The role of chiral mixing in dilepton production

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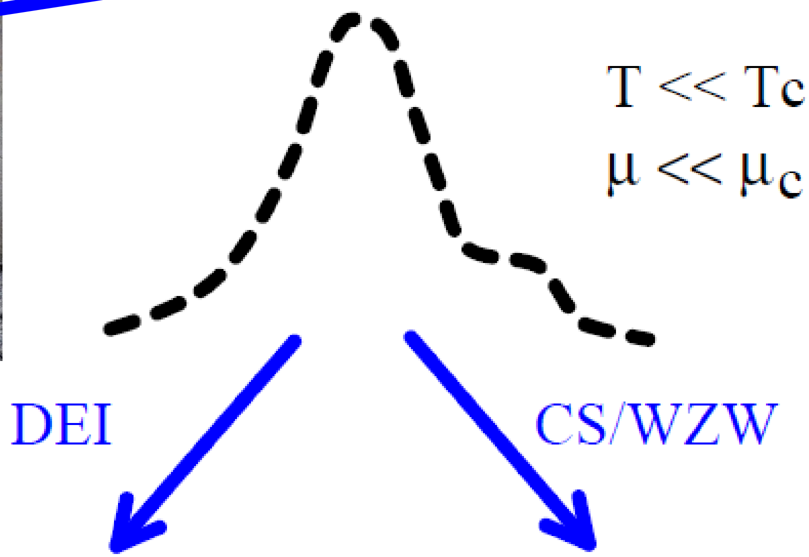
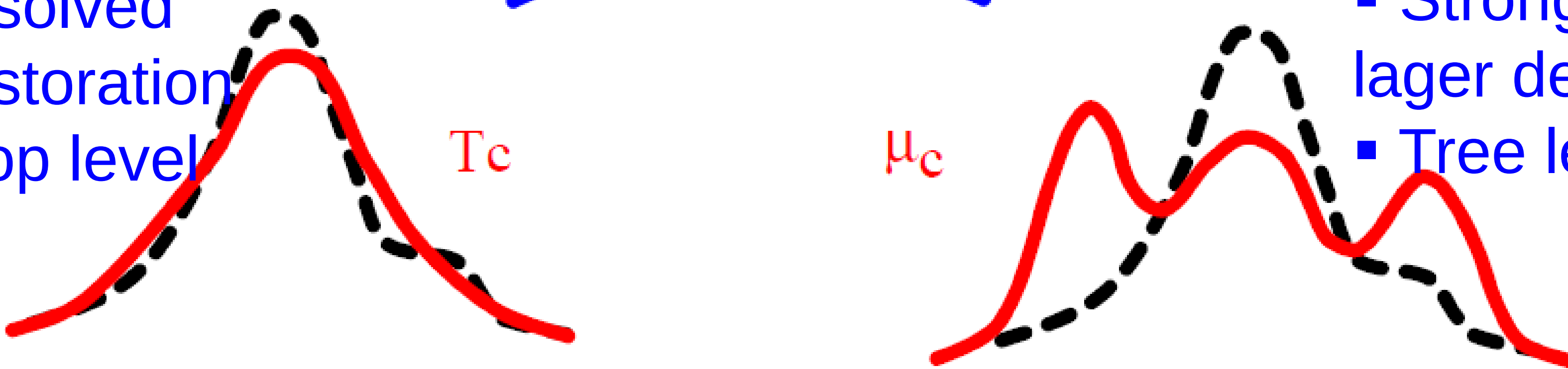
Why chiral mixing?

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, J-PARC!

Known

- Resolved at restoration
- Loop level

NEW!

