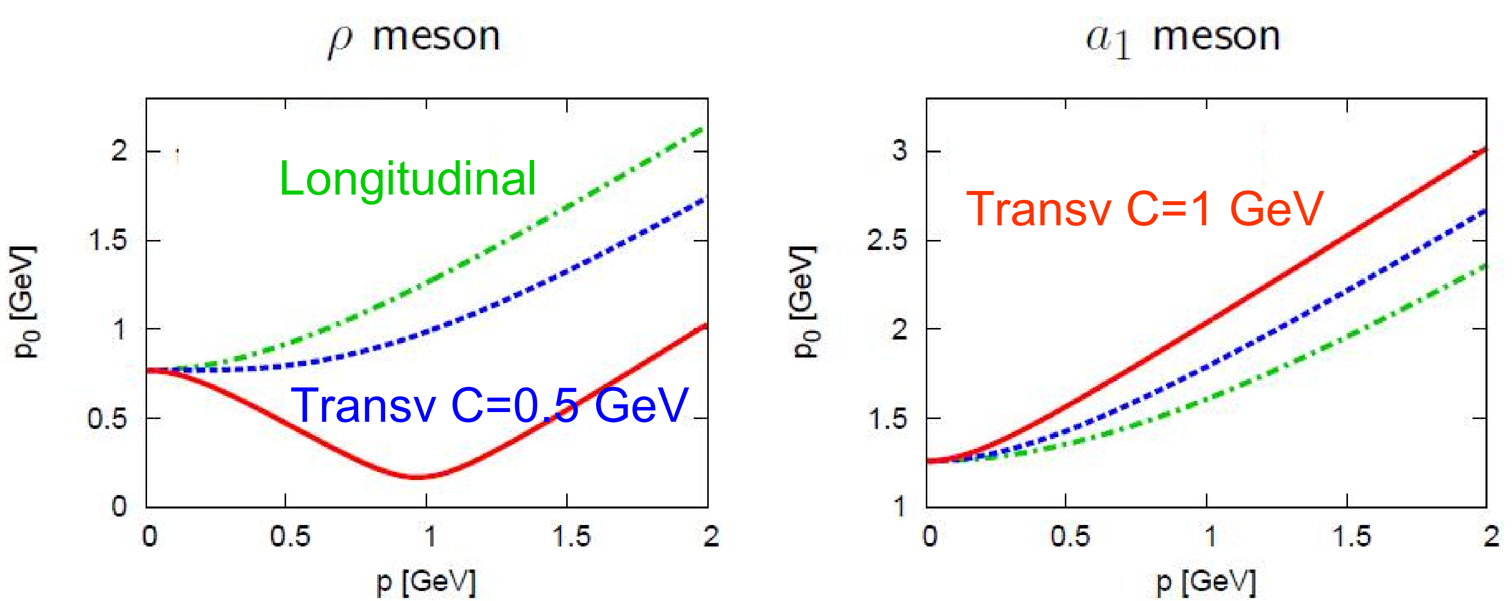
Cold dense matter

[Domokos, Harvey ('07)]

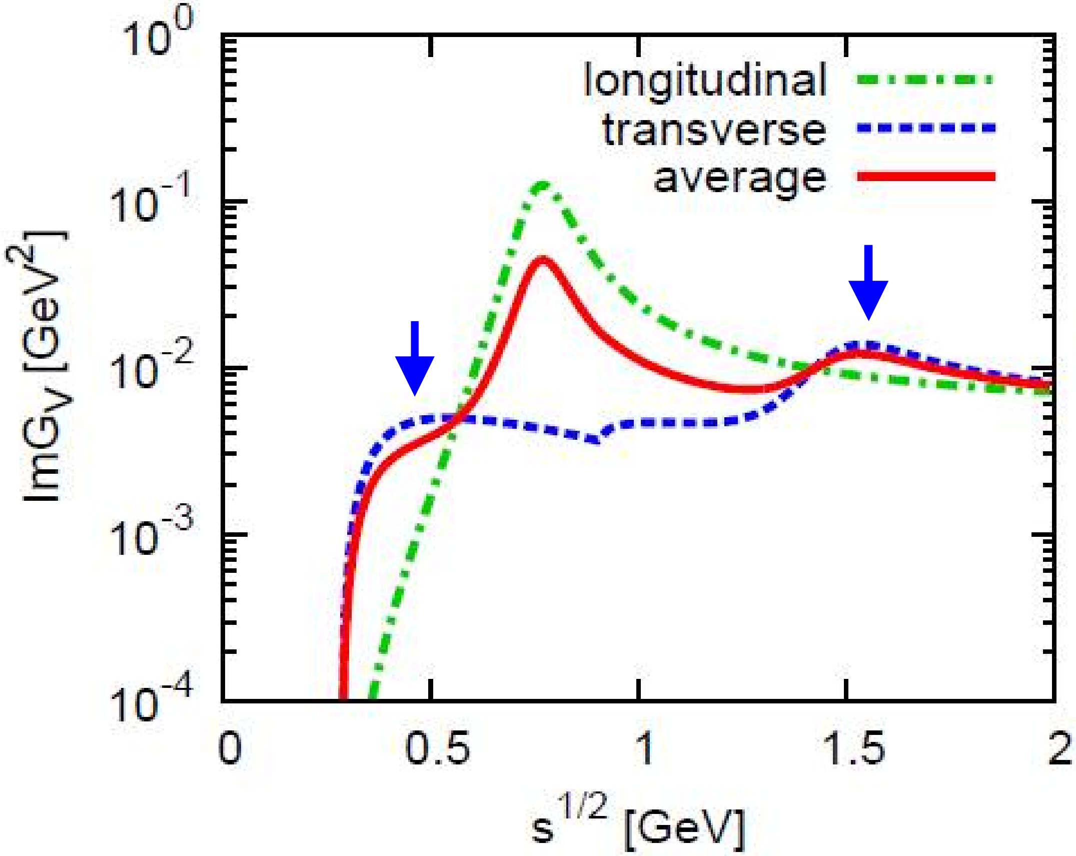
Holographic approach at finite μ_B

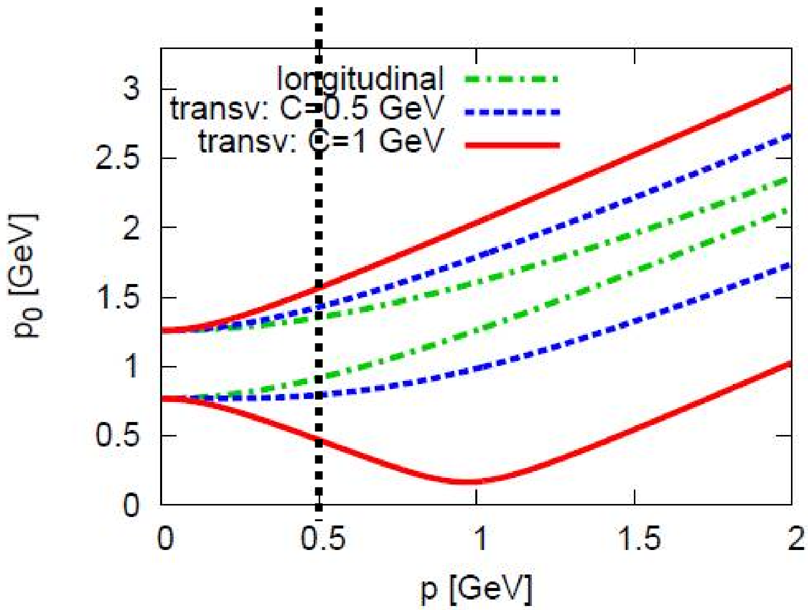
$$S_{4\mathrm{dim}} = \int d^4x \left[\frac{1}{2}(\partial_\mu \pi)^2 - \frac{1}{2}m_\pi^2\pi^2 - \frac{1}{4}(\rho_{\mu\nu})^2 - \frac{1}{4}(a_{\mu\nu})^2 + \frac{1}{2}m_\rho^2\rho_\nu^2 + \frac{1}{2}m_a^2 a_\mu^2 + C\epsilon^{ijk}(\rho_i\partial_j a_k + a_i \partial_j \rho_k)\right]$$

