Probing Chiral Symmetry Restoration with Dileptons

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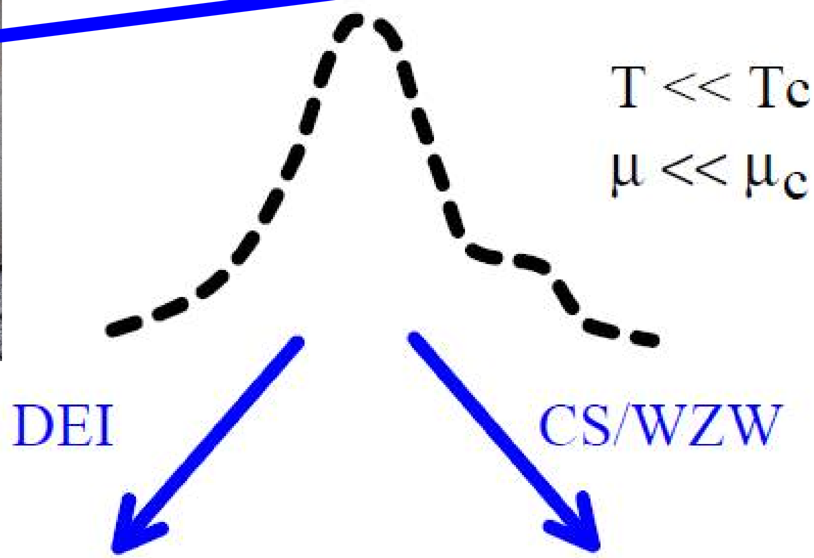
Why chiral mixing?

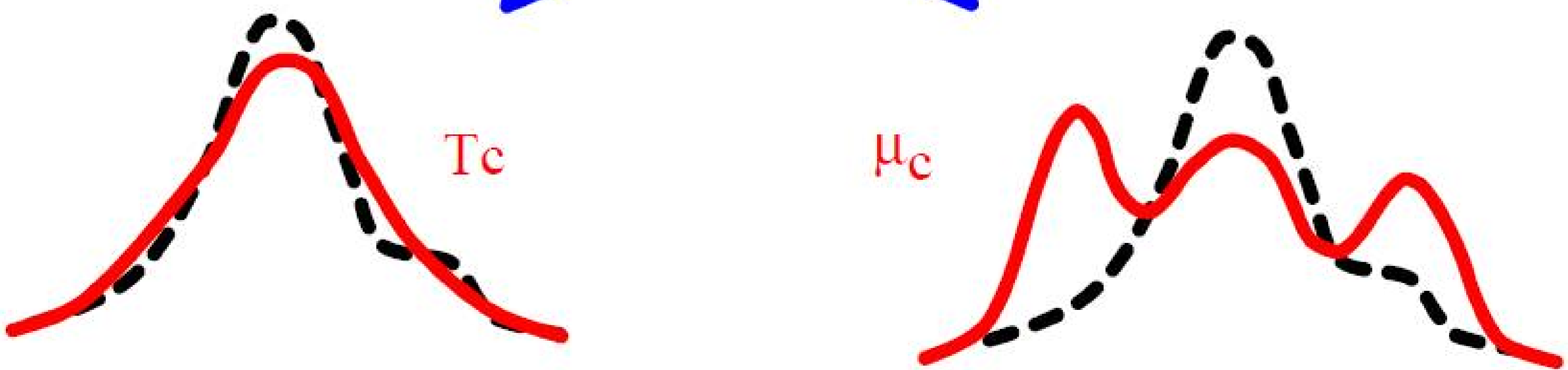
Q. Do we see any signal of chiral symmetry restoration in dilepton measurement?

- 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!

<VV> ← chiral mixing → <AA>

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





Hot dilute matter

Cold dense matter

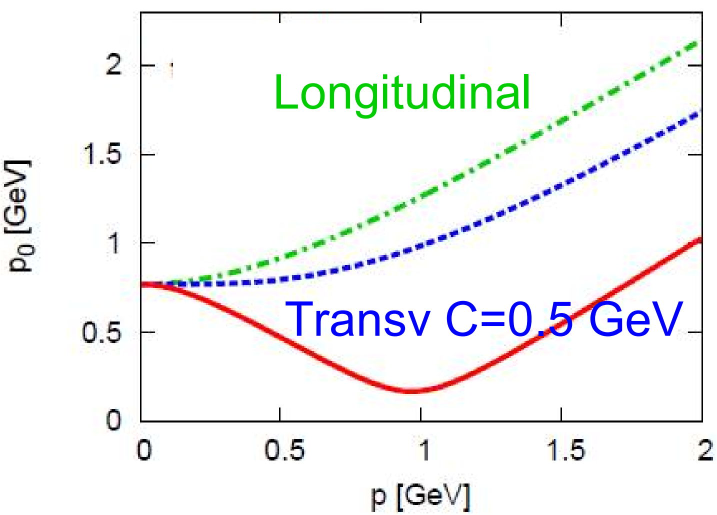
[Domokos, Harvey ('07)]

Holographic approach at finite μ_B

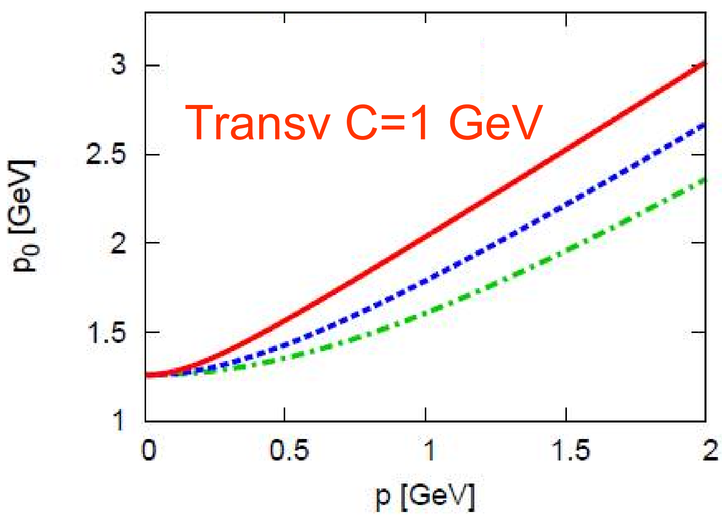
$$S_{4\mathrm{dim}} = \int d^4x \left[\frac{1}{2}(\partial_\mu \pi)^2 - \frac{1}{2} m_\pi^2 \pi^2 - \frac{1}{4}(\rho_{\mu\nu})^2 - \frac{1}{4}(a_{\mu\nu})^2 + \frac{1}{2} m_\rho^2 \rho_\nu^2 + \frac{1}{2} m_a^2 a_\mu^2 + C\epsilon^{ijk}(\rho_i \partial_j a_k + a_i \partial_j \rho_k) \right]$$

