Parity Doubling in Cold and Dense QCD

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Outline

I. Introduction to chiral mixing via WZW

II. Parity doubling of V&AV mesons, spectral functions, dilepton production rates

III. In-medium widths of vector mesons

   i. rho-N resonances

   ii. Kaon and anti-kaon in dense matter

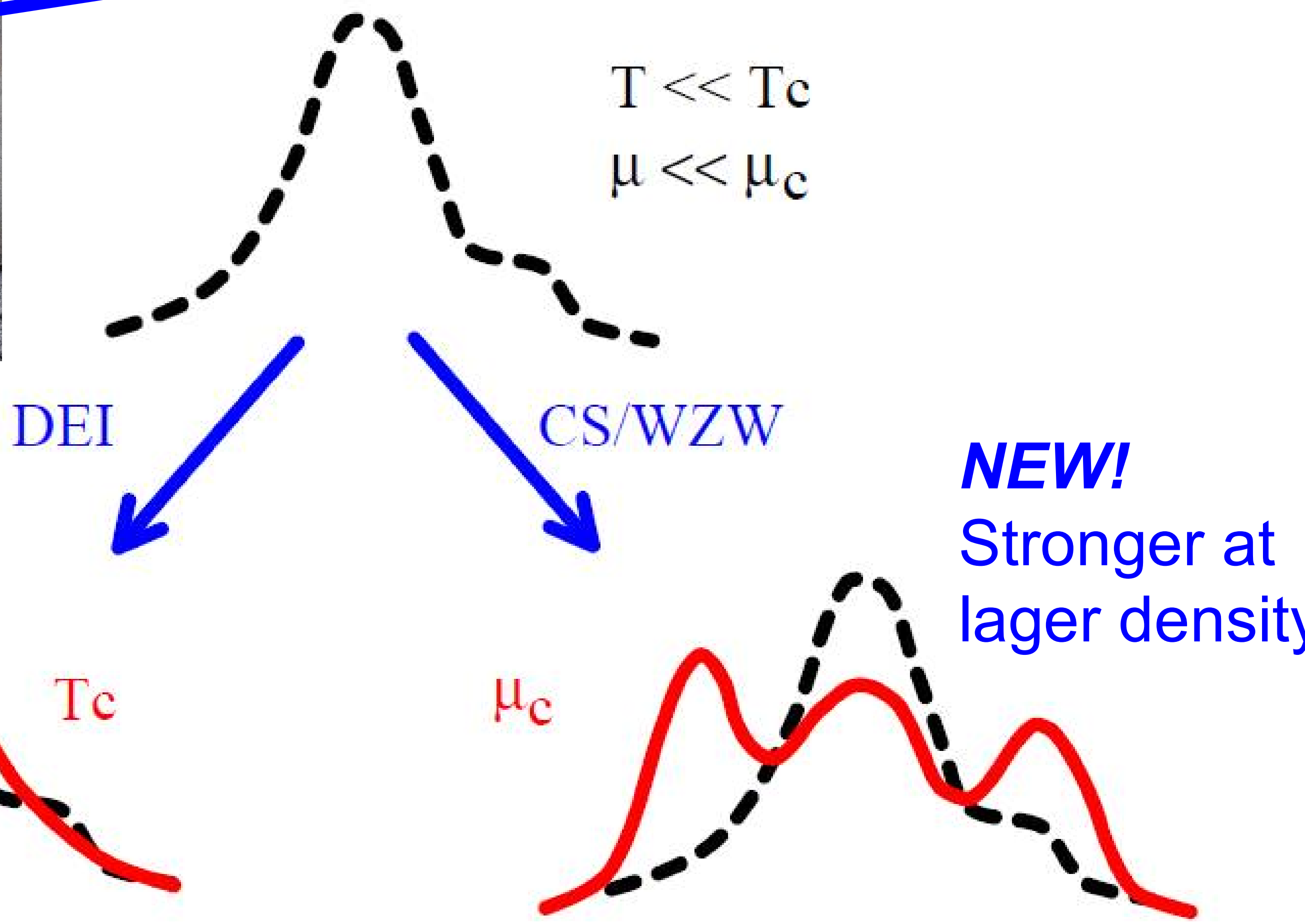
Why chiral mixing?

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/SIS/NICA/J-PARC/RHIC-BES!



Hot dilute matter **Cold dense matter**

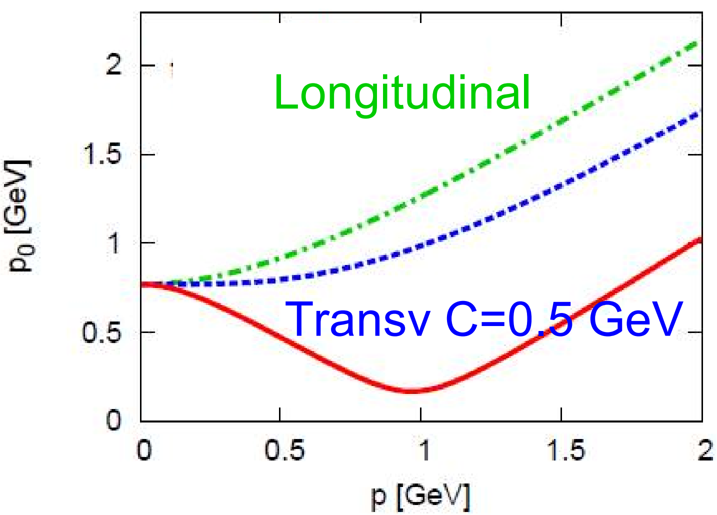
[Domokos, Harvey ('07)]

Holographic approach at finite μ_B

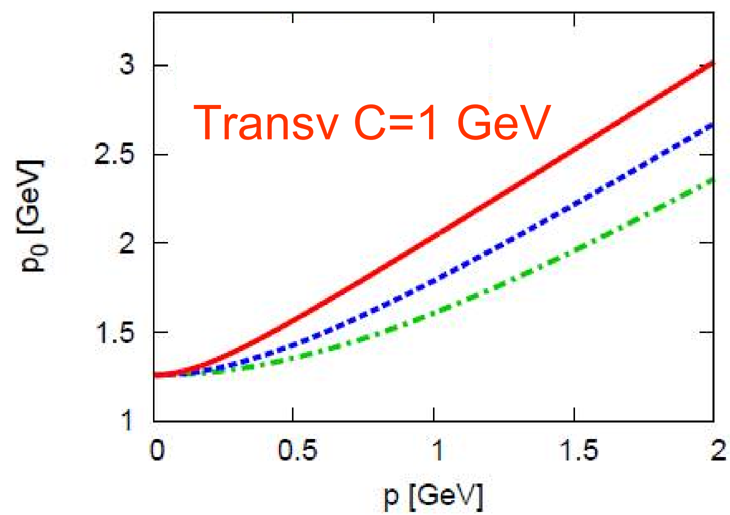
$$S_{4\text{dim}} = \int d^4x \left[\frac{1}{2}(\partial_\mu \pi)^2 - \frac{1}{2}m_\pi^2\pi^2 - \frac{1}{4}(\rho_{\mu\nu})^2 - \frac{1}{4}(a_{\mu\nu})^2 + \frac{1}{2}m_\rho^2\rho_\nu^2 + \frac{1}{2}m_a^2 a_\mu^2 + C\epsilon^{ijk}(\rho_i\partial_j a_k + a_i\partial_j\rho_k)\right]$$