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



Spectral function: Not BW





- C = 1 GeV, 3-momentum p = 0.5 GeV
- 1 bump of transv. rho, 1 bump of transv. a1

[Harada, CS ('09)]

Chiral mixing induced from WZW

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

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

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

- Mixing strength: C = 0.1 GeV at ρ_0
  - AdS/QCD → C = 1 GeV at ρ_0 → vector cond.!?
  - Why so large? --- higher-lying states in large Nc

  cf. VMD in SS

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

Weak mixing ... No impact?

A missing piece: χ sym. restoration

<AA> → <VV>

CS, 2019

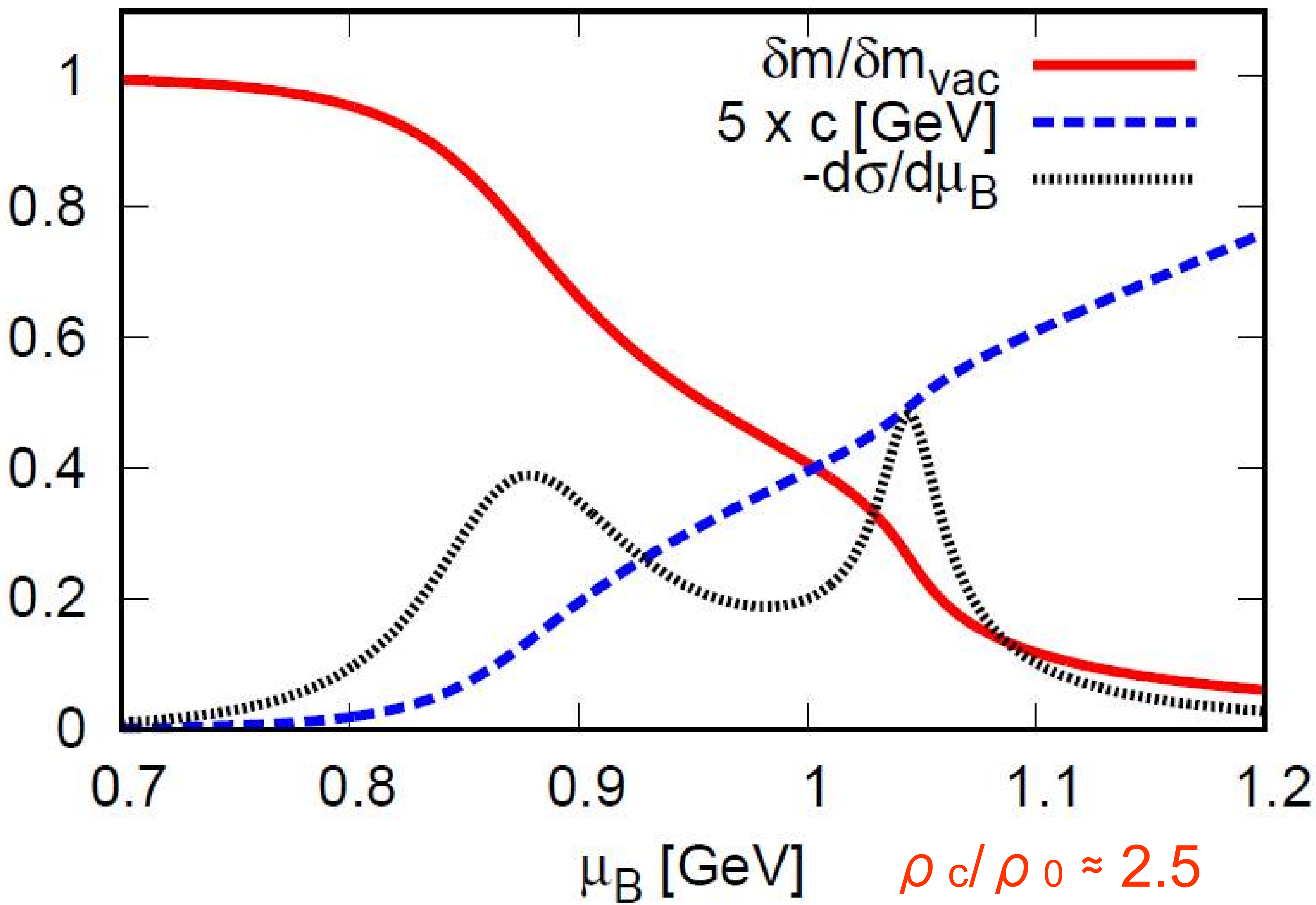
Chiral restoration vs. mixing

- Dispersion relations for small 3-momenta

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

- The mixing effect will be enhanced as δ m decreases!
  - In-medium δ m
  - In-medium mixing C ← Quark-nucleon hybrid model [NS: Marczenko et al. (19,20)]

Mass difference vs. mixing : T=50 MeV



$\rho_c / \rho_0 \approx 2.5$

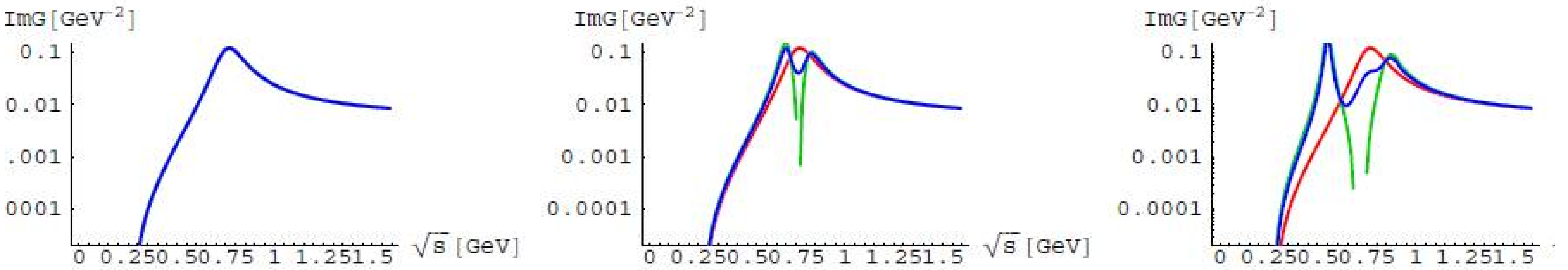
Vector-current correlator

$$G_V^L = \left(\frac{g_\rho}{m_\rho}\right)^2 \frac{-s}{D_V}, \quad G_V^T = \left(\frac{g_\rho}{m_\rho}\right)^2 \frac{-sD_A + 4C^2\bar{p}^2}{D_V D_A - 4C^2\bar{p}^2},$$