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

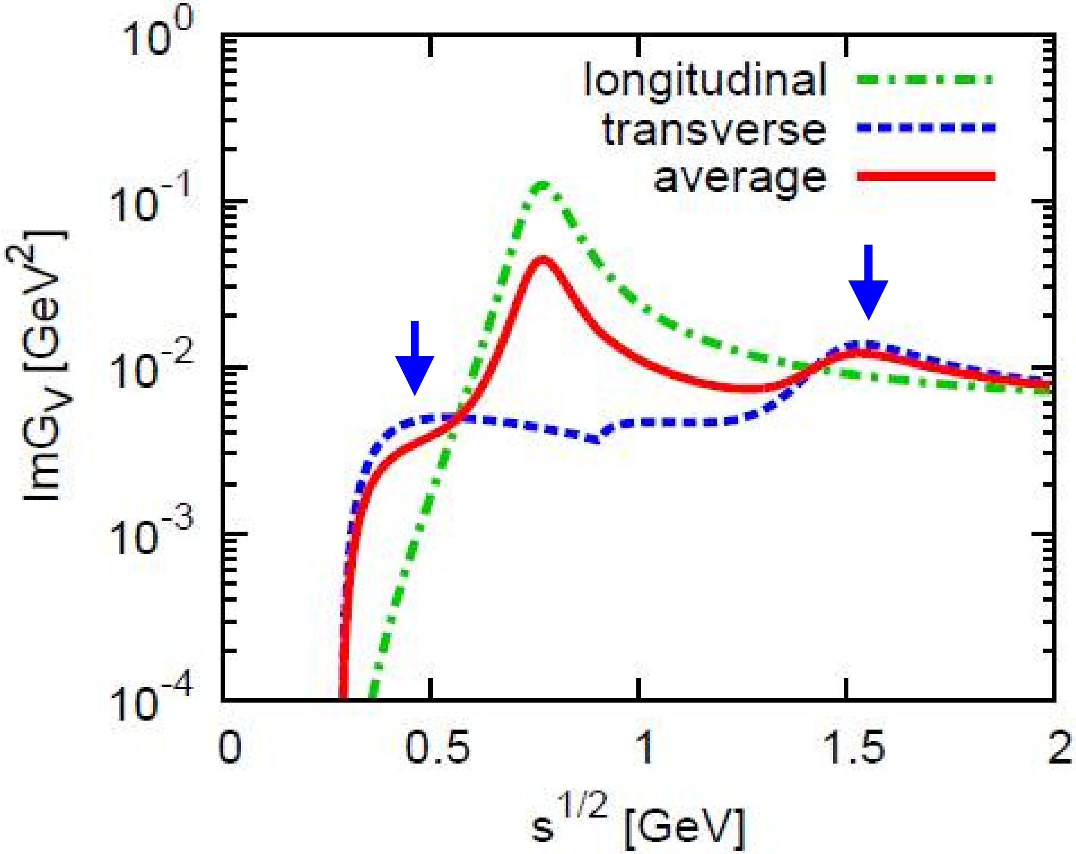
ρ meson

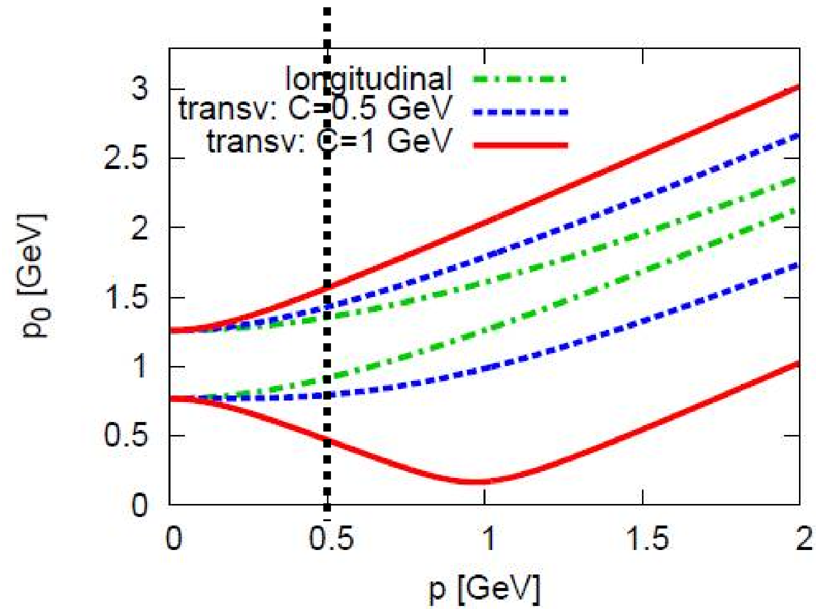


a_1 meson



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 by WZW

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

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

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

- 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

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

Weak mixing ... No impact?

A missing piece: χ sym. restoration

<AA> → <VV>

CS, arXiv:1906.05077

Chiral restoration vs. mixing

- Dispersion relations for small 3-momenta

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

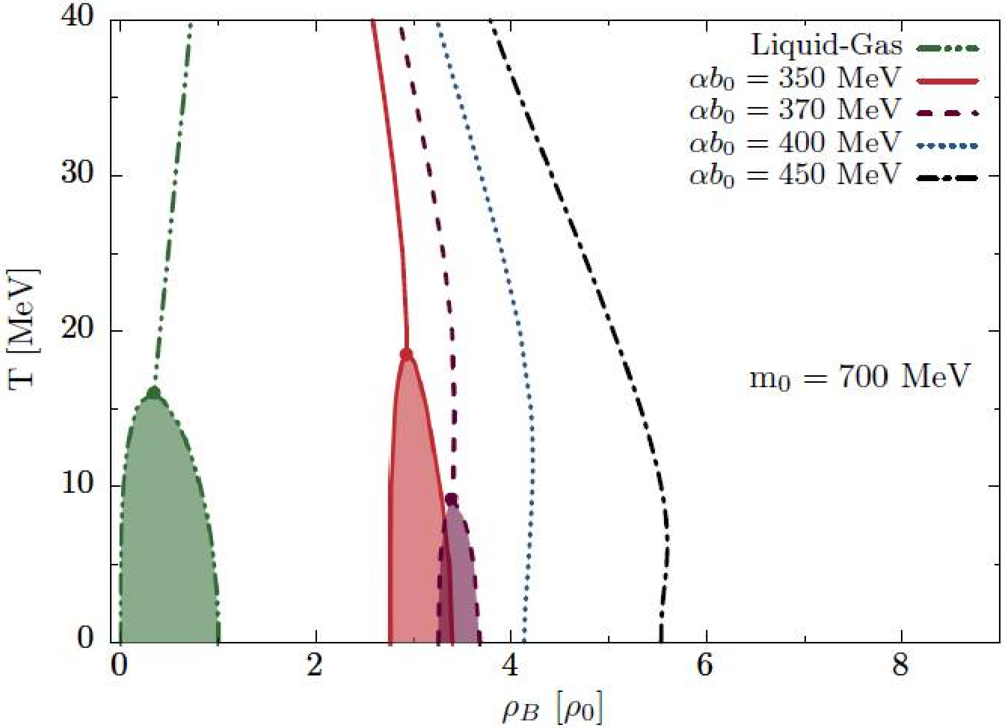
- The mixing effect will be enhanced as δ m decreases!
  - In-medium δ m
  - In-medium mixing C

Set-up: rho/omega

- Mass difference = order parameter
  - Chiral restoration → $<\sigma>$
  - Density effect → $<\omega_0>$