- Stronger at lager density
- Tree level

Hot dilute matter

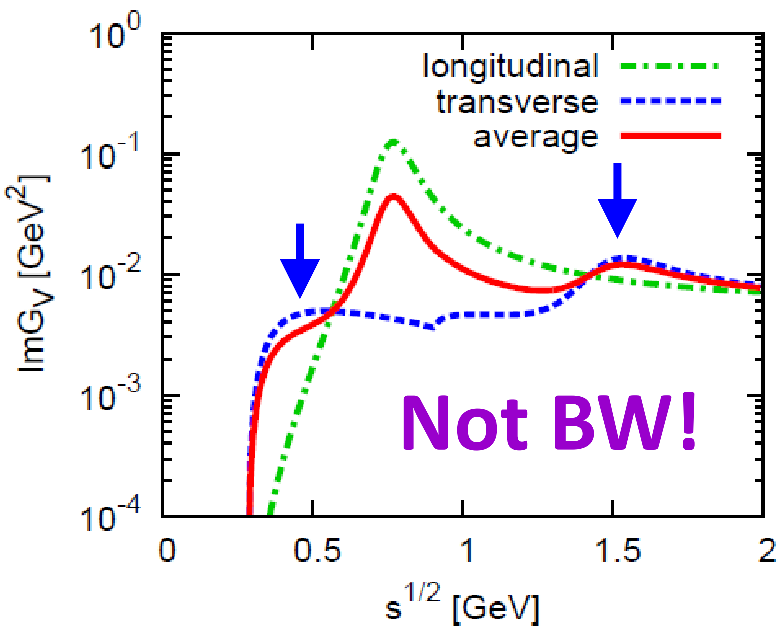
Cold dense matter

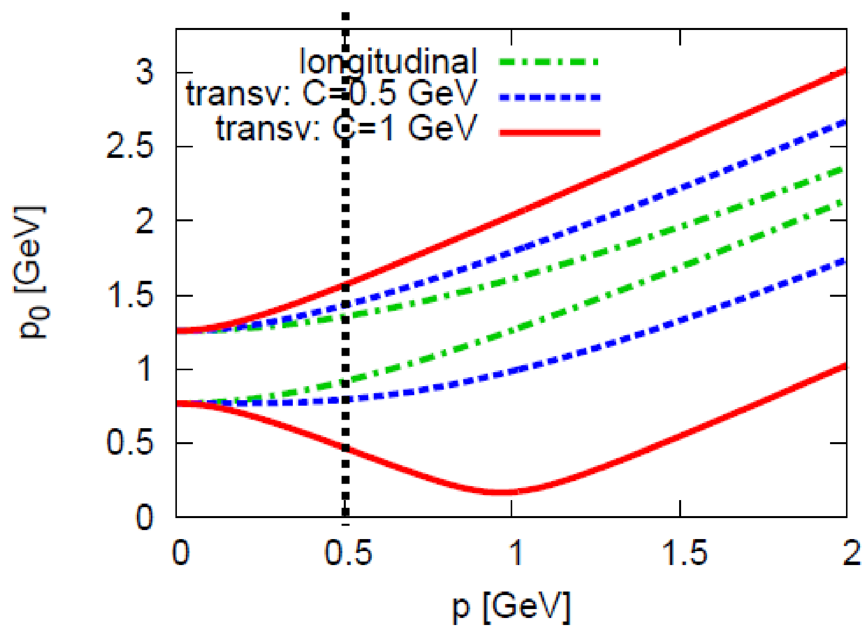
[Domokos, Harvey ('07)]

Direct V-A mixing at finite μB

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

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





[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

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

Weak mixing ... No impact?

A missing piece: χsym. restoration

<AA> → <VV>

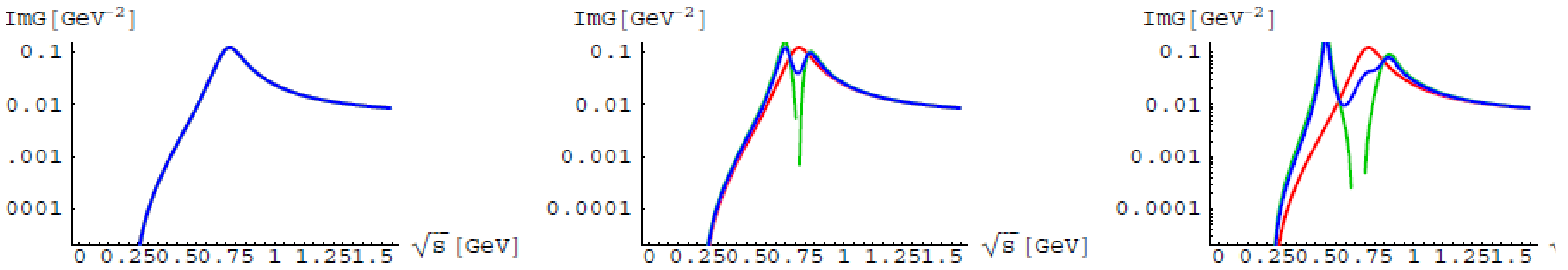
Chiral restoration vs. mixing

- Dispersion relations for small 3-momenta

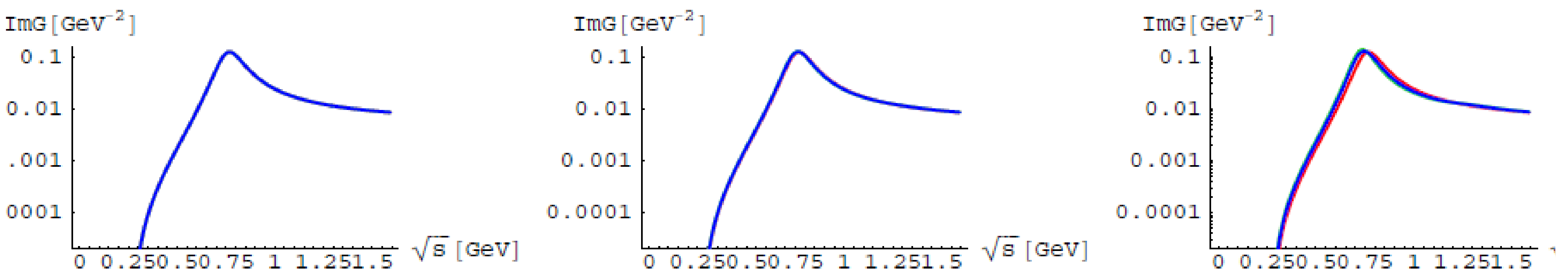
$$p_0^2 \simeq m_{a_1,\rho}^2 + \left(1 \pm \frac{4C^2}{m_{a_1}^2 - m_\rho^2}\right)\bar{p}^2$$

- 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)]