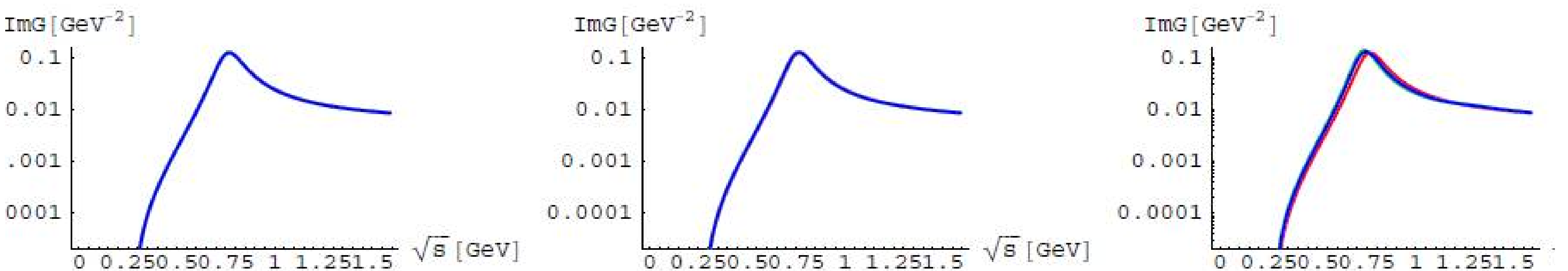
$$D_{V,A} = s - m_{\rho,a_1}^2 + i m_{\rho,a_1} \Gamma_{\rho,a_1}(s),$$

- m and Γ : ***in-medium*** masses and widths
- Strategy of an illustrative computation:
  - Modify only mass and width of axial-vector states.
  - Set G_A equal to G_V at CSR, according to
  - Γ_a1 = Γ(a1→ρ π) + δ Γ(f_pi) → Γ_ρ