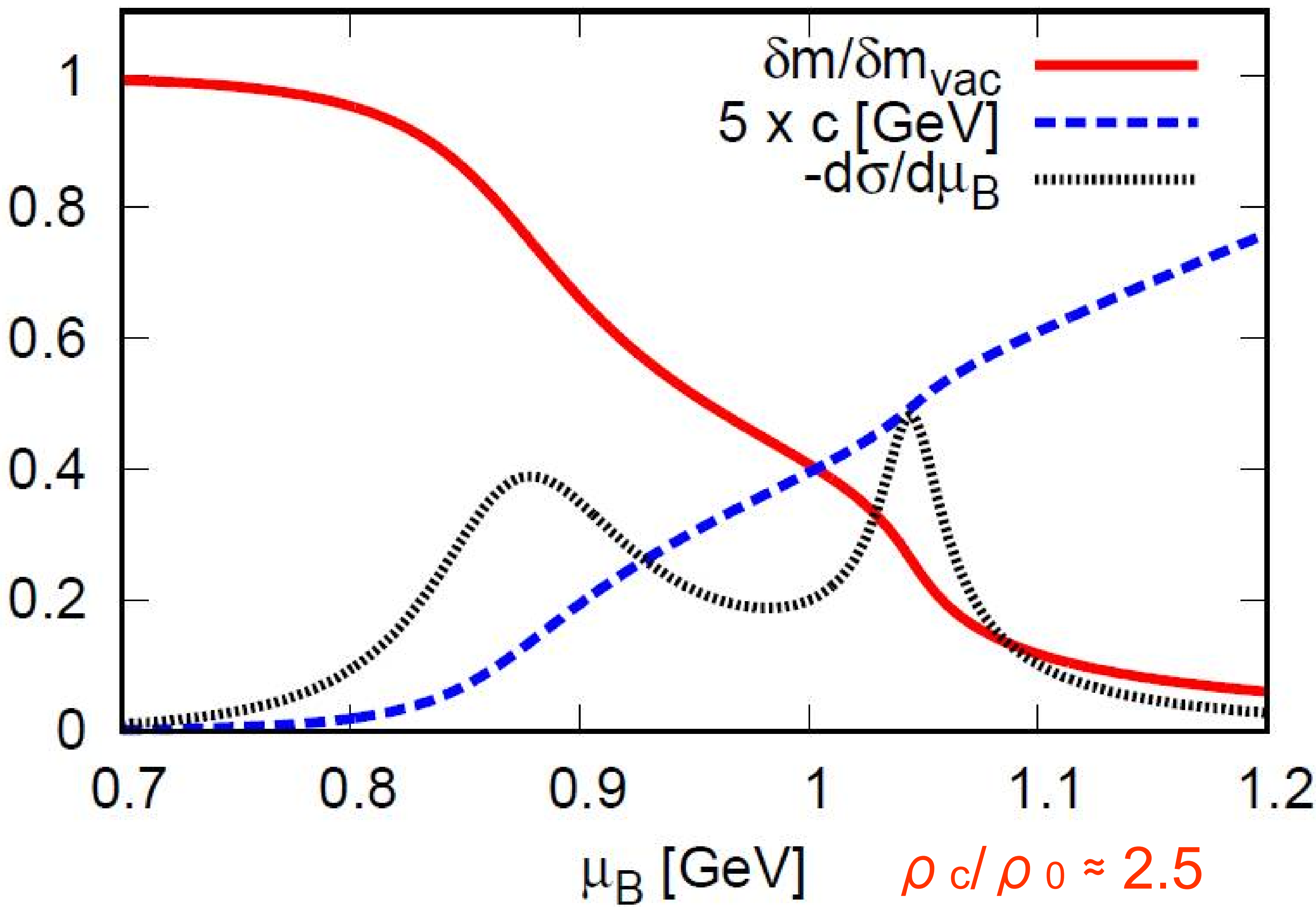
  Chiral MF models

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



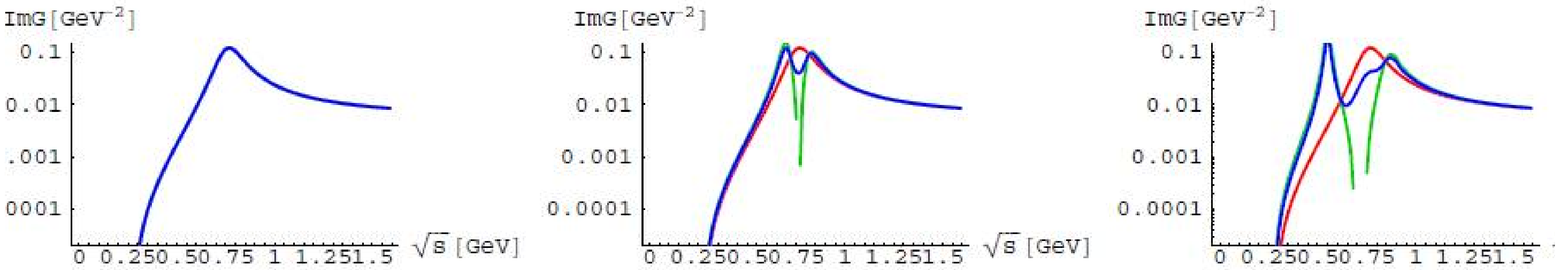
✓Nuclear ground state
✓Extended with deconf to quark matter, constrained by NS
[Marczenko et al. (2019)]
→ Masses & mixing