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

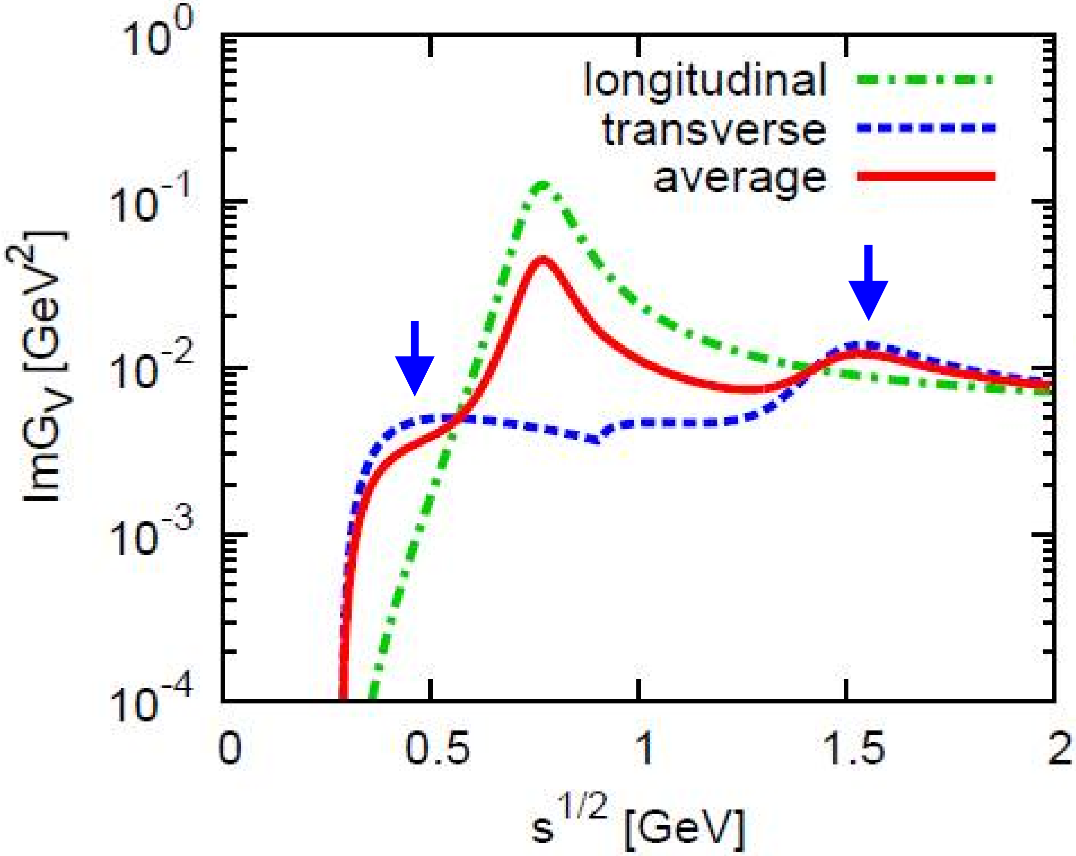
ρ meson

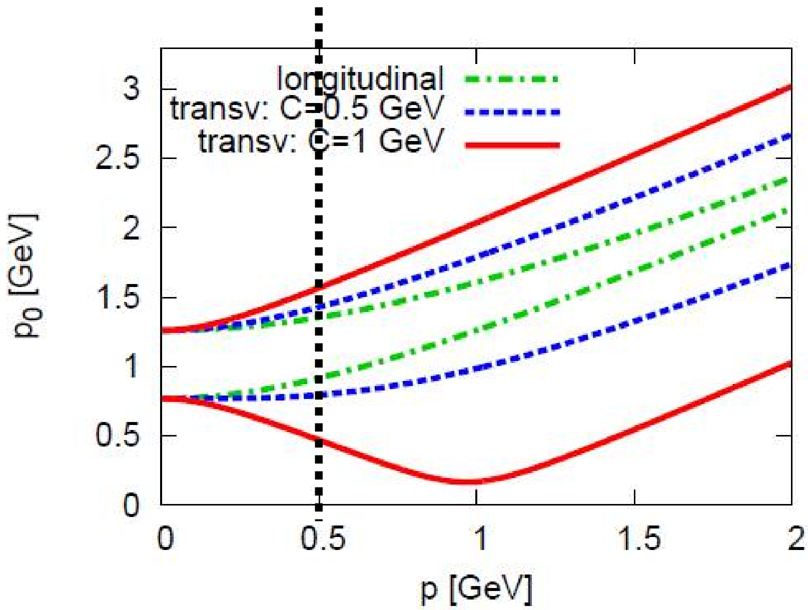


a_1 meson



Spectral function: Not BW





- C = 1 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

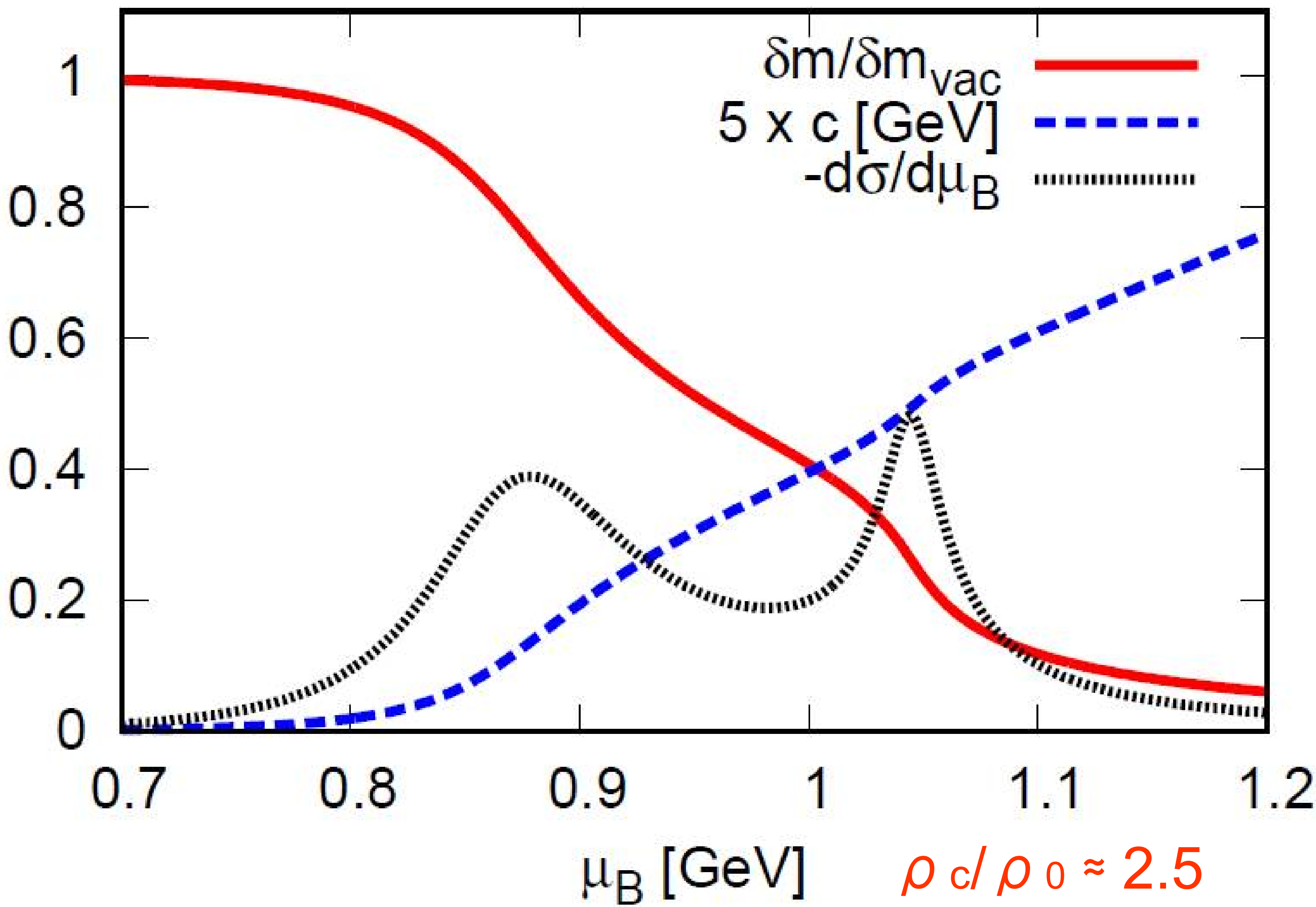
Chiral restoration vs. mixing

- 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 δm decreases!
  - In-medium δm
  - 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