Spectral function at T = 50 MeV



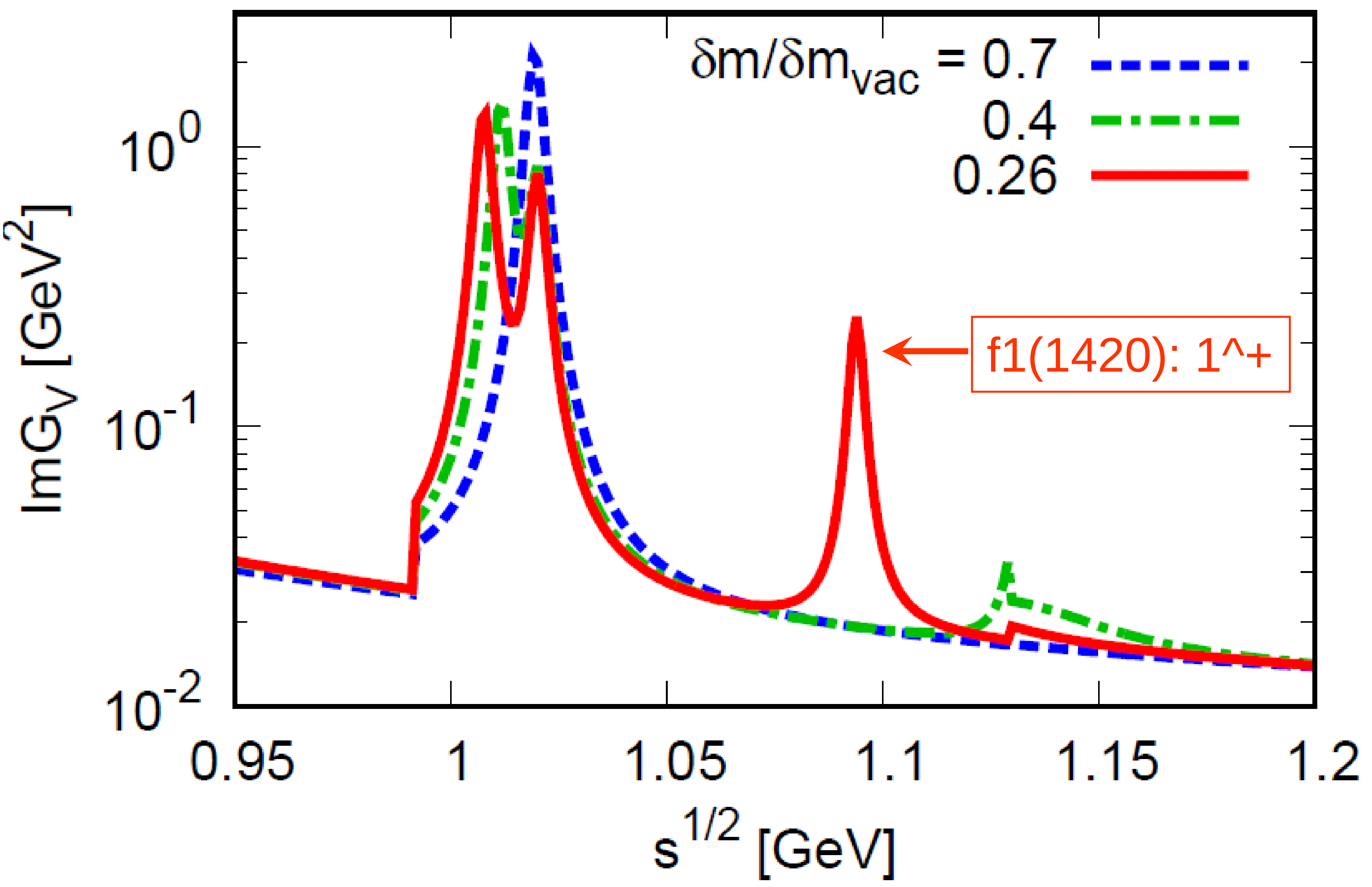
Low μ → Near μc



(top) chiral restoration (bottom) no restoration

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

Phi spectra at T = 50 MeV



R. Ejima, P. Gubler, C. Sasaki and K. Shigaki, in preparation

TOWARD A MEASUREMENT OF CHIRAL RESTORATION AT J-PARC

For more details, talk by Ren Ejima

ϕ meson in nuclear matter

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

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

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

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

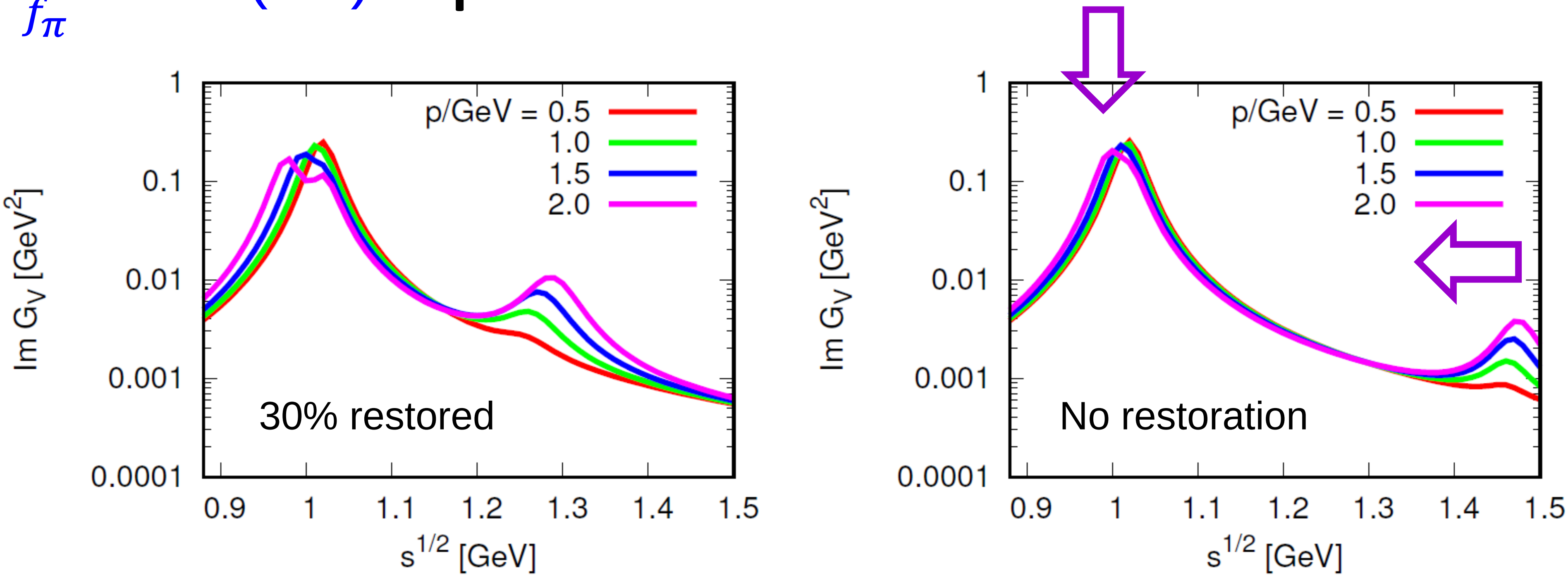
- Li, Lee, Brown (97): kaon production in Ni+Ni at 1 & 1.8 A GeV