Mass difference vs. mixing : T=50 MeV

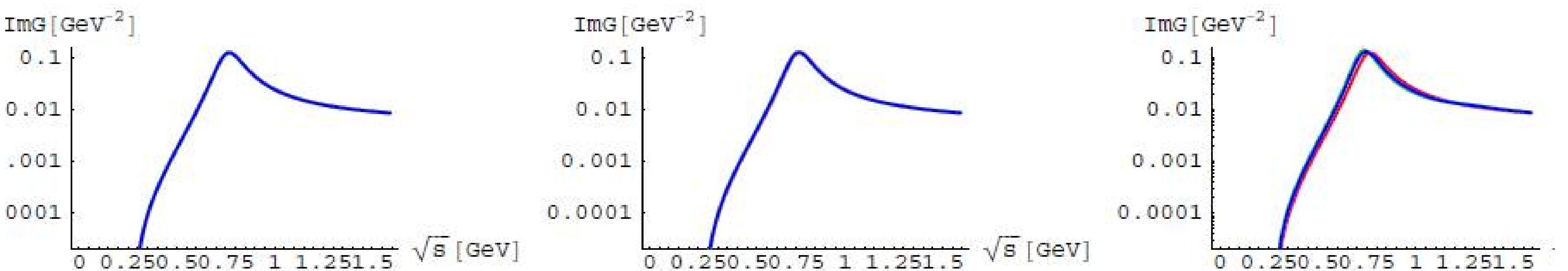


$\rho_c / \rho_0 \approx 2.5$

Spectral function at T = 50 MeV



Low μ Near μ c

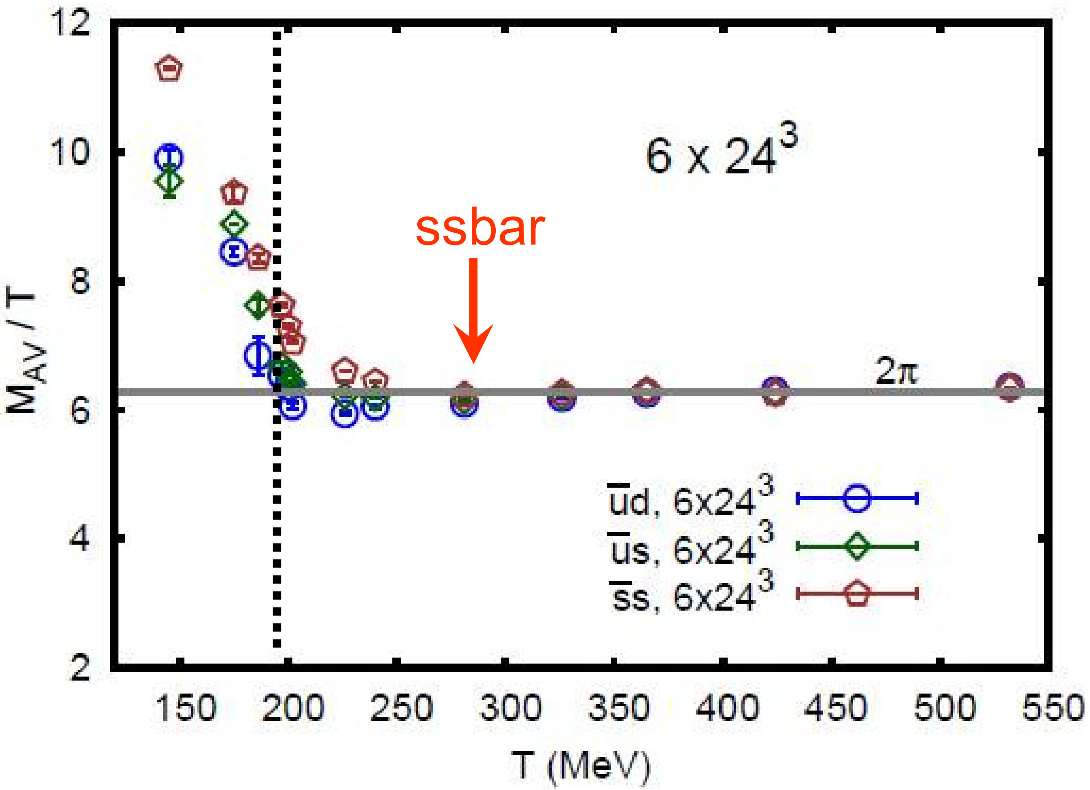


(top) chiral restoration (bottom) no restoration

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

Set-up: phi

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



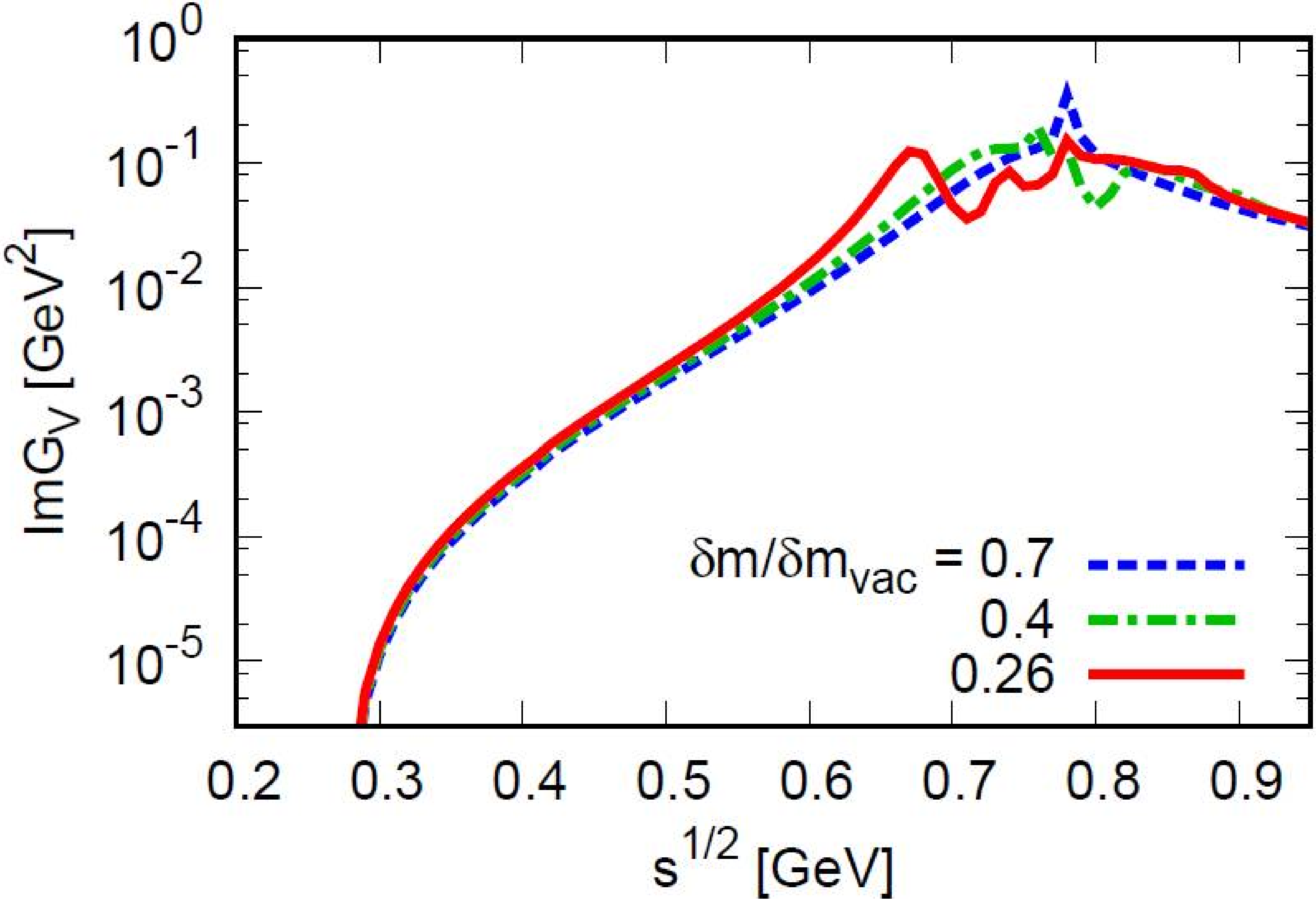
[Cheng et al., ('11)]