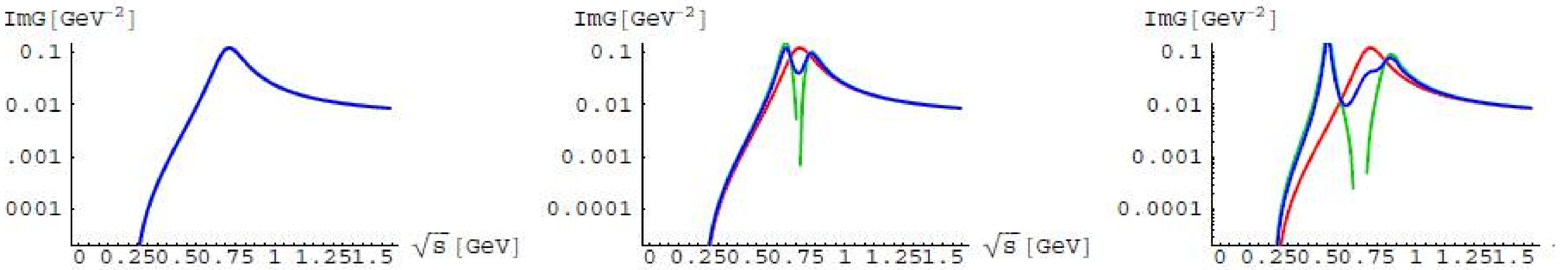
$$G_V^L = \left(\frac{g_\rho}{m_\rho}\right)^2 \frac{-s}{D_V}, \quad G_V^T = \left(\frac{g_\rho}{m_\rho}\right)^2 \frac{-sD_A + 4C^2\bar{p}^2}{D_V D_A - 4C^2\bar{p}^2},$$

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

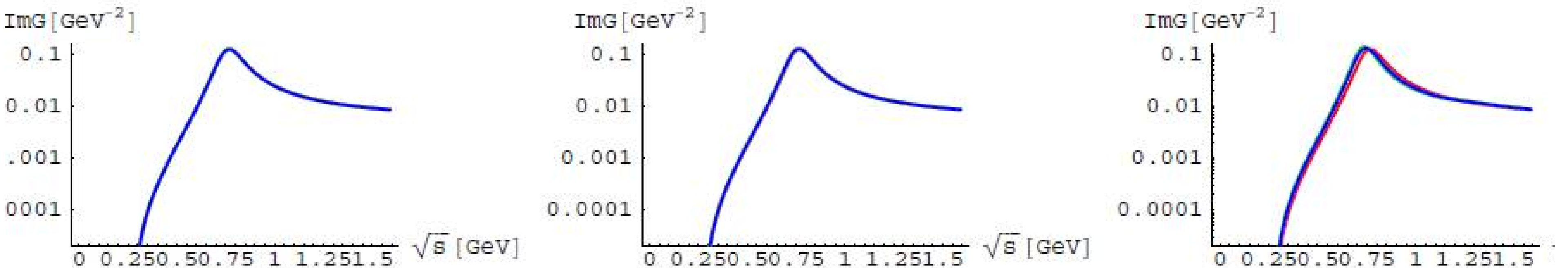
- ❑m and Γ : ***in-medium*** masses and widths
- ❑Strategy of an illustrative computation:
  - Modify only mass and width of axial-vector states.
  - Set G_A equal to G_V at CSR, according to