Spectral function at T = 50 MeV



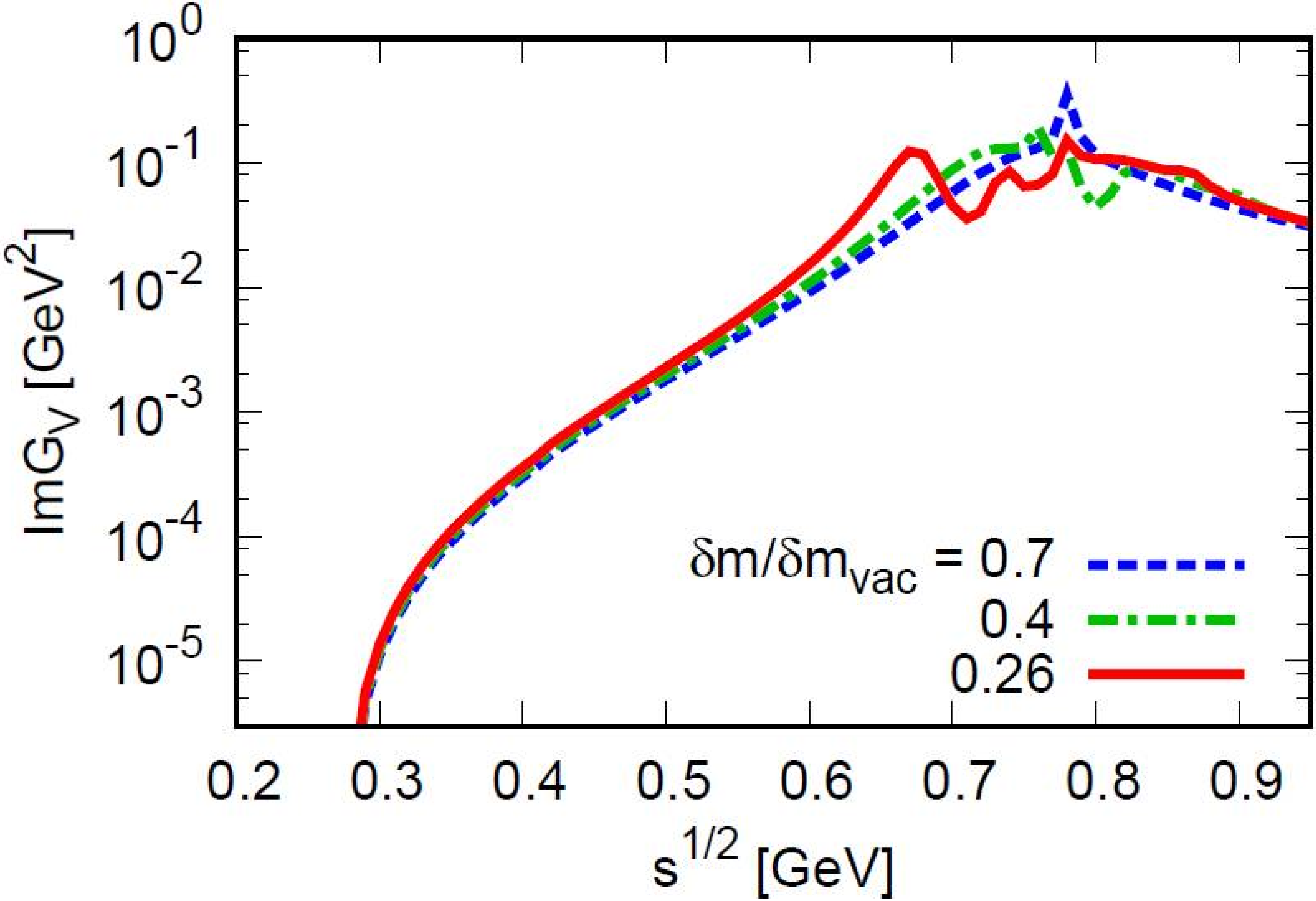
Low μ → Near μc



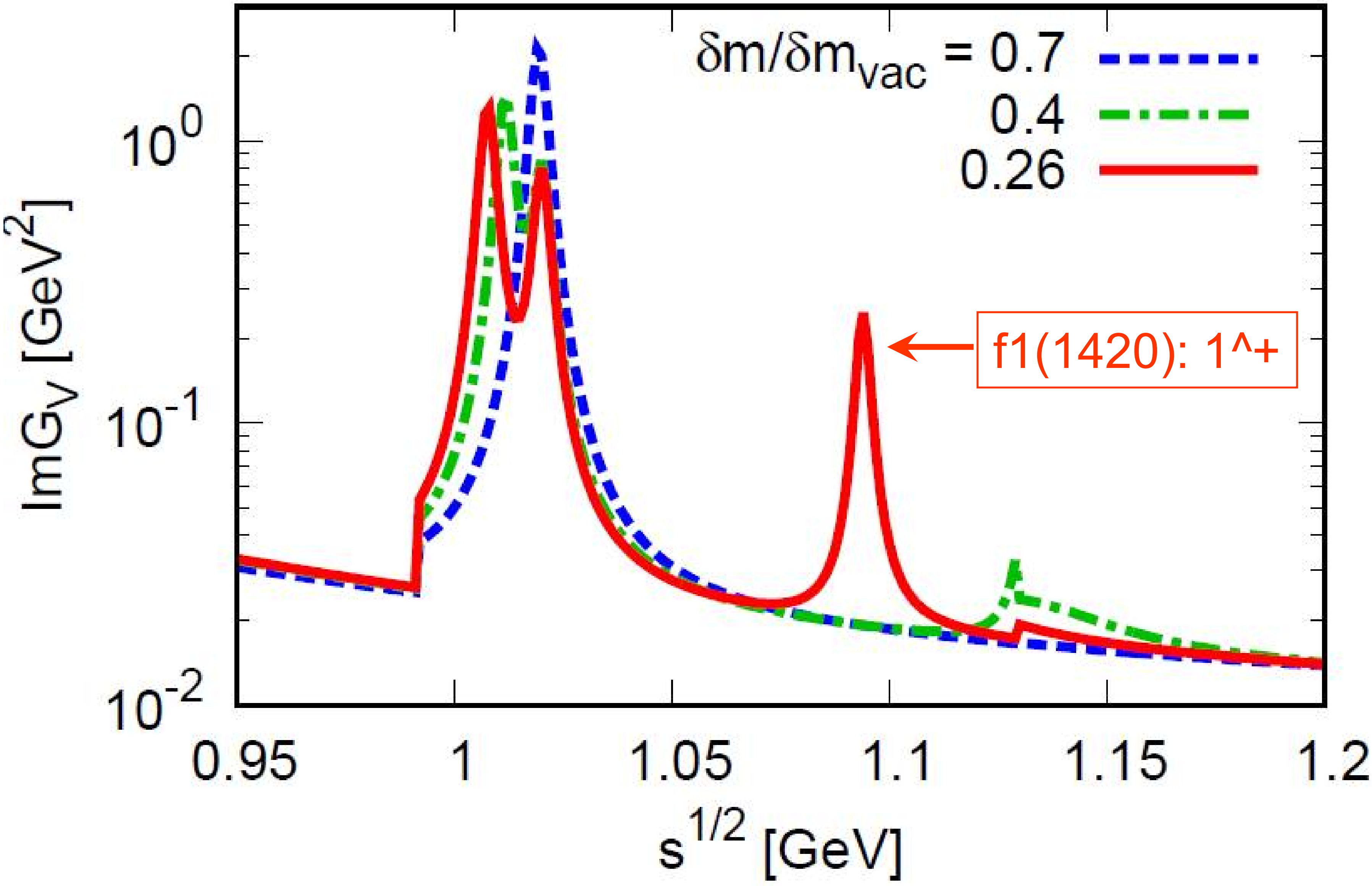
(top) chiral restoration (bottom) no restoration