$\delta m(q) \approx 0.26$ at μc

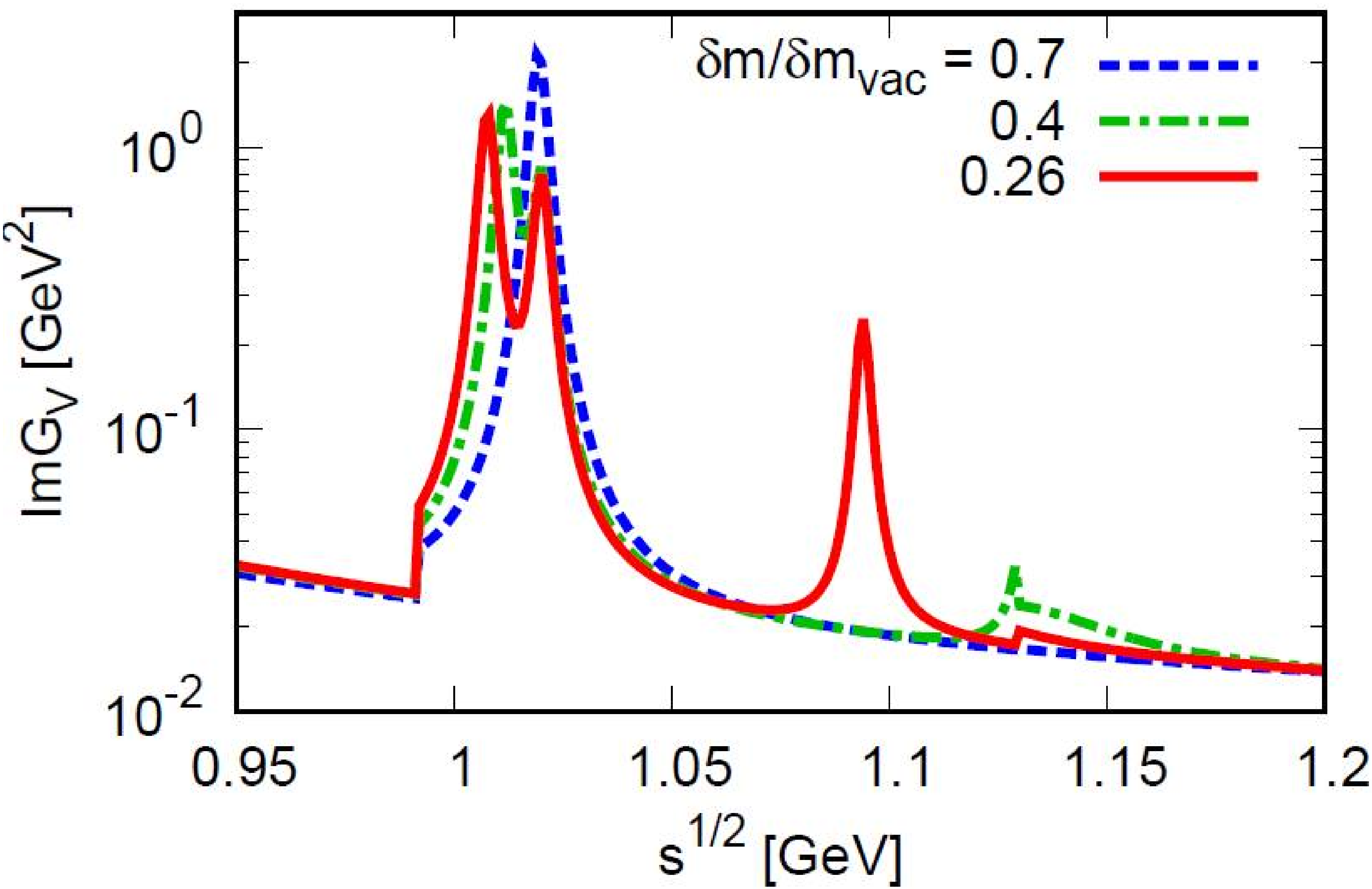
Assumptions:

- $\delta m(s) \approx 0.26$ at $1.2\ \mu c$
- Constant mass of vector states

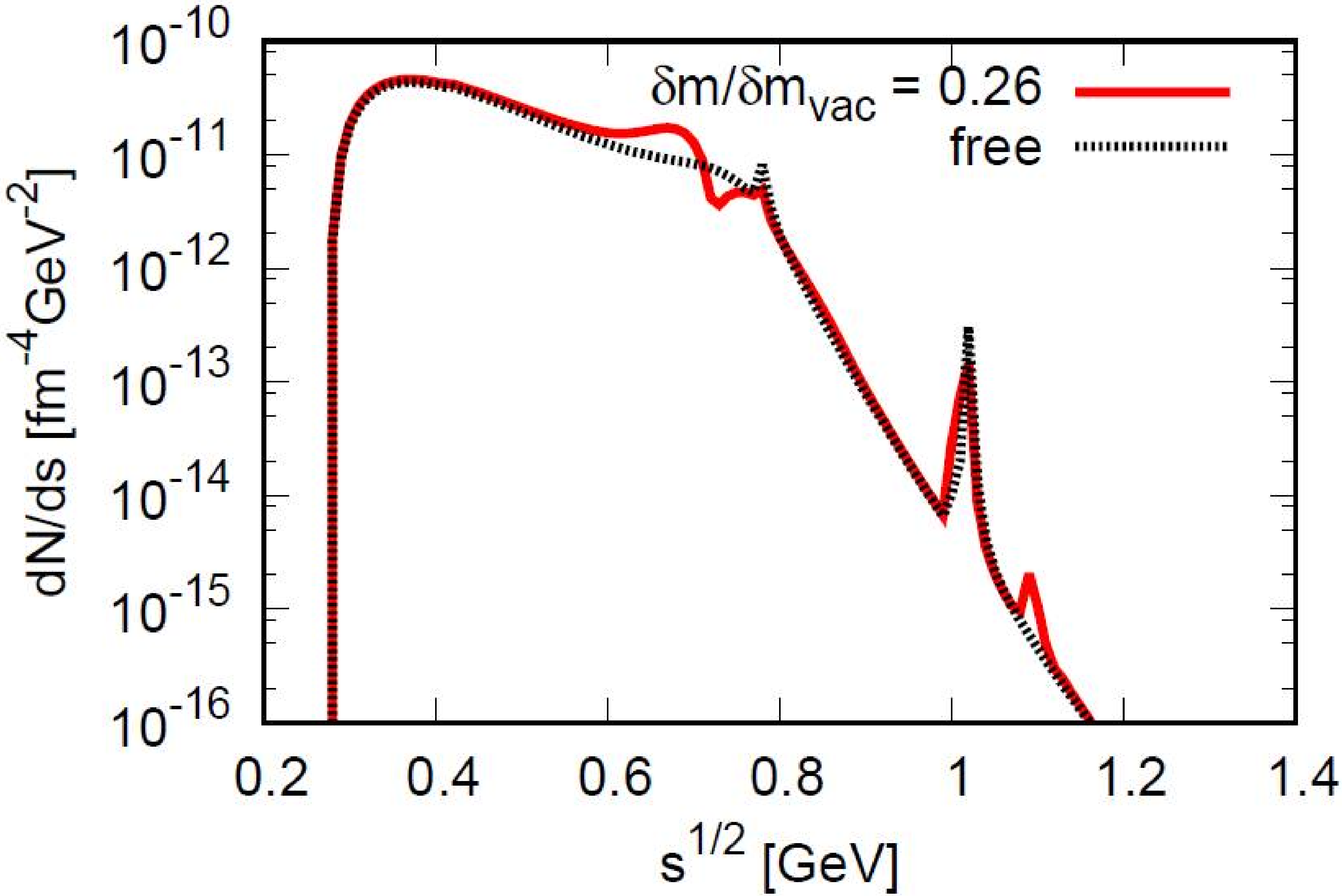
Rho/omega spectrum at T = 50 MeV



Phi spectra at T = 50 MeV



Dilepton rates at T =50 MeV

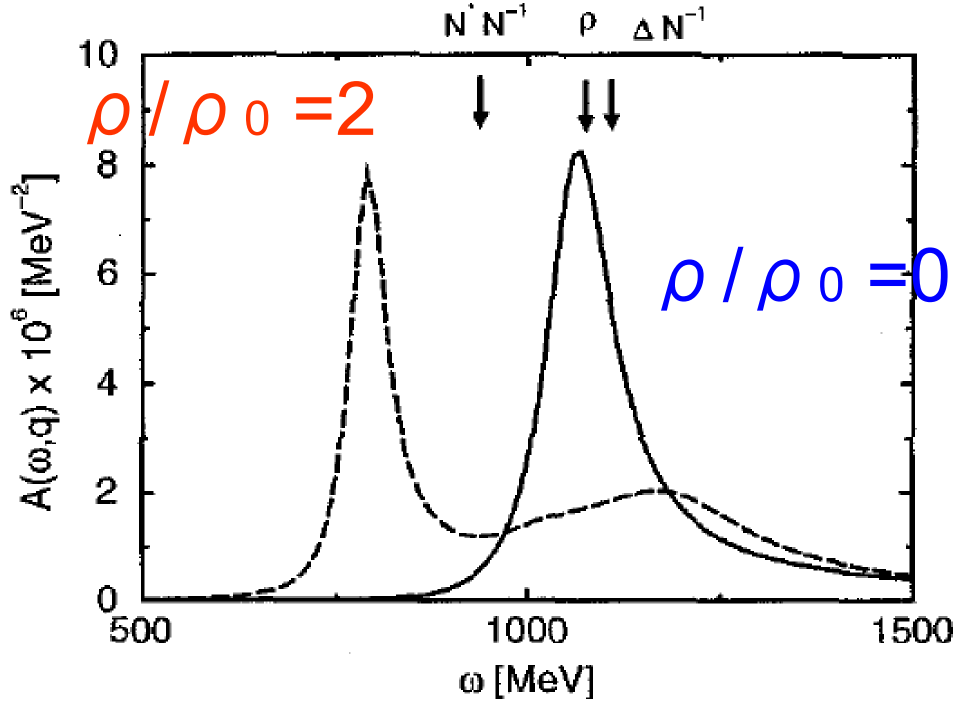


Baryon resonances in ρ N channel

N(1750) and Δ(1905)

→ level mixing

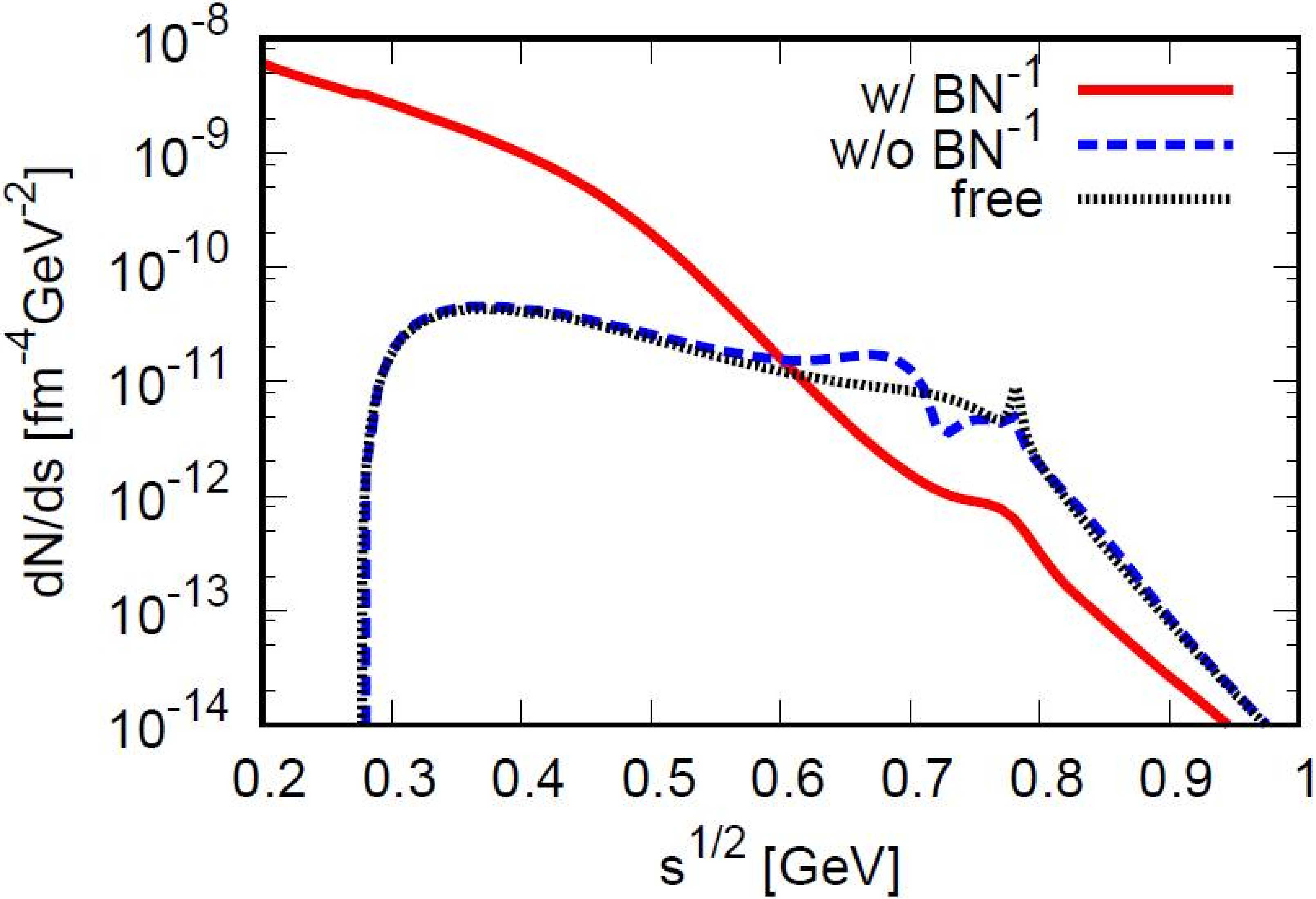
[Friman, Pirner (97)]