    Γ_a1 = Γ(a1→ρ π) + δ Γ(f_pi) → Γ_ρ

Spectral function at T = 50 MeV



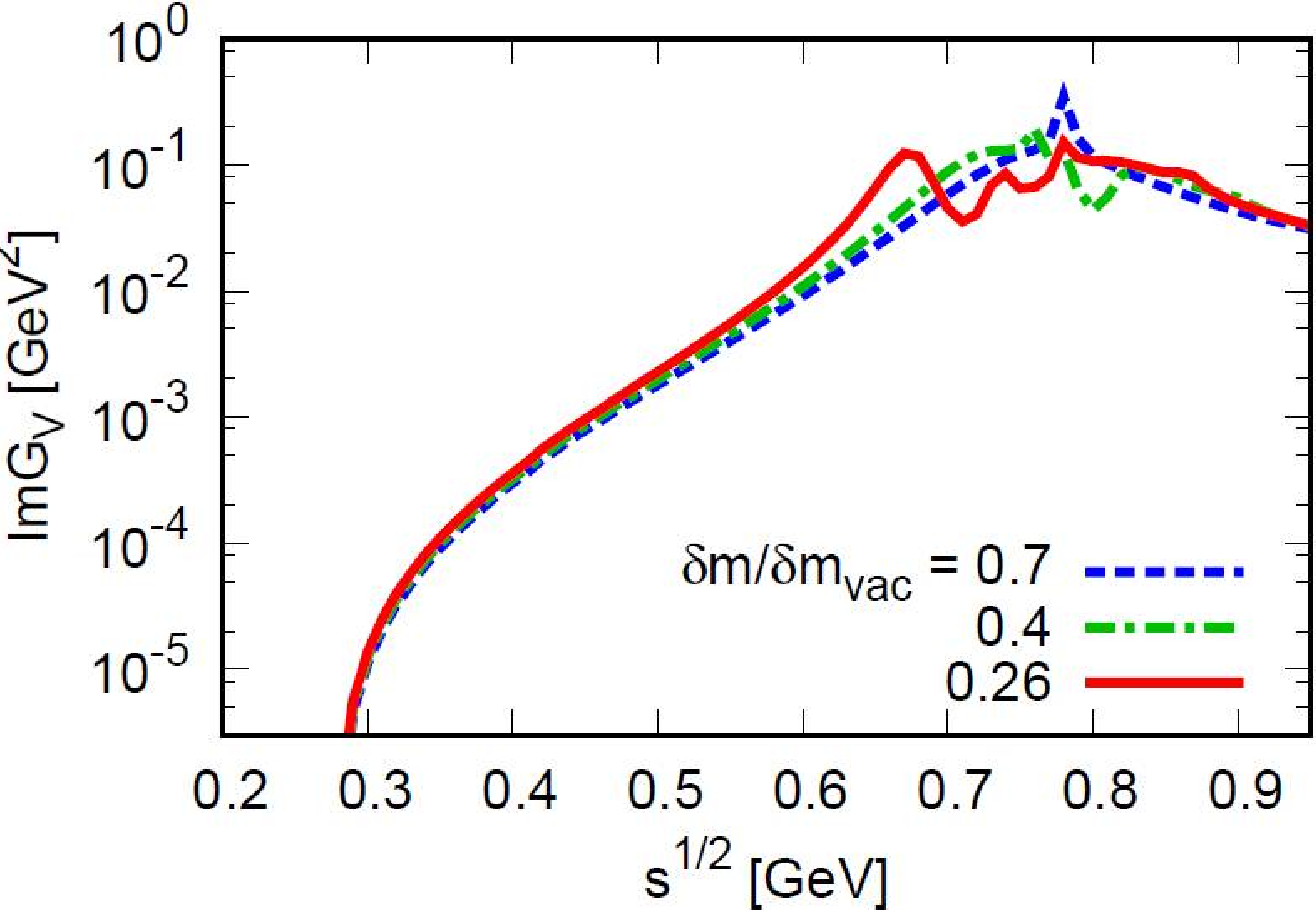
Low μ → Near μ c



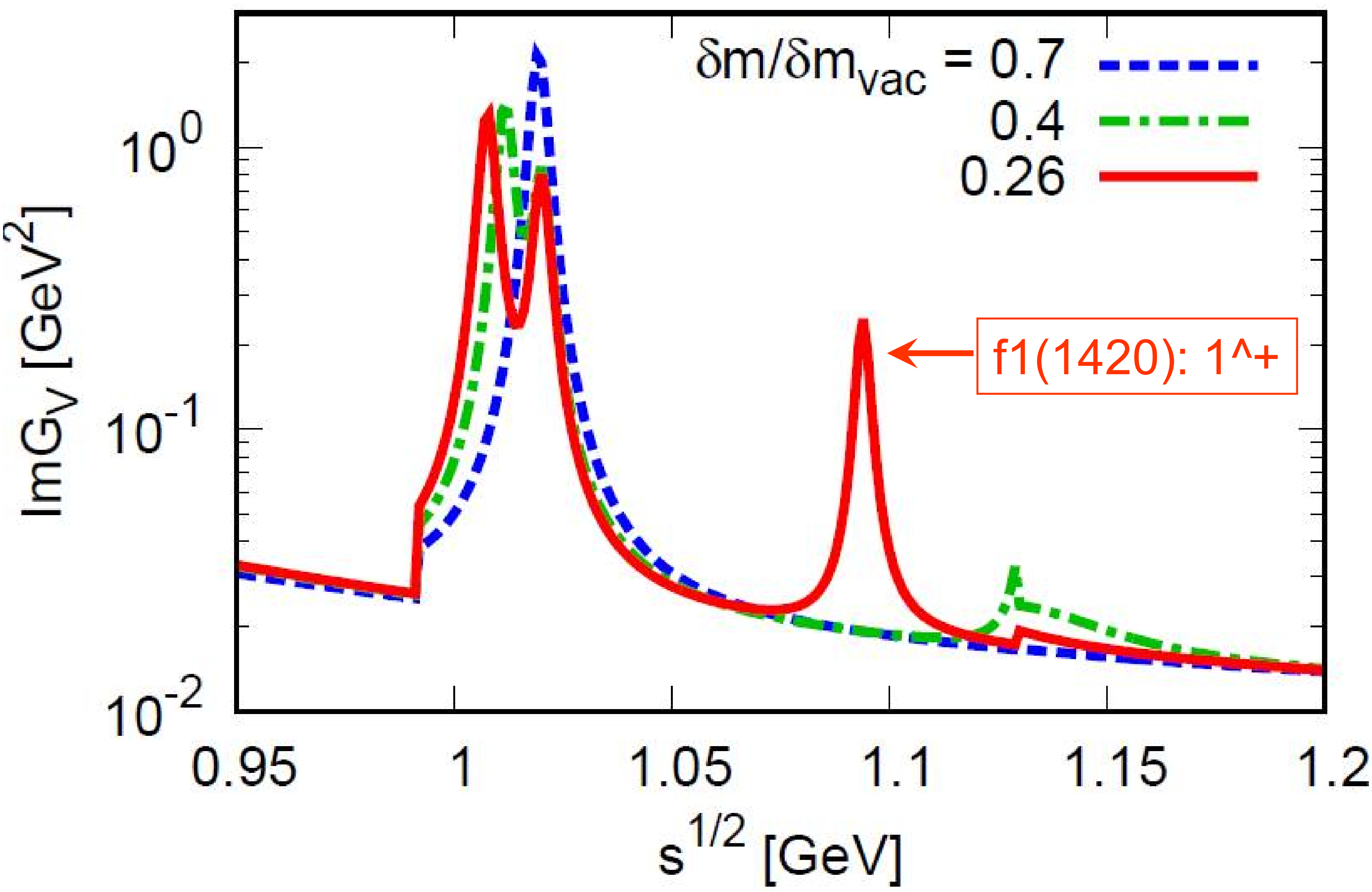
(top) chiral restoration (bottom) no restoration

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

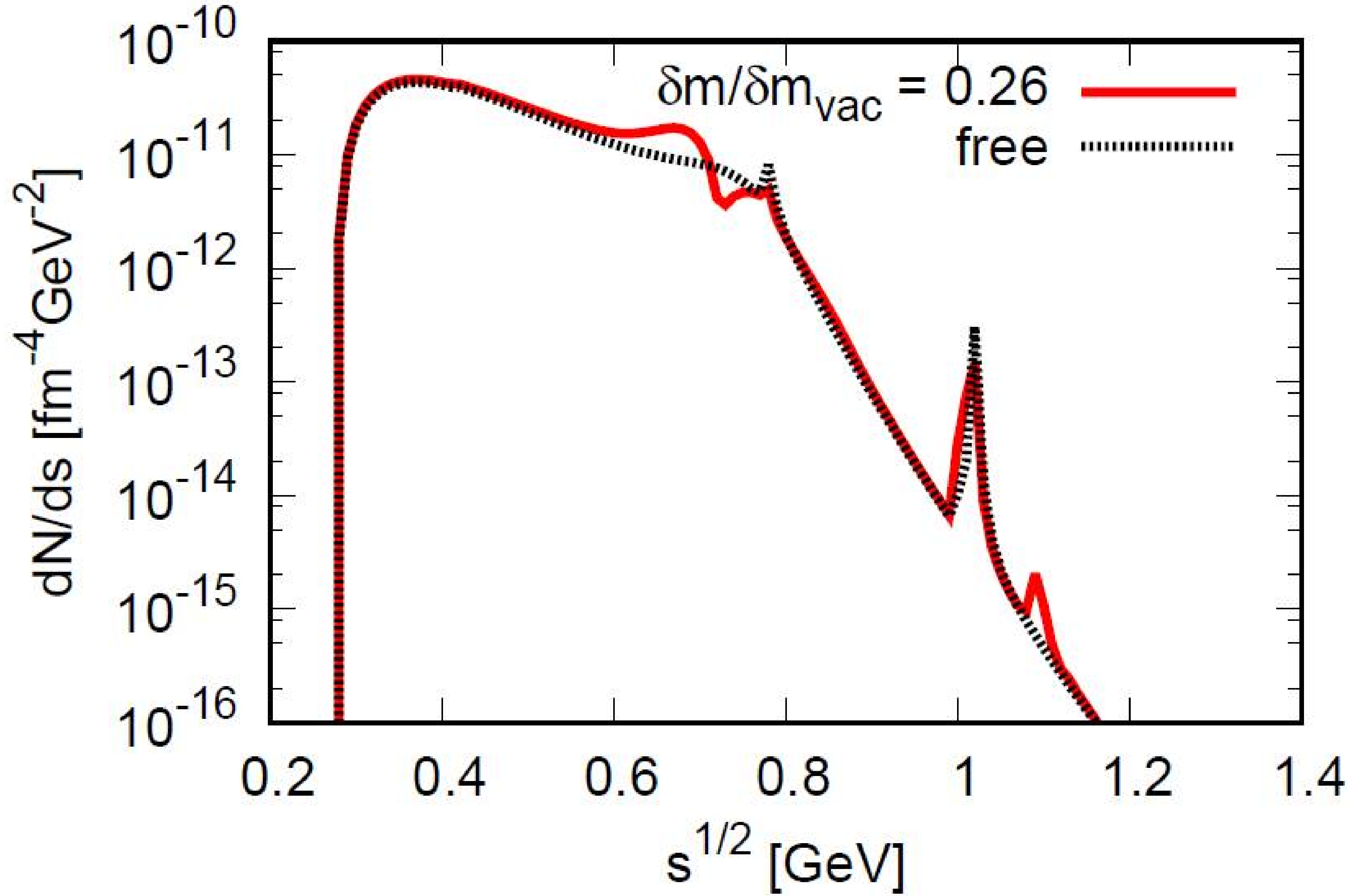
Rho/omega spectrum at T = 50 MeV



Phi spectra at T = 50 MeV



Dilepton rates at T =50 MeV



In-medium broadening

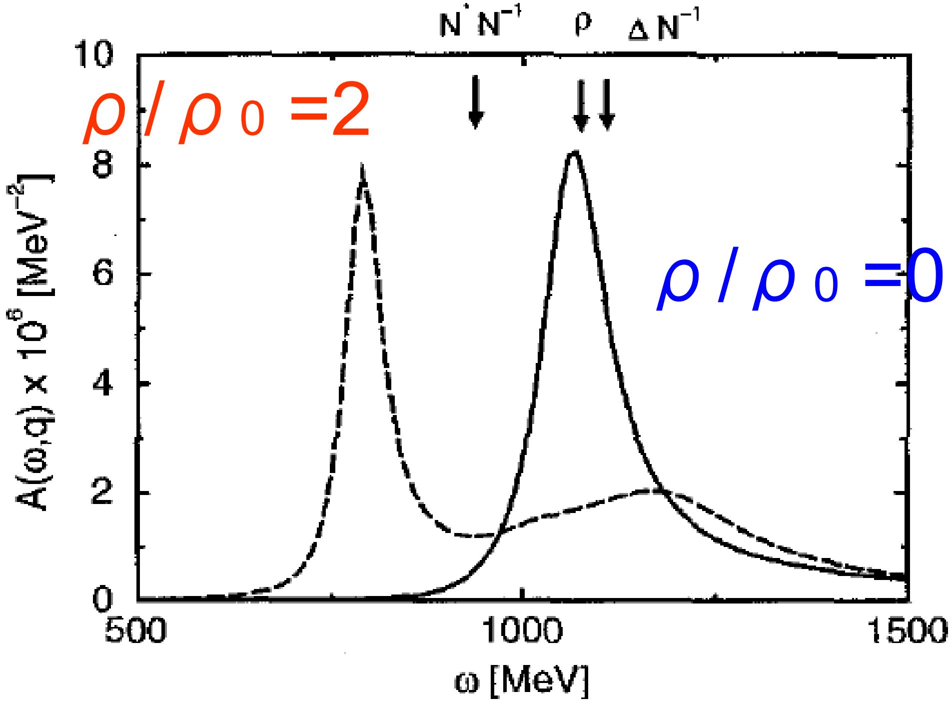
Γ _v,vac → Γ _v,med(ρ)