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

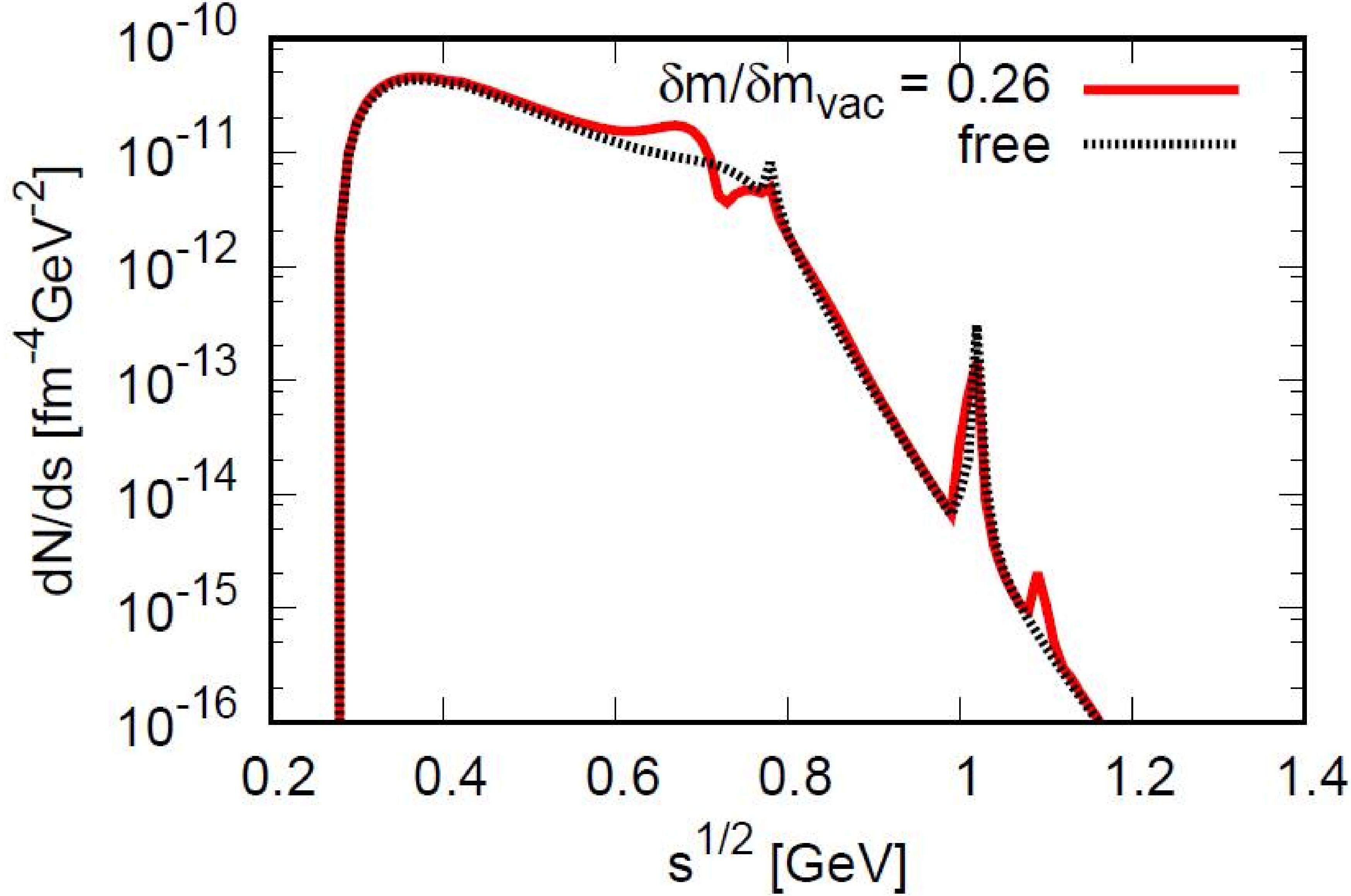
Rho/omega spectrum at T = 50 MeV



Phi spectra at T = 50 MeV



Dilepton rates at T =50 MeV

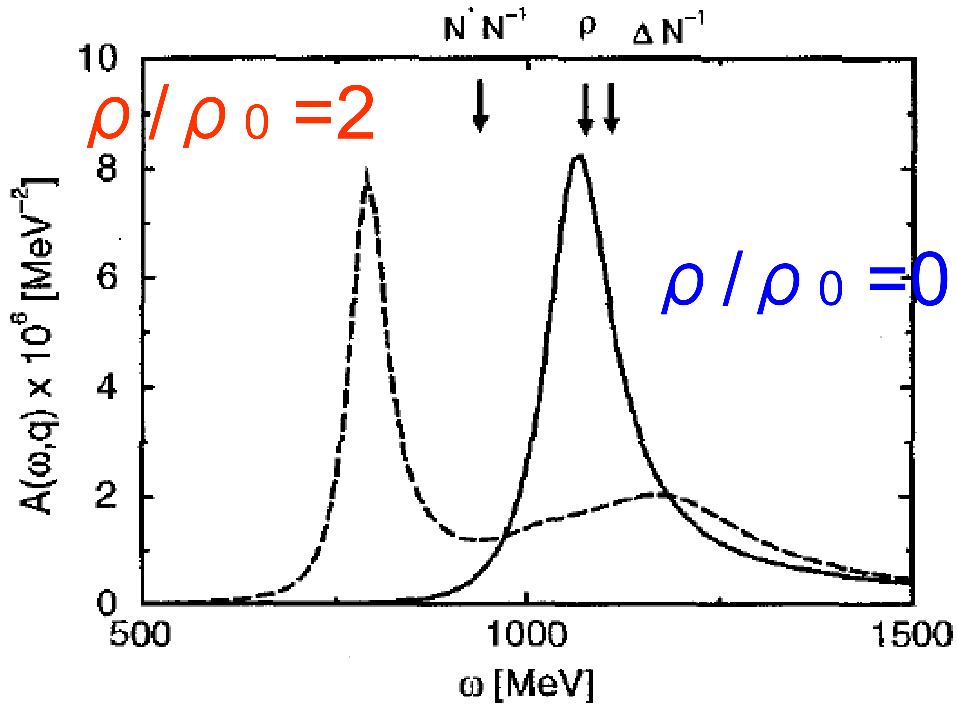


Baryon resonances in ρ N channel

N(1720) and Δ(1905)

→ level mixing

[Friman, Pirner (97)]



B	$l_{\rho N}$	$SI(\rho B N^{-1})$	$\Gamma^0_{\rho N}$ [MeV]	$(\frac{f^2_{\rho BN}}{4\pi})_{est}$	$(\frac{f^2_{\rho BN}}{4\pi})_{fit}$	[MeV]
N(939)	p	4	–	4.68	5.8	0
Δ(1232)	p	16/9	–	18.72	23.2	15
N(1520)	s	8/3	24	6.95	5.5	250
Δ(1620)	s	8/3	22.5	1.01	0.7	50
Δ(1700)	s	16/9	45	1.2	1.2	50
N(1720)	p	8/3	105	8.99	9.2	50
Δ(1905)	p	4/5	210	17.6	18.5	50

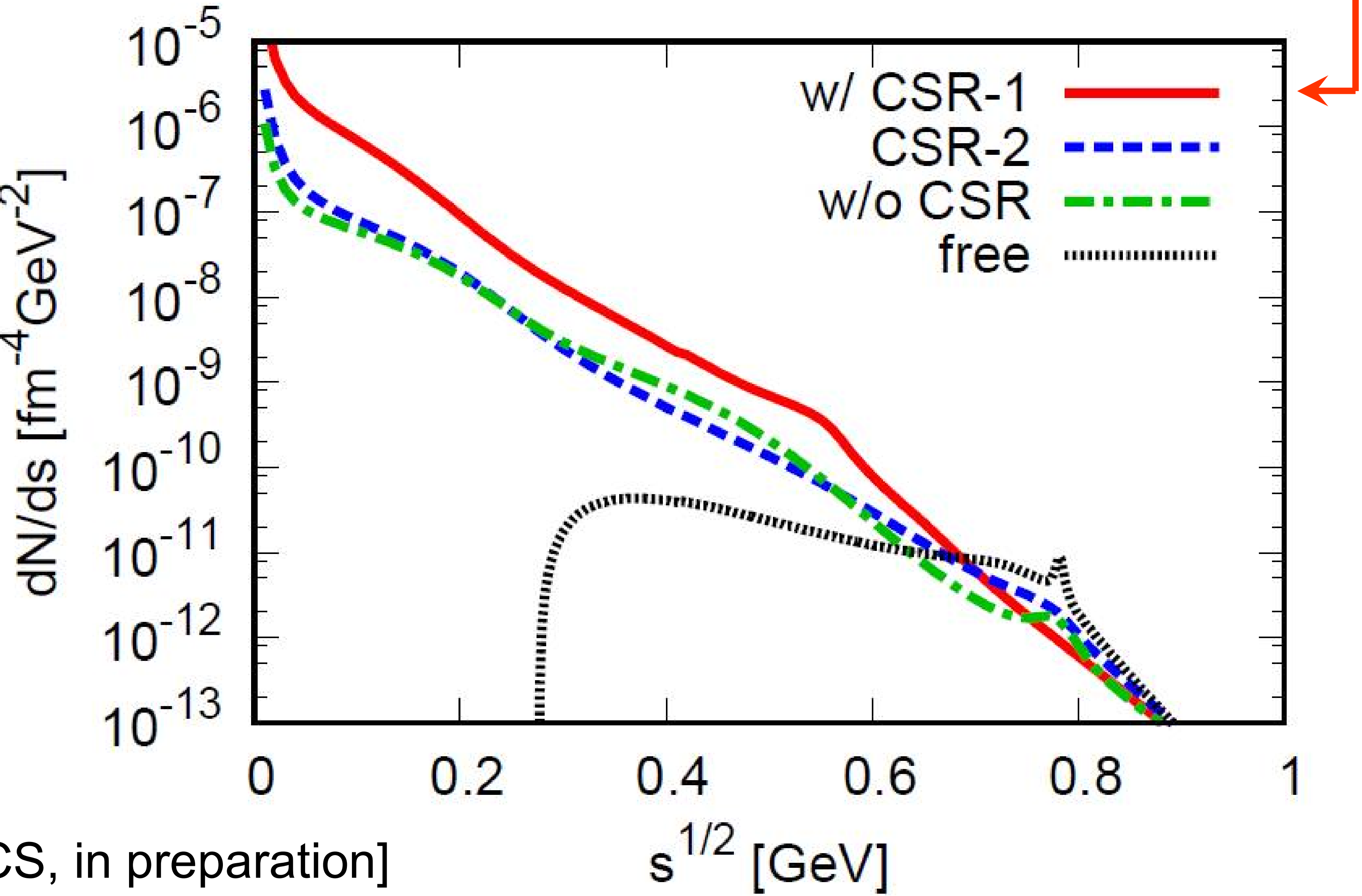
← γ A reaction data

$$\Gamma_B(s;\rho) = \Gamma_B^0(s) + \Gamma_B^{med} \frac{\rho}{\rho_0}$$

[Rapp, et al. (98)]

[Kim, Lee ('21): QCDSRs, mrho = 500-600 MeV]