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

$T \approx 0$ & $\rho_B \approx \rho_0$

$\frac{f_\pi^*}{f_\pi} \approx 0.7$ (left)

ϕ meson in nuclei

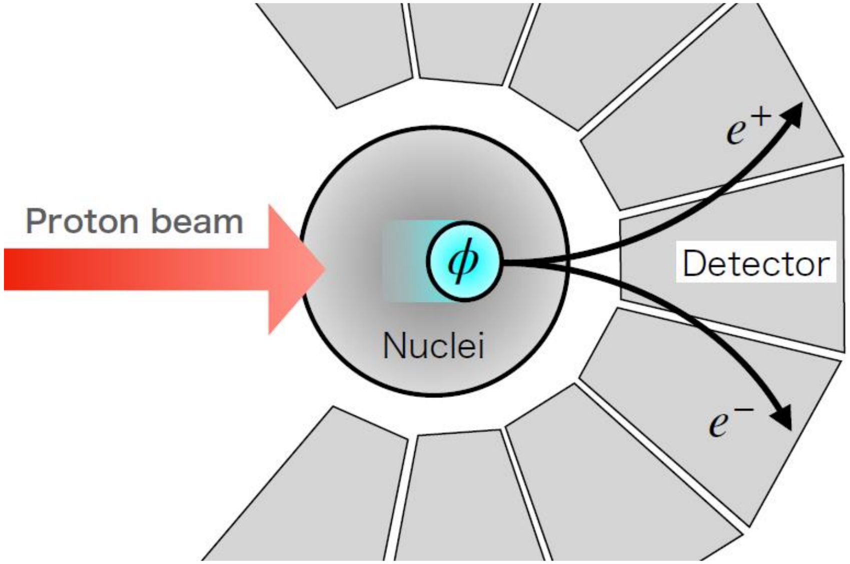


✓ Strong evidence of partial (~30%) restoration in pionic atoms [Nishi et al., Nature Physics, 2023]

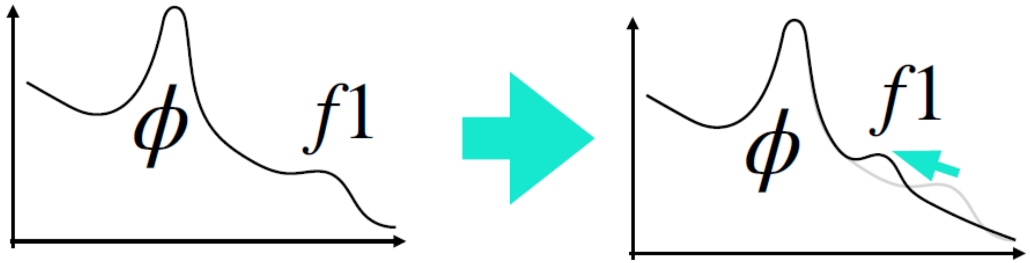
❑ Density-induced chiral mixing in broken phase

❑ More structure & their shift due to f_π^* in SF

E16 experiment at J-PARC



- Measurements of spectral change of vector mesons in nuclei
- Proton beam at 30-50 GeV