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

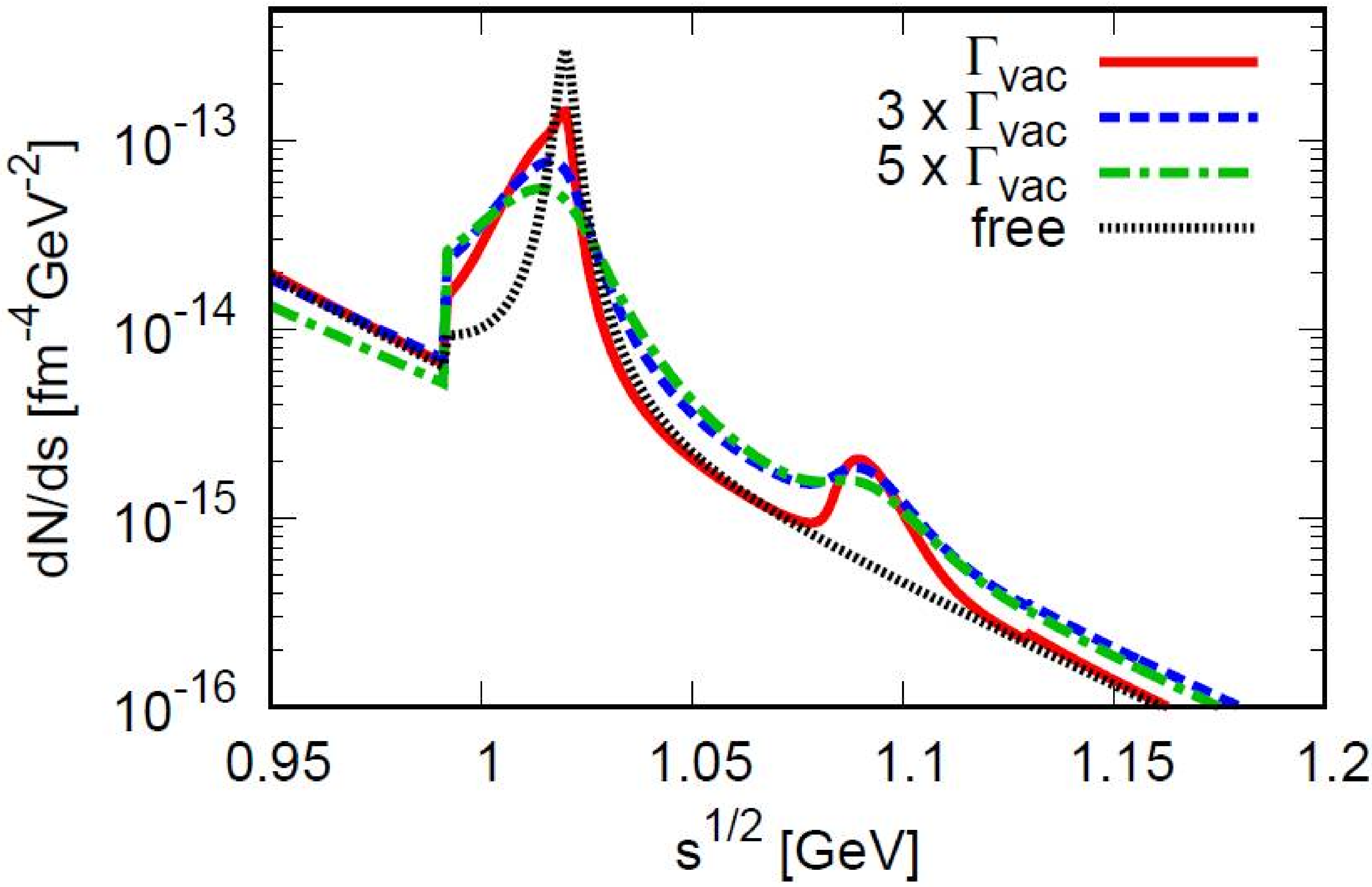
[Rapp, et al. (98)]

Signals diminished by p-wave states



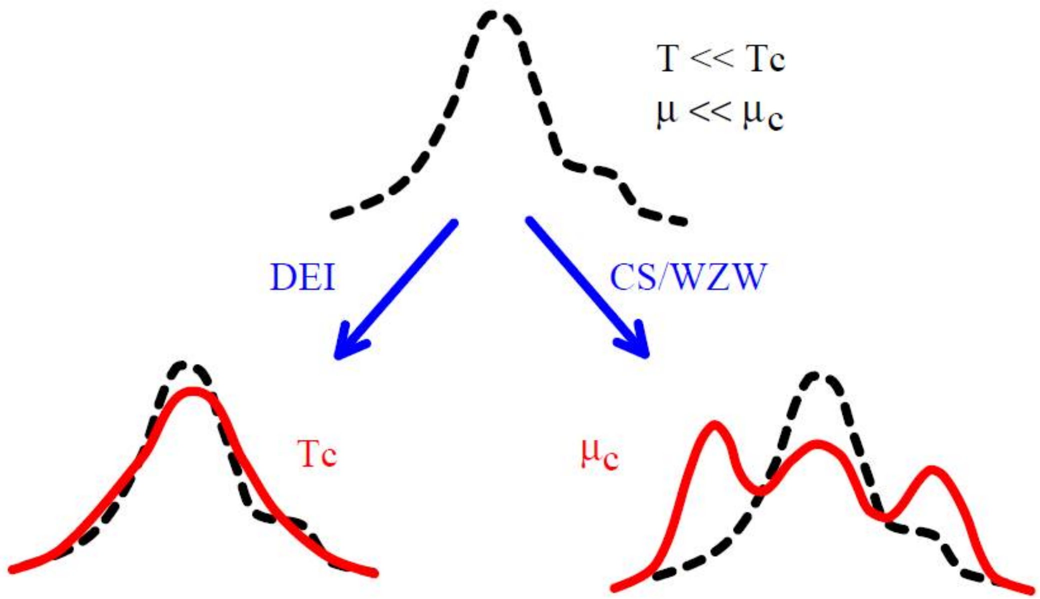
[in-medium $\phi \rightarrow KK$: Kaiser et al. (95), Ramos & Oset (00)]

ϕ remains well-defined resonance!



Summary

❑ Parity doubling of vector mesons



❑ Chiral sym. restoration in cold dense matter

- Clear structural change in the dilepton rates
- Especially, in the phi-sector at T = 50-80 MeV
- Big discovery potential at HIAF/FAIR/NICA!

Backup

[Harada, CS ('09)]

Vector-current correlator

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

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

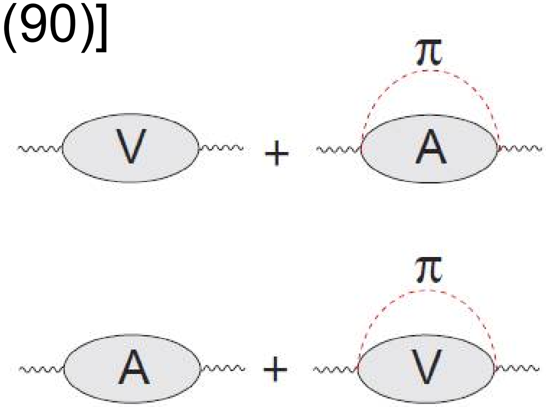
$$D_{V,A} = s - m_{\rho,a_1}^2 + i m_{\rho,a_1} \Gamma_{\rho,a_1}(s),$$

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

Low-energy theorem

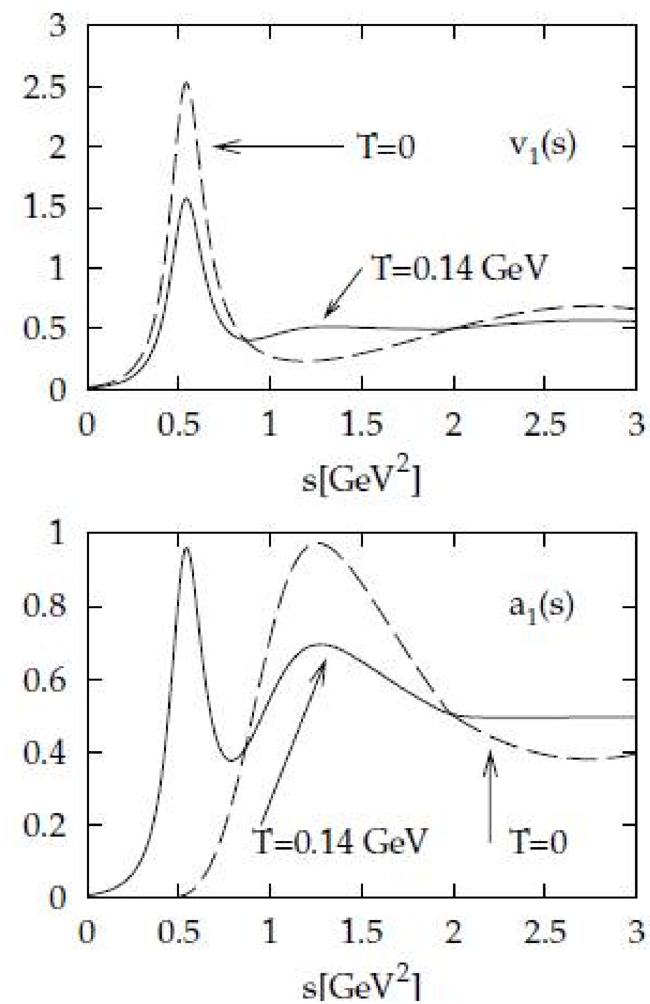
$$G_V^{\mu\nu}(T) = (1-\epsilon)G_V^{\mu\nu}(0) + \epsilon\, G_A^{\mu\nu}(0)$$
$$G_A^{\mu\nu}(T) = (1-\epsilon)G_A^{\mu\nu}(0) + \epsilon\, G_V^{\mu\nu}(0)$$
$$\epsilon = \frac{T^2}{6F_\pi^2}$$

[Dey, Eletsky and Ioffe (90)]



$$\epsilon = \frac{4\rho_B \sigma_{\pi N}}{3F_\pi^2 m_\pi^2}$$

[Krippa (98)]



ε →1/2: chiral restoration? NO!