Baryon resonances in ρ N channel

N(1720) and Δ(1905)

→ level mixing

[Friman, Pirner (97)]



B	$l_{\rho N}$	$SI(\rho BN^{-1})$	$\Gamma^0_{\rho N}$ [MeV]	$(\frac{f^2_{\rho BN}}{4\pi})_{\text{est}}$	$(\frac{f^2_{\rho BN}}{4\pi})_{\text{fit}}$	[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

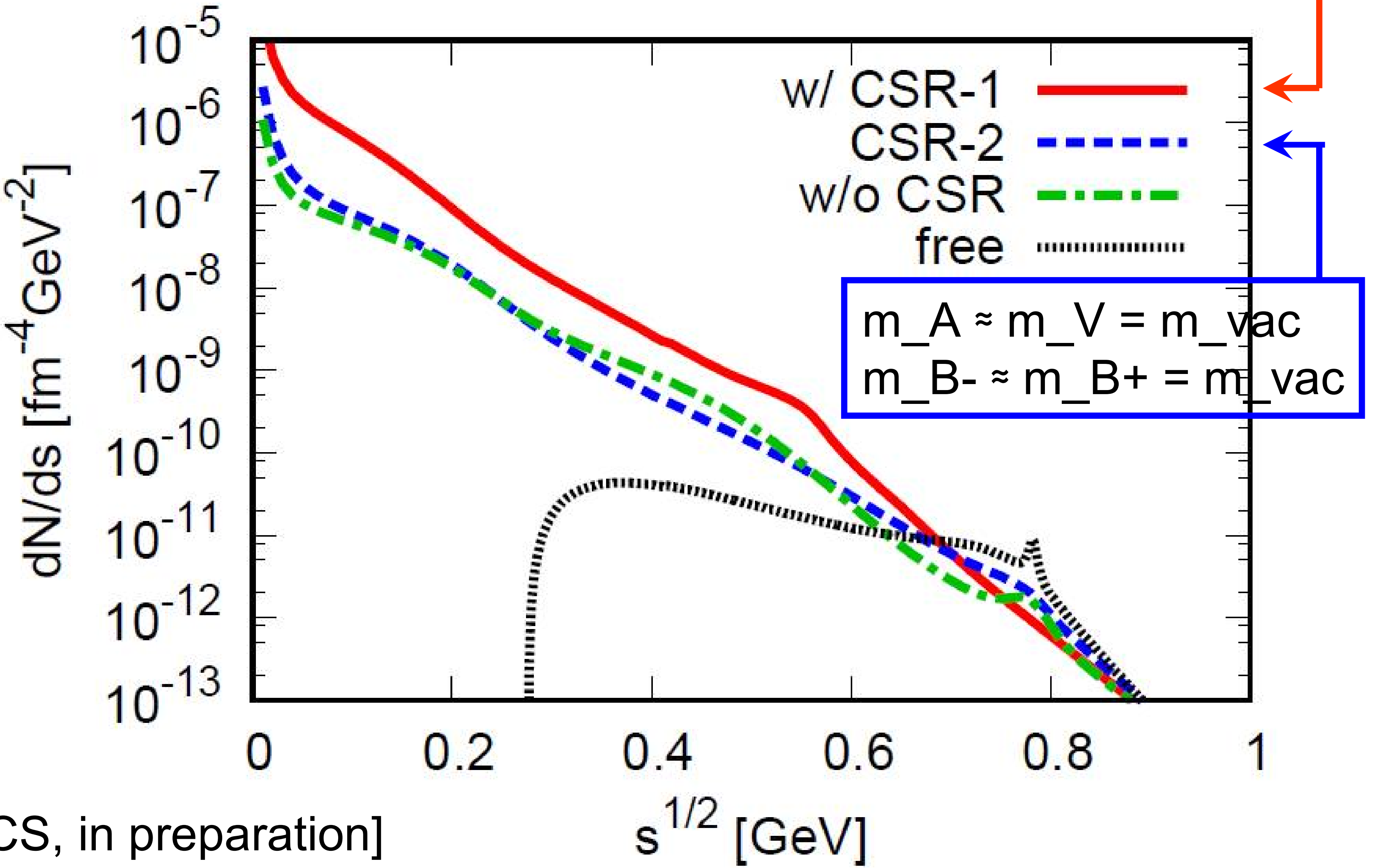
← γ A reaction data

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

[Rapp, et al. (98)]

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

Signals diminished by p-wave states



[CS, in preparation]

ϕ meson in nuclear matter

- No ϕ N resonances, but the kaon cloud.
- Kaon in nuclear matter: Kaplan, Nelson (86)

$$m_K^* = \left[m_K^2 - a_K \rho_S + (b_K \rho)^2\right]^{1/2} + b_K \rho,$$

$$m_{\bar{K}}^* = \left[m_K^2 - a_{\bar{K}} \rho_S + (b_K \rho)^2\right]^{1/2} - b_K \rho,$$

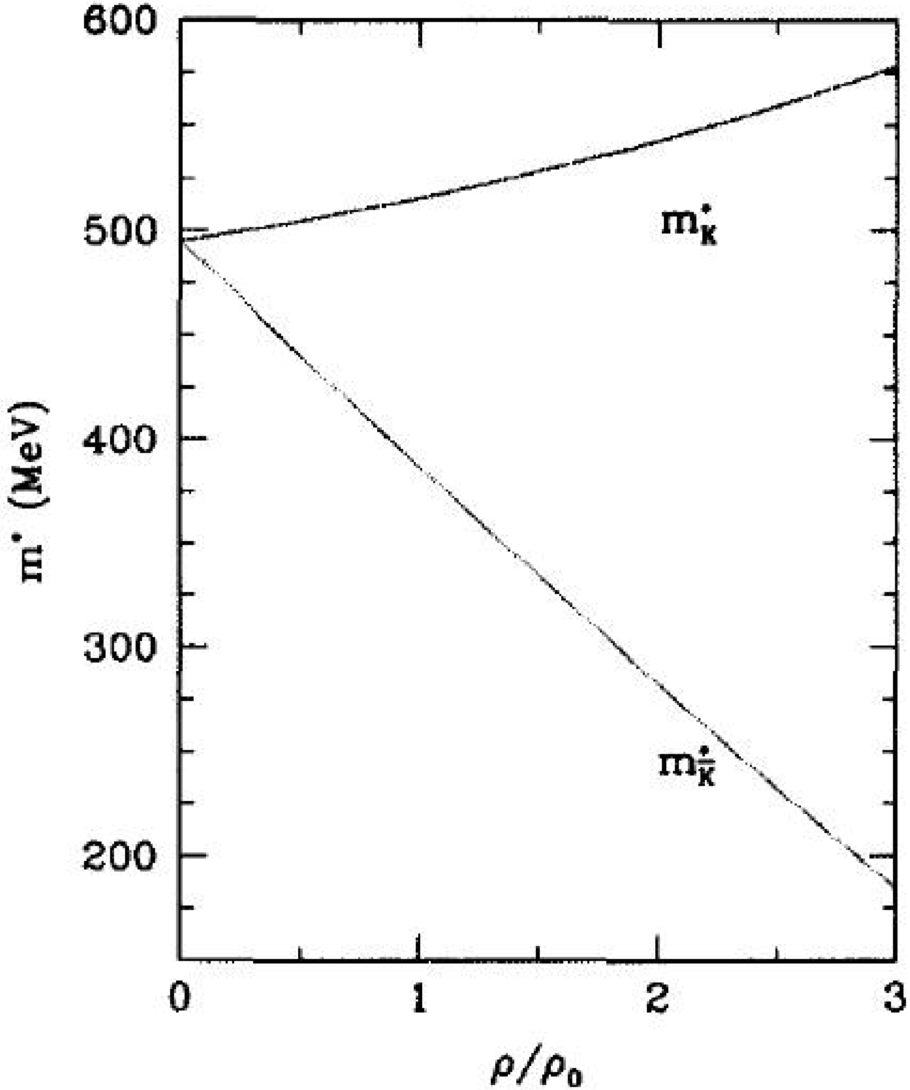
$$b_K = 3/(8 f_\pi^2) \qquad a_K = a_{\bar{K}} = \Sigma_{KN}/f_\pi^2$$