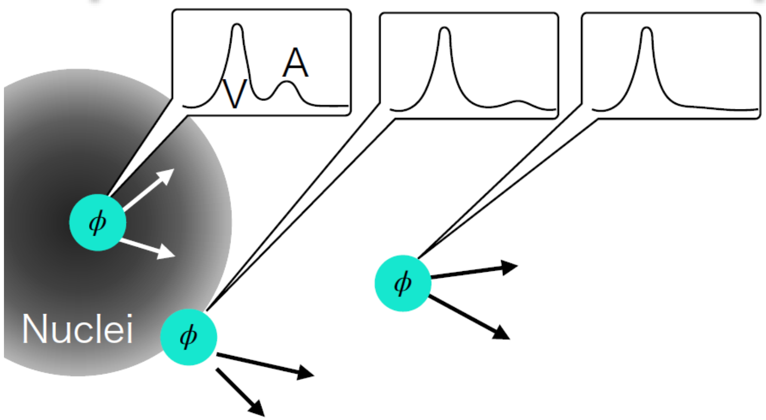


Run 1 (Dec 2024):
15k ϕ mesons
Run 2 (?):
69k ϕ mesons

Dilepton production

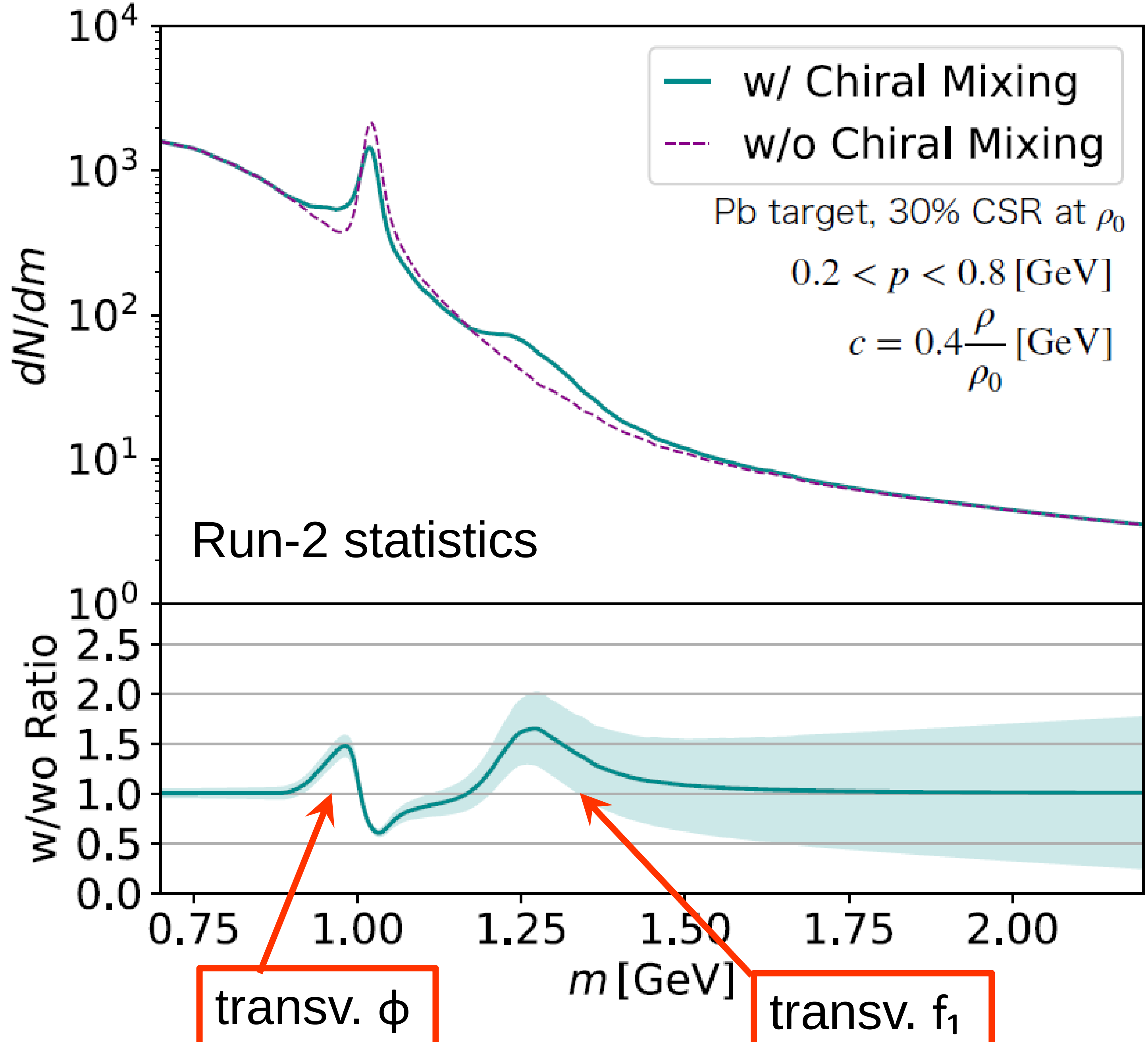
$$\mathrm{InvMassDist} = \int \left[\left[\int \mathrm{Im}G_V(s,p,\rho) \frac{dN}{d\vec{p}d\rho dt} \frac{d\vec{p}}{2p_0} d\rho dt \right. + \int \mathrm{Bkg}(s,p)dp \right] g(m-s)ds$$