[Harada, CS, Weise (08)]

From low T to high T

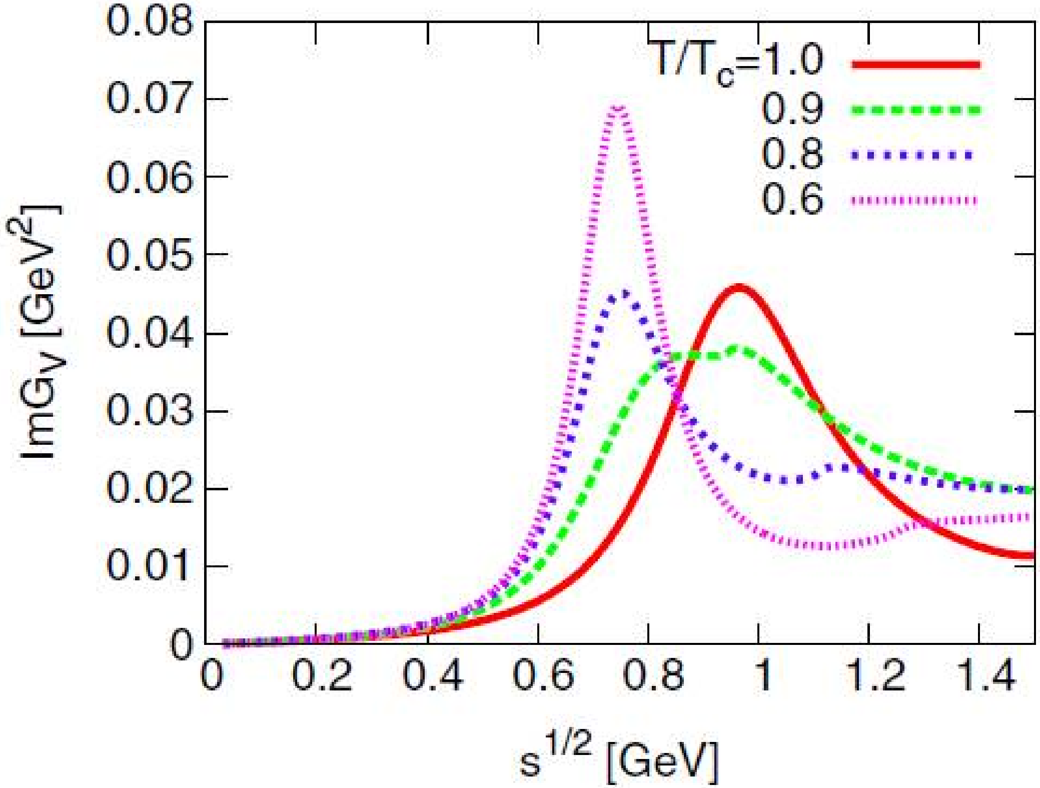


Figure: mpi = 0

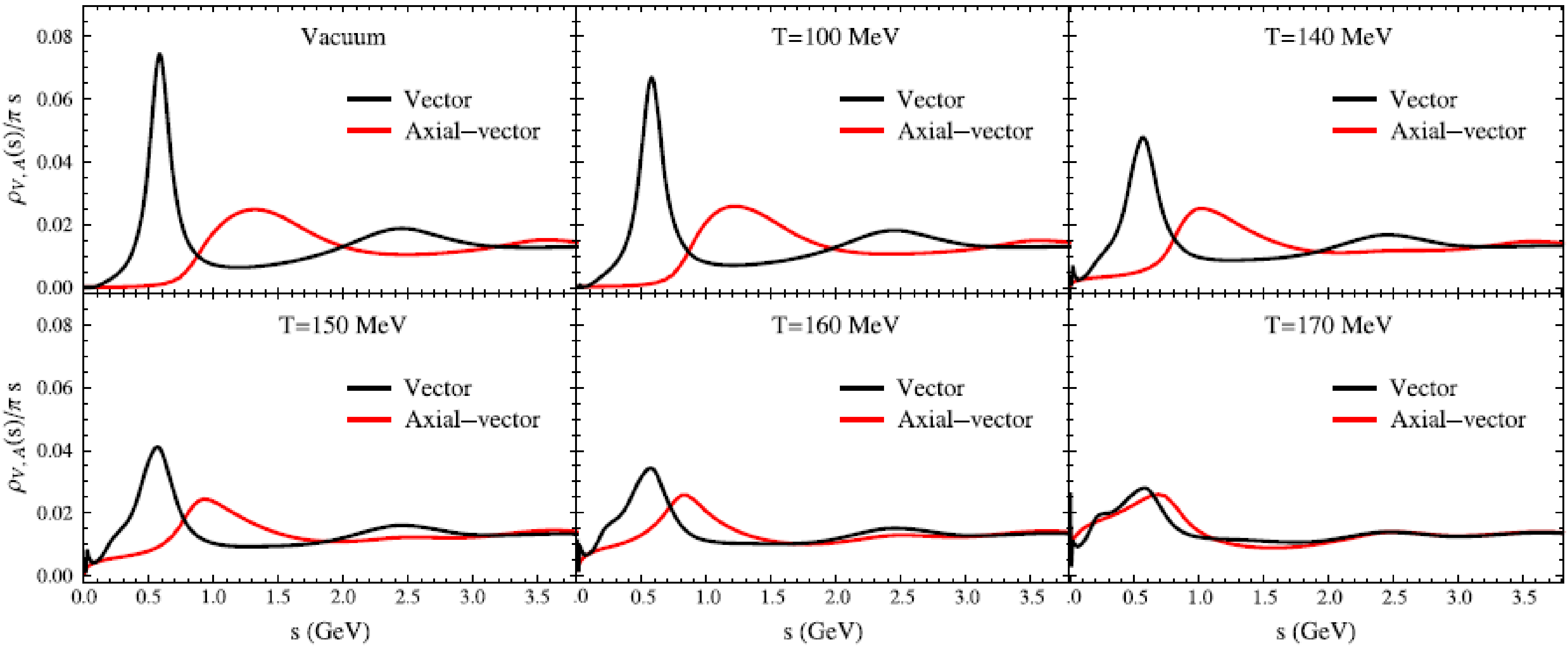
Off chiral limit:
Mixing ≈ 0.06 mpi at Tc

2 bumps → 1 bump

- Chiral EFT for pions, rho and a1 at 1 loop
- Intrinsic tem. effect in the a1 ρ π interaction

[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', …