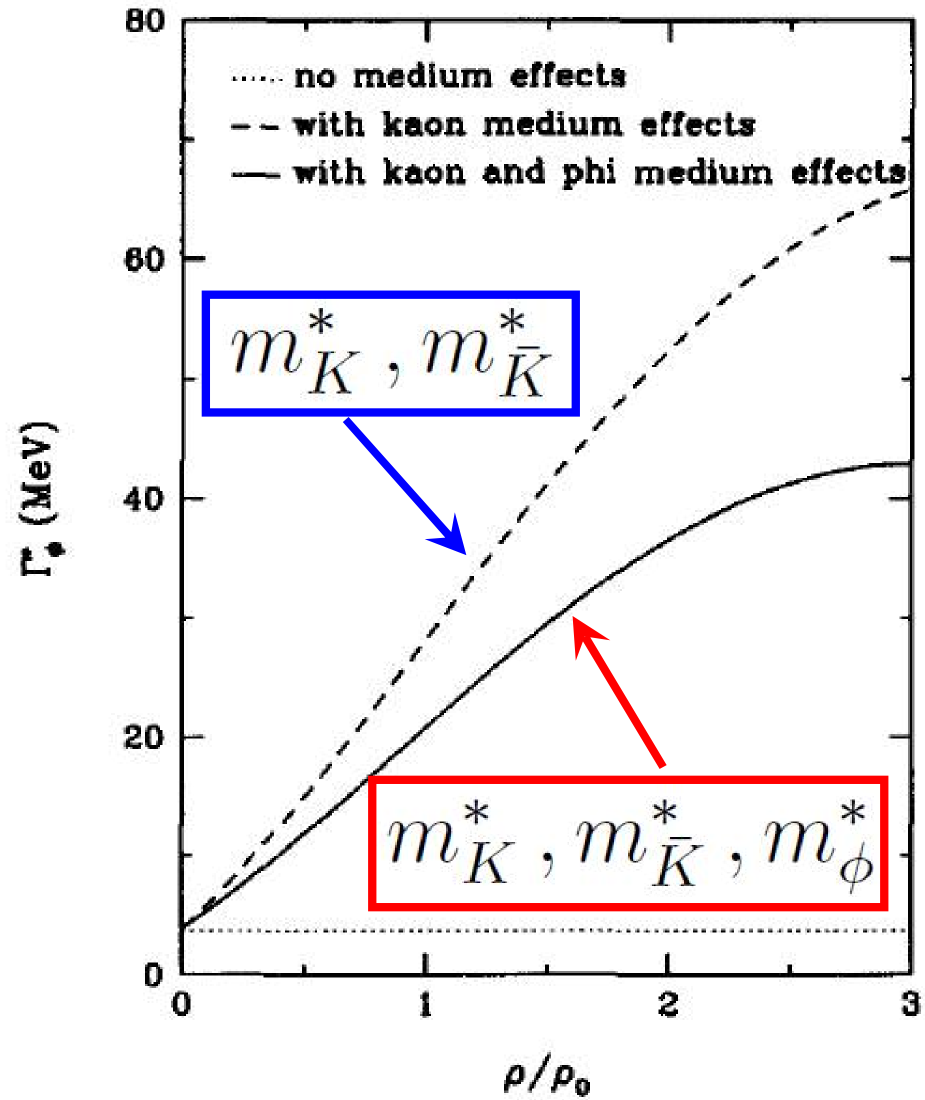
- Li, Lee, Brown (97): kaon production in Ni+Ni at 1 & 1.8 A GeV

$$a_K \approx 0.22 \text{ GeV}^2 \text{ fm}^3 \text{ and } a_{\bar{K}} \approx 0.45 \text{ GeV}^2 \text{ fm}^3$$

[Li, Lee, Brown (97)] [Chung, Ko, Li (98)]

Kaon and anti-kaon

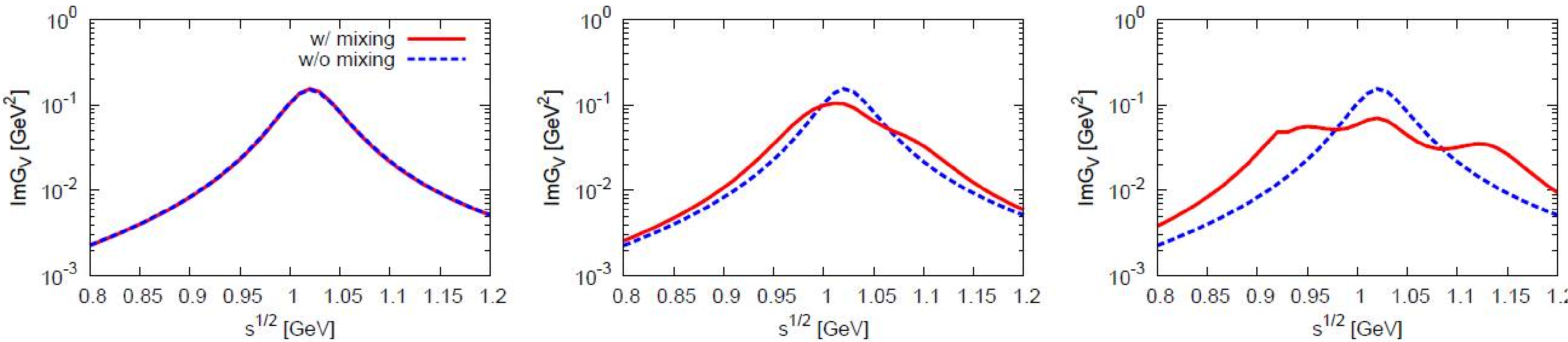




[CS, in preparation]

Spectral function of ϕ meson

- Chiral mixing ≈ C x 3-momenta
- Spectral function at chiral crossover with p = 0.1, 0.5, 1.0 GeV



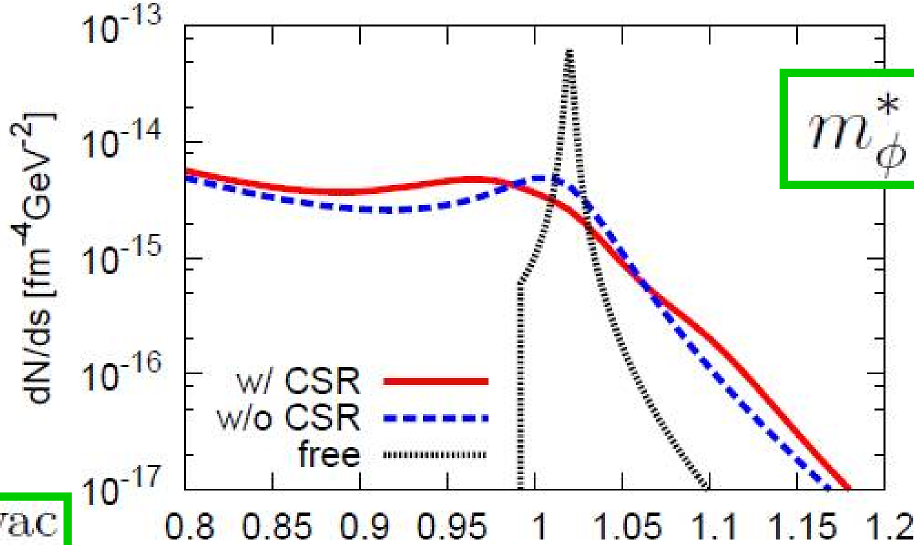
- Binning of DL data in momenta > 0.5 GeV

[CS, in preparation]