Spectral Fx Kinematic dist Background Detector responce



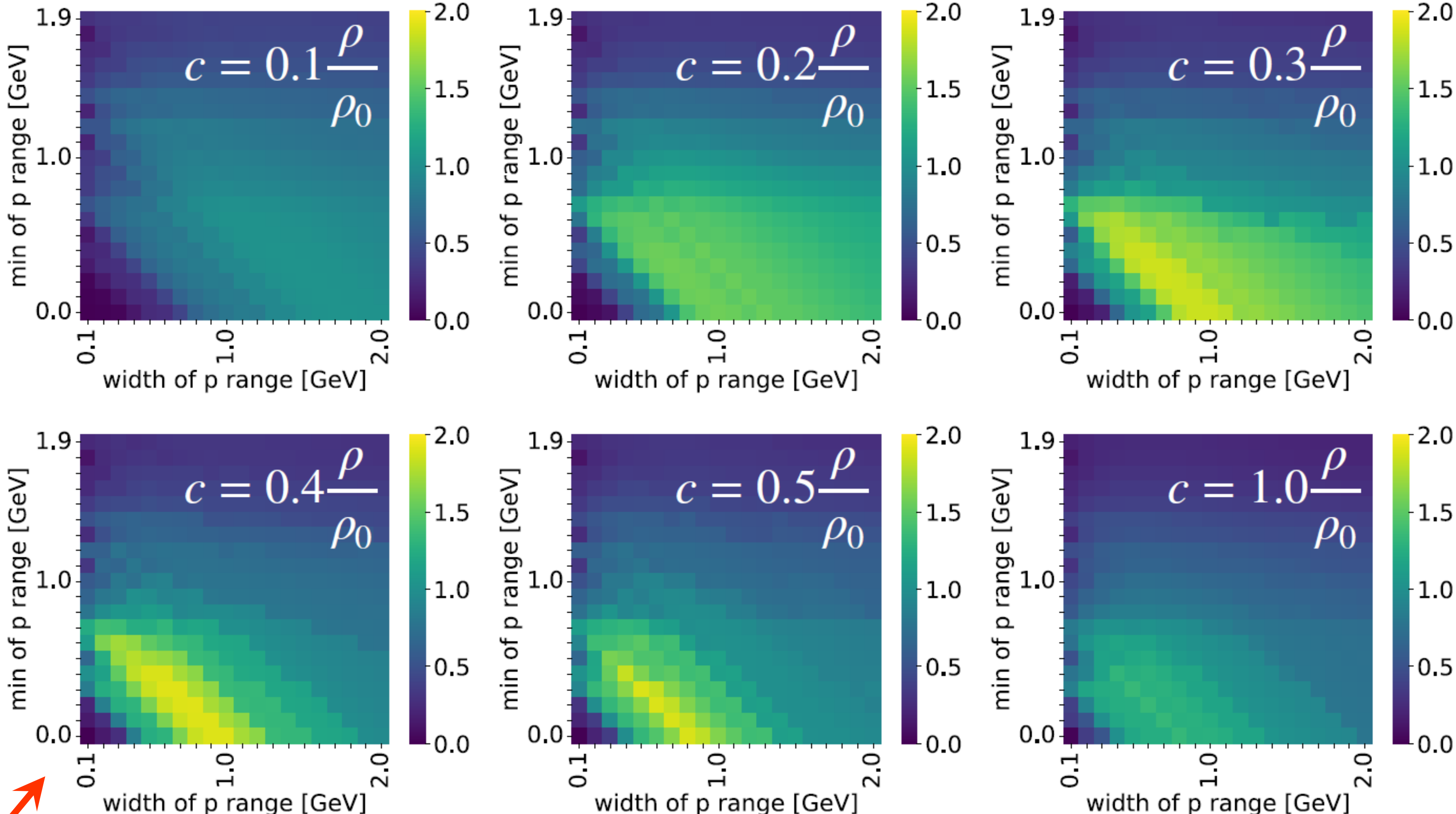
PHSD for p+Pb at 30 GeV

Simulated by JAM & Geant4:
π^0 Dalitz
$\pi^{\pm}$&γ conversion
combinatorial



w/ Chiral Mixing
w/o Chiral Mixing
Pb target, 30% CSR at ρ_0
$0.2 < p < 0.8$ [GeV]
$c = 0.4\frac{\rho}{\rho_0}$ [GeV]
Run-2 statistics
dN/dm
w/wo Ratio
m [GeV]
10^0
10^1
10^2
10^3
10^4
0.0
0.5
1.0
1.5
2.0
2.5
0.75
1.00
1.25
1.50
1.75
2.00
transv. ϕ
transv. f_1

Statistical significance



p: 0.2 – 0.8 GeV

Signatures with ≈ 2σ

SUMMARY

Final remarks

- Parity doubling of hadrons as signatures of chiral symmetry restoration in a medium
- Density-induced chiral mixing in cold dense matter
  - Estimated signatures at J-PARC E16 experiment (p+Pb) via dilepton production
  - Run-2 adequate