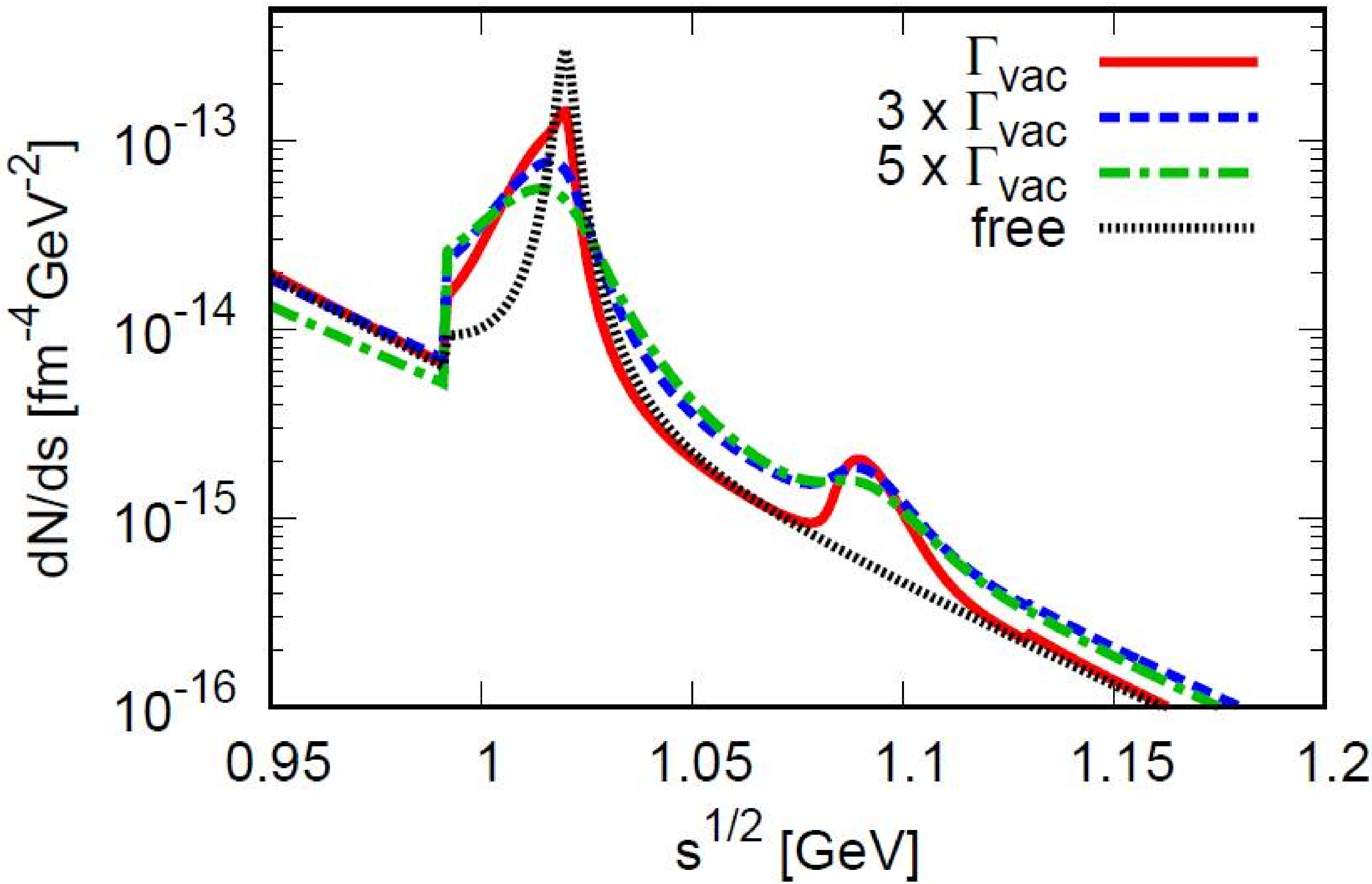
Signals diminished by p-wave states



[CS, in preparation]

[cf. SU(3) coupled-channel: Oset & Ramos (00)]

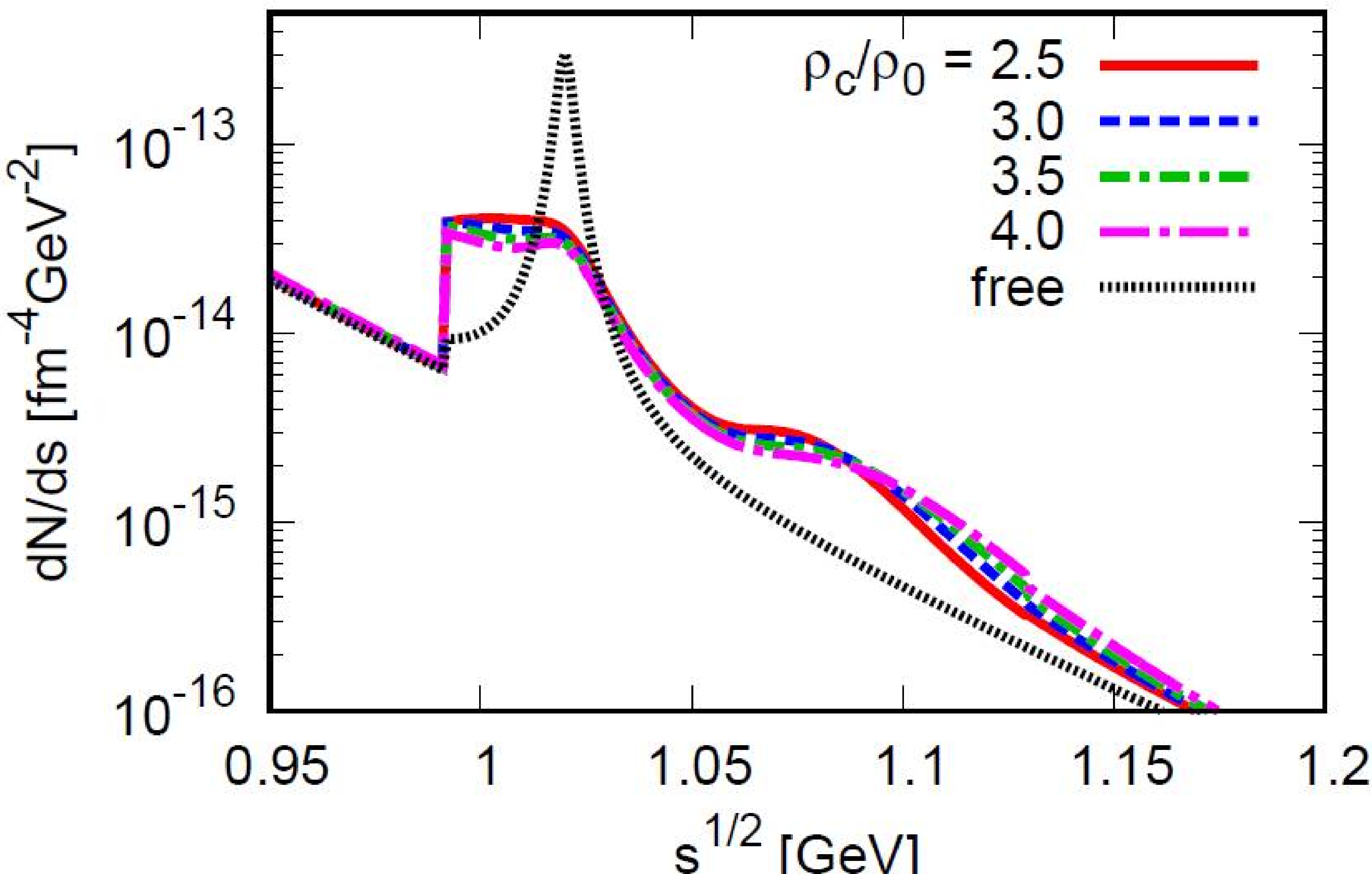
ϕ remains well-defined resonance!