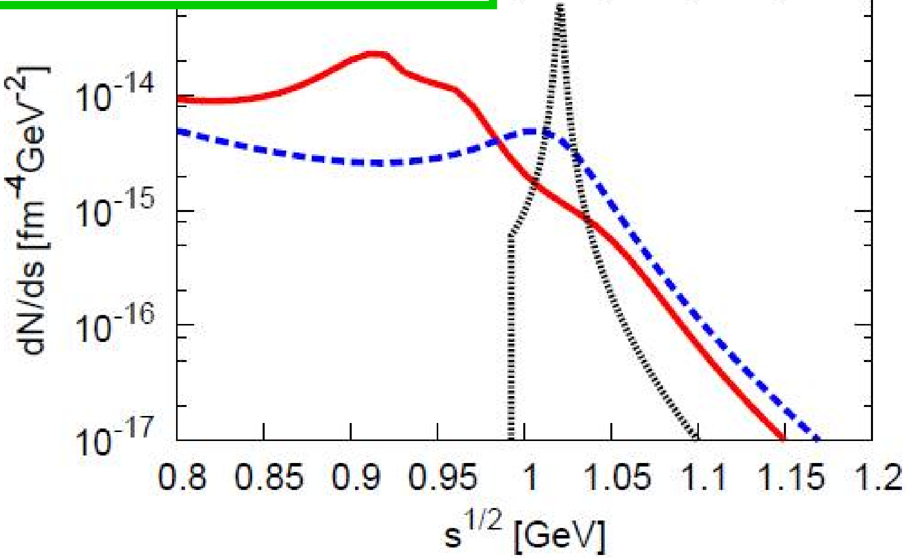
Int.over p > 0.5 GeV

Dilepton rates at T=50 MeV

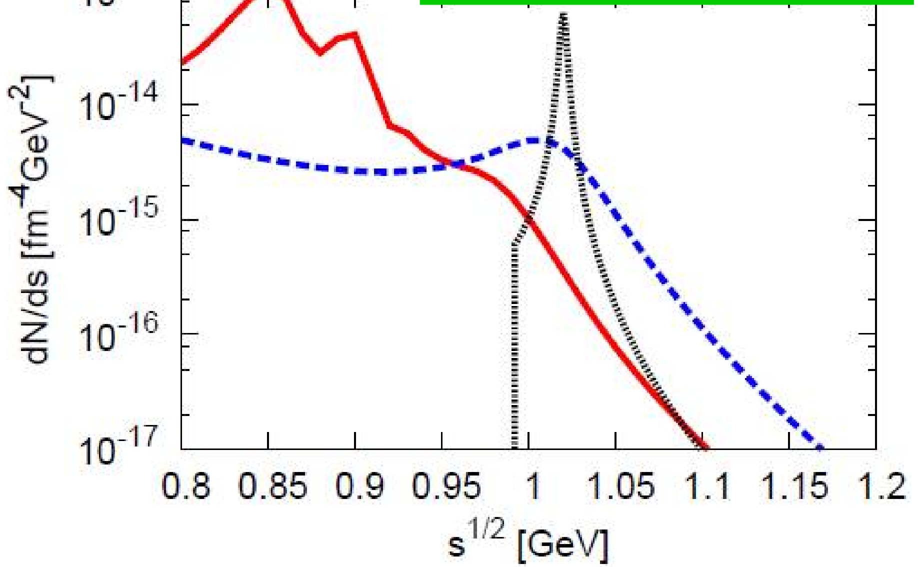
$m_\phi^* = m_\phi^{\mathrm{vac}}$



$m_\phi^* = 0.95\, m_\phi^{\mathrm{vac}}$



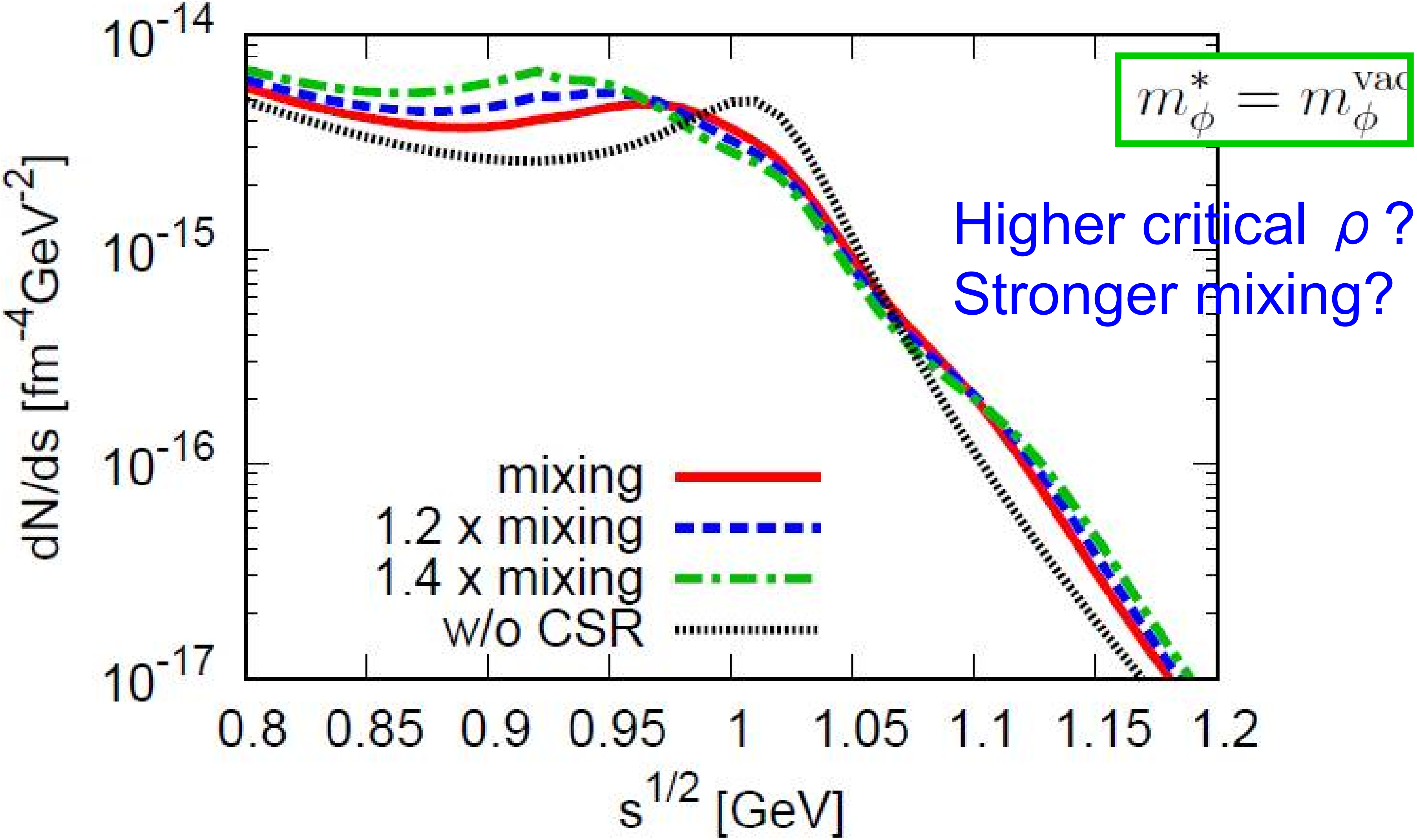
$m_\phi^* = 0.9\, m_\phi^{\mathrm{vac}}$



[CS, in preparation]

Int.over p > 0.5 GeV

Dilepton rates at T=50 MeV



Higher critical ρ ?
Stronger mixing?