BACKUP

Vector-current correlator

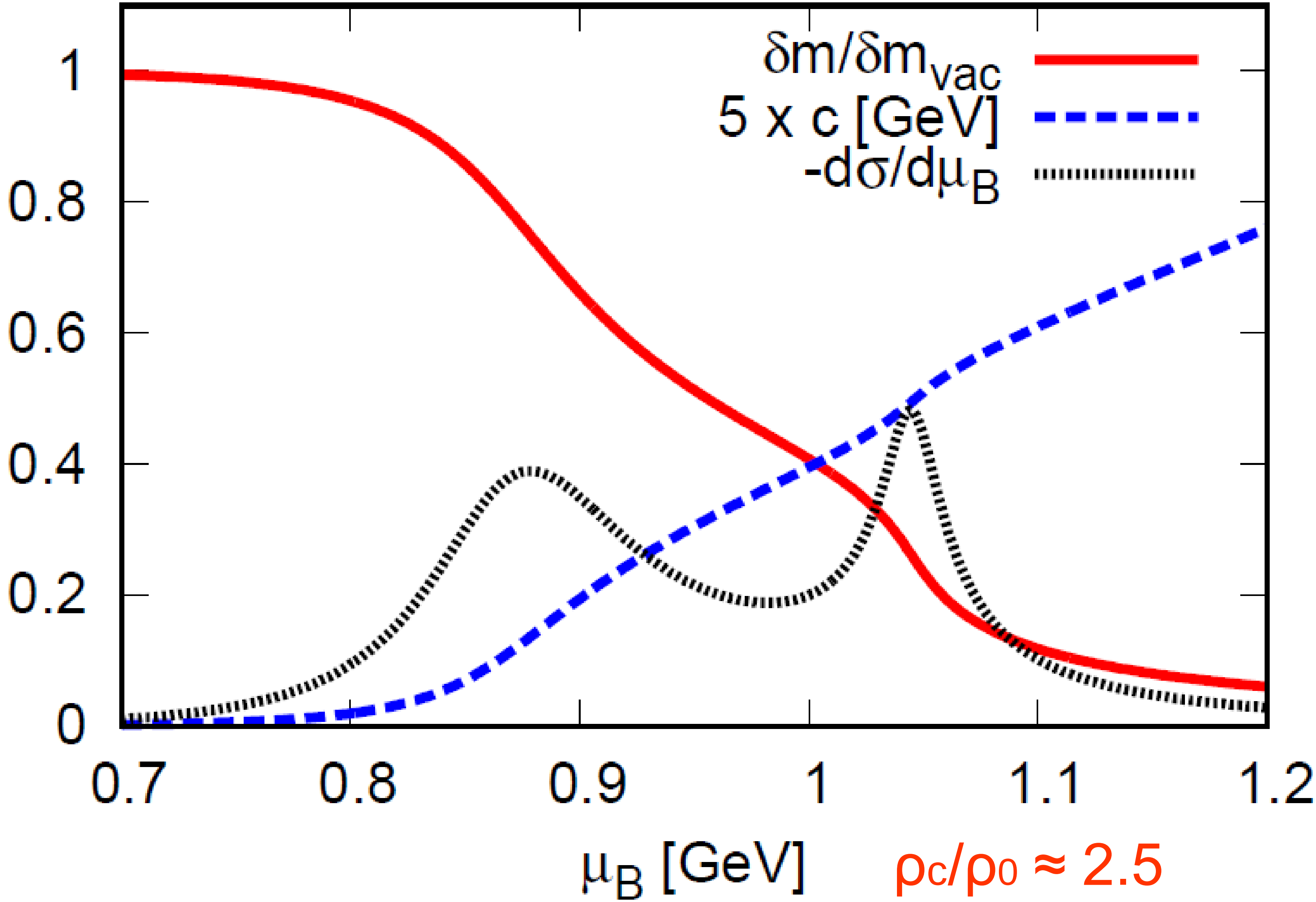
$$G_V^L = \left(\frac{g_\rho}{m_\rho}\right)^2 \frac{-s}{D_V}, \quad G_V^T = \left(\frac{g_\rho}{m_\rho}\right)^2 \frac{-sD_A + 4C^2\bar{p}^2}{D_V D_A - 4C^2\bar{p}^2},$$

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

- 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→ρπ) + δΓ(f_pi) → Γ_ρ

Mass difference vs. mixing : T=50 MeV



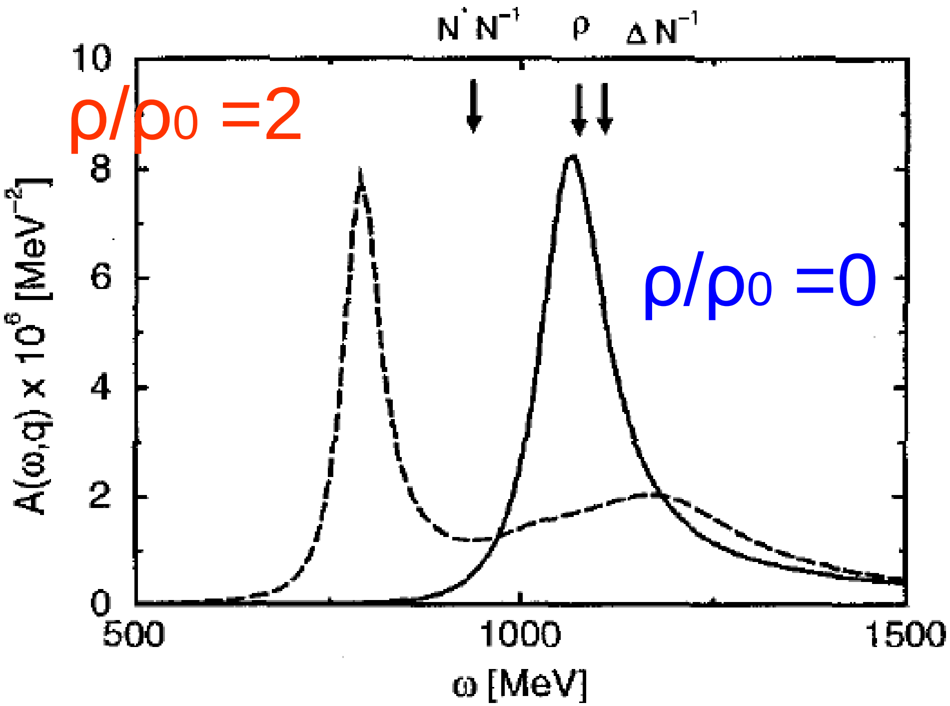
$\rho_c/\rho_0 \approx 2.5$

Baryon resonances in ρN 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]	$(\frac{f^2_{\rho BN}}{4\pi})_{est}$	$(\frac{f^2_{\rho BN}}{4\pi})_{fit}$	[illegible] [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