[CS, in preparation]

c = 0.1 - 0.15 GeV for ρ_c/ρ_0 = 2.5 - 4.0

ϕ remains well-defined resonance!



Summary

- Chiral mixing in a medium
  - Induced by pions → vanishes at CSR
  - Induced by density → exists at any density
- Chiral sym. restoration in cold dense matter
  - Clear structural change in the dilepton rates
  - Big discovery potential at FAIR/NICA/RHIC-BES
  - More reliable estimate of mixing strength: lattice Q_2CD, FRG/DS
  - Many-body effects near CSR in more refined approaches → widths, life time of phi

Backup

Low-energy theorem at T $\neq$ 0

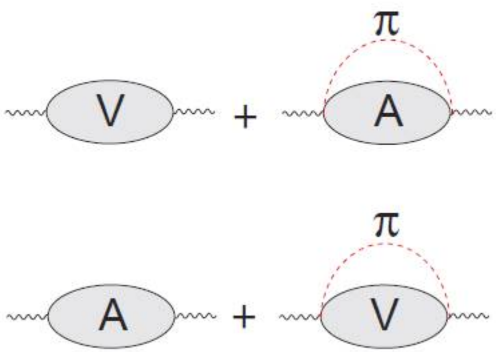
$$G_V^{\mu\nu}(T) = (1-\epsilon)G_V^{\mu\nu}(0) + \epsilon\, G_A^{\mu\nu}(0)$$

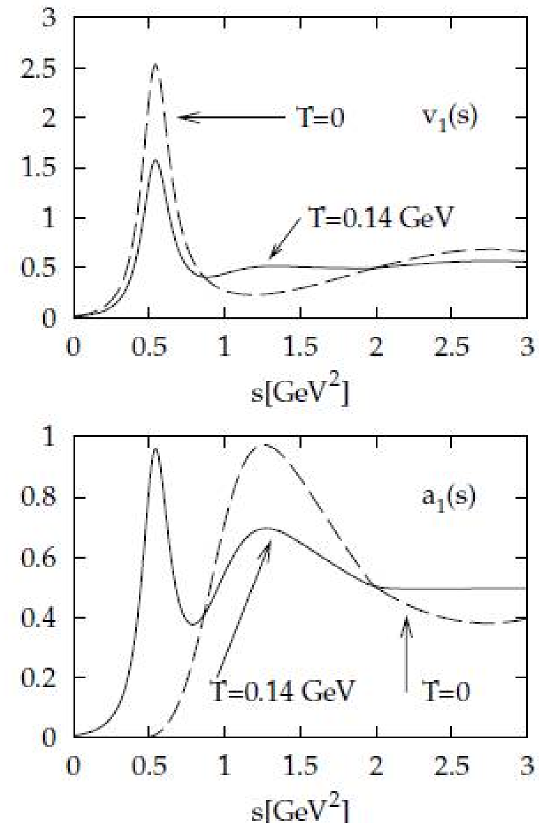
$$G_A^{\mu\nu}(T) = (1-\epsilon)G_A^{\mu\nu}(0) + \epsilon\, G_V^{\mu\nu}(0)$$

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

[Dey, Eletsky and Ioffe (90)]

[finite ρ : Krippa (98)]





- **$\varepsilon \rightarrow 1/2$: chiral restoration? NO!**
- **Higher T: reducing $\pi\ \rho$ a1 int.: 2 → 1 bump**

Chiral mixing ≈ 0.06 mpi at Tc [Harada, CS, Weise (08)]

[Harada, CS ('09)]

Vector-current correlator

$$G_V^{\mu\nu}(p_0,\vec{p}) = P_L^{\mu\nu} G_V^L(p_0,\vec{p}) + P_T^{\mu\nu} G_V^T(p_0,\vec{p}),$$

$$G_V^L = \left(\frac{g_\rho}{m_\rho}\right)^2 \frac{-s}{D_V}, \quad G_V^T = \left(\frac{g_\rho}{m_\rho}\right)^2 \frac{-sD_A + 4C^2\vec{p}^2}{D_V D_A - 4C^2\vec{p}^2},$$

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

$$G_V = \frac{1}{3}\left[G_V^L + 2G_V^T\right]$$

[Sakai and Sugimoto (2005)]

VDM from holography

- Infinite tower of vector mesons

$$F(q^2) = \sum_{n=0}^{\infty} \frac{g_{\rho_n} \cdot g_{\rho_n \pi\pi}}{m_{\rho_n}^2 - q^2} \stackrel{q^2 \to 0}{\longrightarrow} 1$$

- Approximately saturated by the lowest 4

n	0	1	2
PDG	776	1465	1720
SS	776	1607	2435

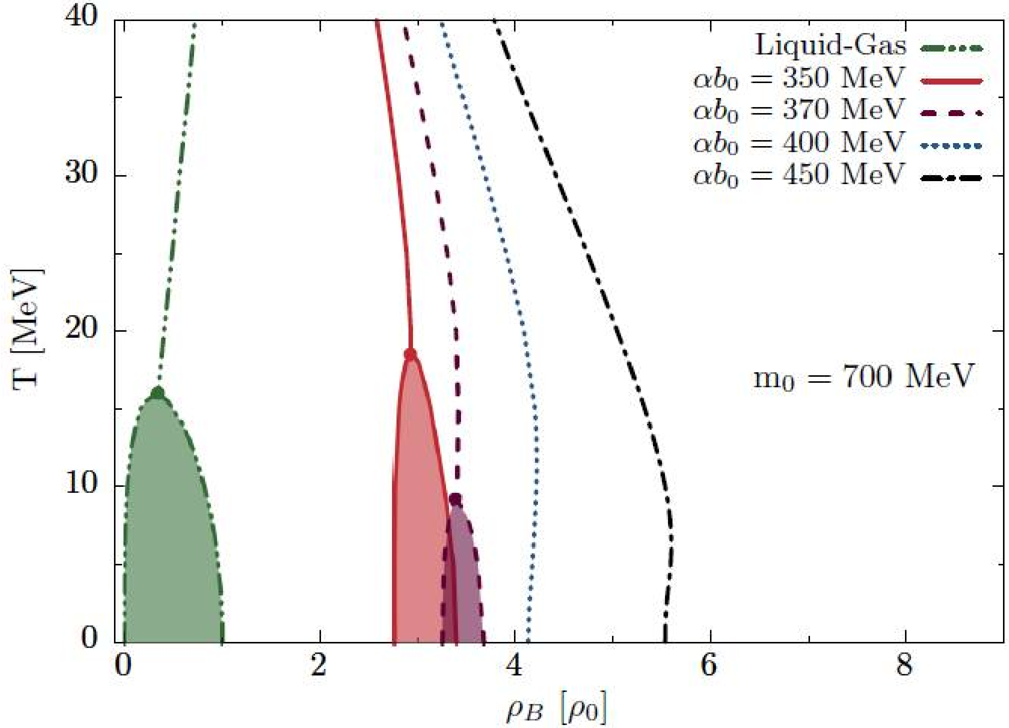
$$F(0) = 1.31 - 0.35 + 0.05 - 0.01 = 1.00$$