Summary

- Chiral sym. restoration in cold dense matter
  - Chiral mixing induced by WZW, exists at any ρ !
  - Clear structural change in spectra/dilepton rates
  - Big discovery potential at FAIR/NICA/RHIC-BES
  - Coarse-grained approach
  - Mixing strength from lattice Q_2CD, FRG, AdS/QFT
- Parity doubling of nucleons in neutron stars
  - Parity doublet model with nucleons and deltas
  - Hadronic picture w/ CSR compatible with all modern constraints! [Marczenko et al. , ApjL (22)]

Backup

Low-energy theorem at T $\neq$ 0

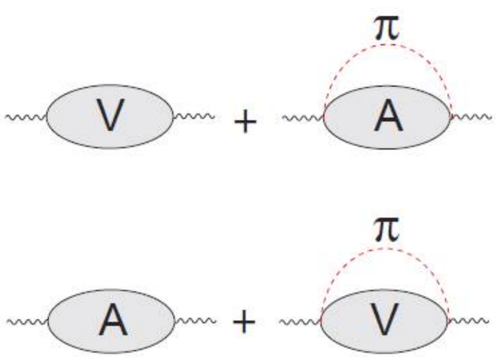
$$G_V^{\mu\nu}(T) = (1-\epsilon)G_V^{\mu\nu}(0) + \epsilon\, G_A^{\mu\nu}(0)$$

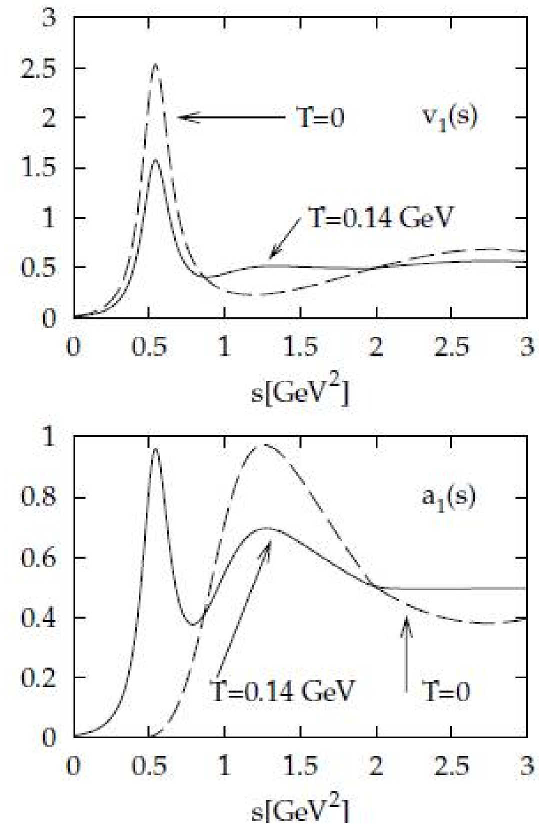
$$G_A^{\mu\nu}(T) = (1-\epsilon)G_A^{\mu\nu}(0) + \epsilon\, G_V^{\mu\nu}(0)$$

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

[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)]

[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

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

[Harada et al. (2006)]

From large Nc to Nc=3

- ❑ Vector mesons integrated out except the lowest → effective Lagrangian of π and ρ
- ❑ Power counting, loop corrections ≈ 1/Nc corr.

✓ a ≈ 2 cf. SS a ≈ 1

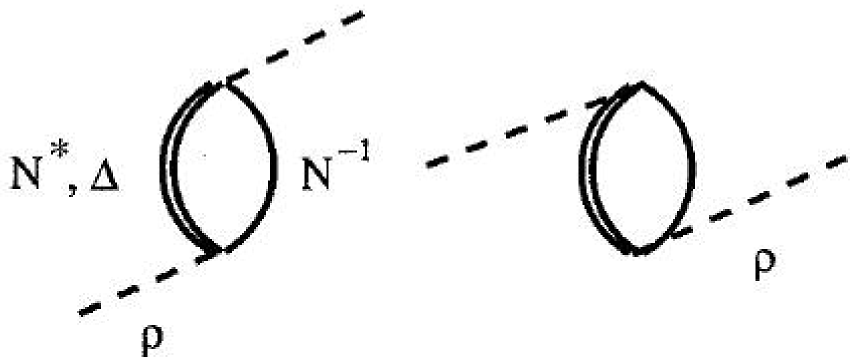
✓ KSRF II O.K.

$$\frac{m_\rho^2}{g_{\rho\pi\pi}^2 F_\pi^2}\bigg|_{\rm SS} \simeq 3.0, \qquad \left(\frac{m_\rho^2}{g_{\rho\pi\pi}^2 F_\pi^2}\bigg|_{\rm exp} \simeq 2.0\right)$$

1/Nc corrections

[Friman, Pirner (97)]

ρ meson self-energy



$$\Sigma_\rho^R(\omega, \boldsymbol{q}) = \frac{4}{3}\frac{f_{N^*N\rho}^2}{m_\rho^2}F(\boldsymbol{q}^2)\boldsymbol{q}^2\rho_B\frac{(\varepsilon_q^{N^*} - m_N)}{\omega^2 - (\varepsilon_q^{N^*} - m_N)^2}$$

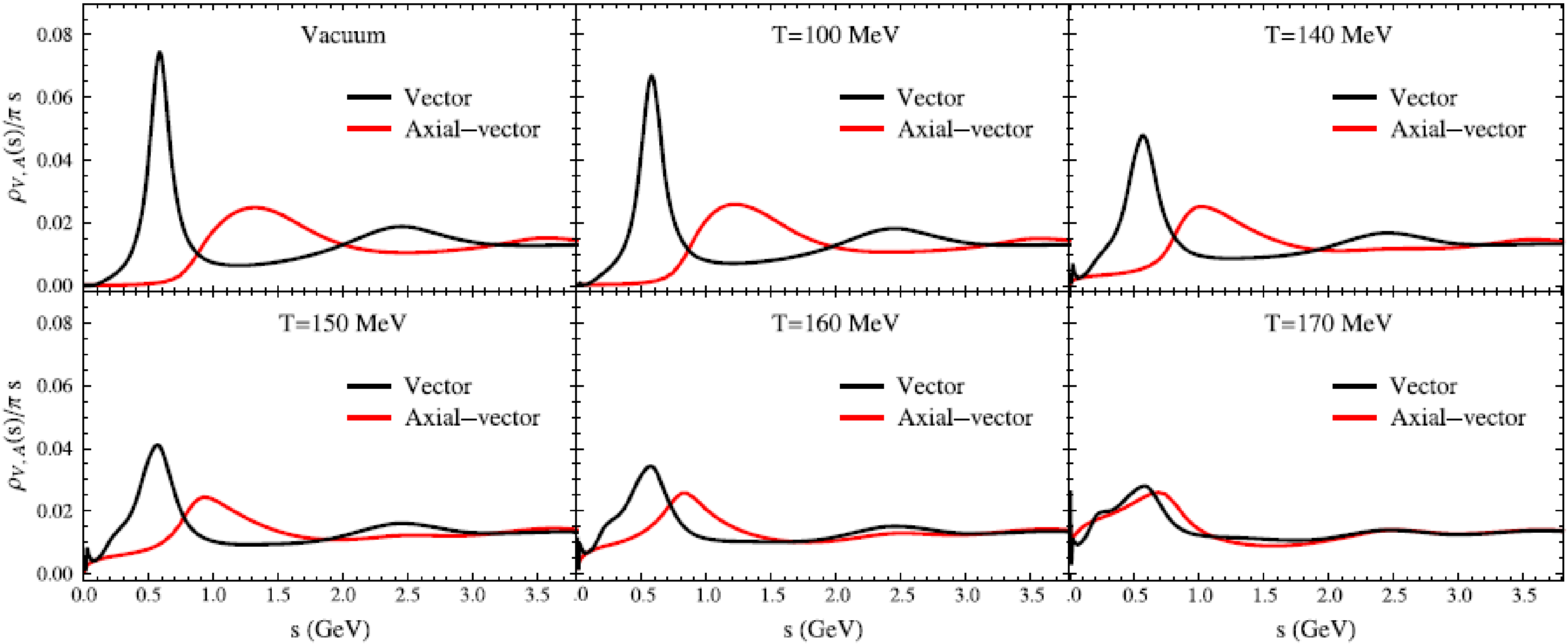
$$+\frac{2}{5}\frac{f_{\Delta N\rho}^2}{m_\rho^2}F(\boldsymbol{q}^2)\boldsymbol{q}^2\rho_B\frac{(\varepsilon_q^{\Delta} - m_N)}{\omega^2 - (\varepsilon_q^{\Delta} - m_N)^2},$$

where

$$\varepsilon_q^{N^*} = \sqrt{\boldsymbol{q}^2 + m_{N^*}} - \frac{i}{2}\Gamma_{N^*},\ \varepsilon_q^{\Delta} = \sqrt{\boldsymbol{q}^2 + m_\Delta} - \frac{i}{2}\Gamma_\Delta,$$

[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', …