Set-up: rho/omega

- Mass difference = order parameter
  - Chiral restoration → < σ >
  - Density effect → < ω_0 >

  } Chiral MF models

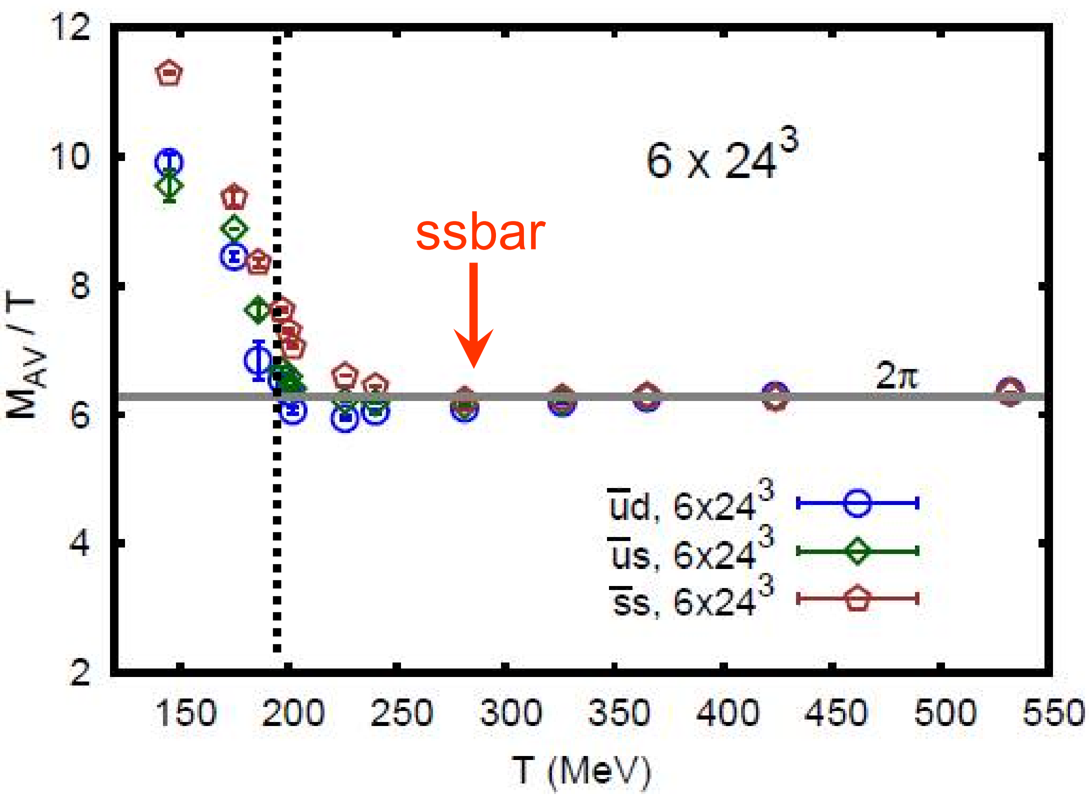
- Nucleon parity-doublet model [Zschiesche et al.]



✓Nuclear ground state
✓Extended with deconf to quark matter, constrained by NS [Marczenko et al. (2019)]
→ Masses & mixing

Set-up: phi

- ❑ Masses of Φ meson and f_1(1420)?
  - Screening mass in LQCD: modification sets in at Tc



[Cheng et al., ('11)]

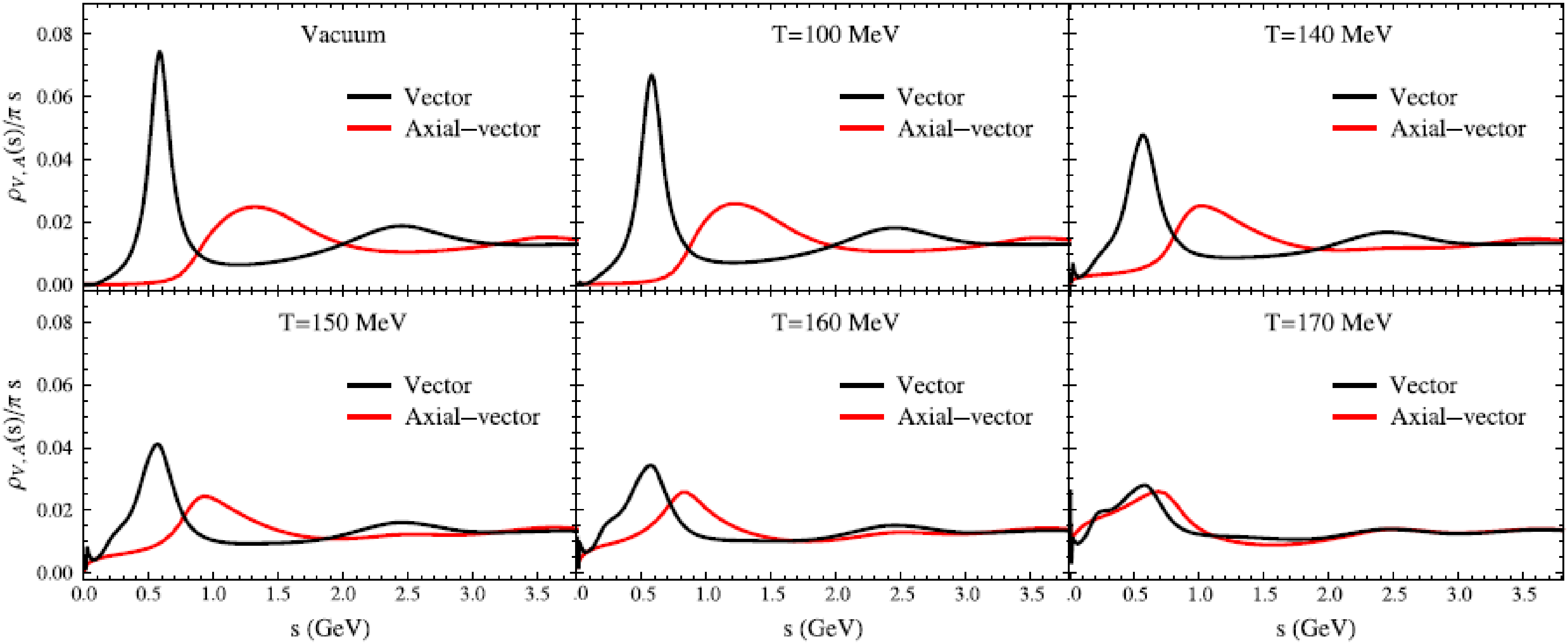
δ m(q) ≈ 0.26 at μ c

Assumptions:

- ➢ δ m(s) ≈ 0.26 at 1.2 μ c
- ➢ Constant mass of vector states

[Hohler, Rapp ('14,'16)]

From low T to high T



- ❑Weinberg SRs [Weinberg ('67); Kapusta, Shuryak ('94)]
- ❑Vector SF & ansatz for a1 mass and width
  - ✓Reduction of a1 mass, width broadening
  - ✓Role of higher-lying states: ρ', a1', …