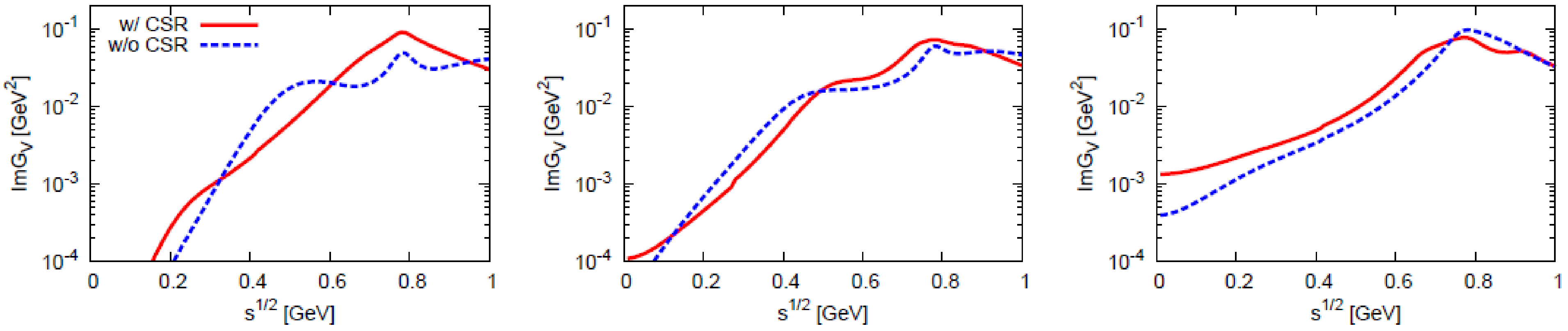
← γA reaction data

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

[Rapp, et al. (98)]

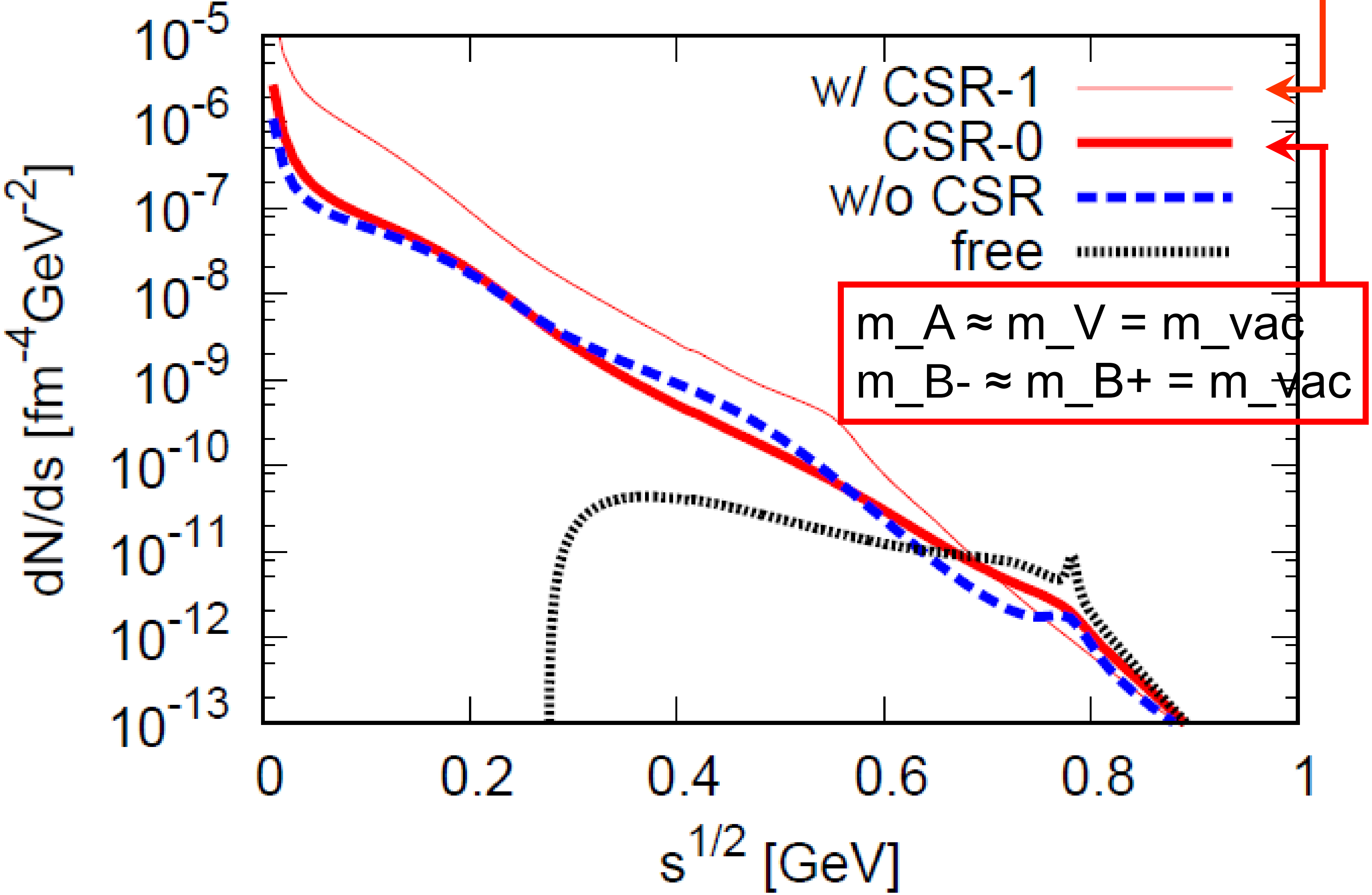
Spectral function of ρmeson

- At chiral crossover with p = 0.1, 0.5, 1.0 GeV
- S-wave vs. p-wave states
- CSR (m_- → m_+) vs. no CSR (m_- ≠ m_+)



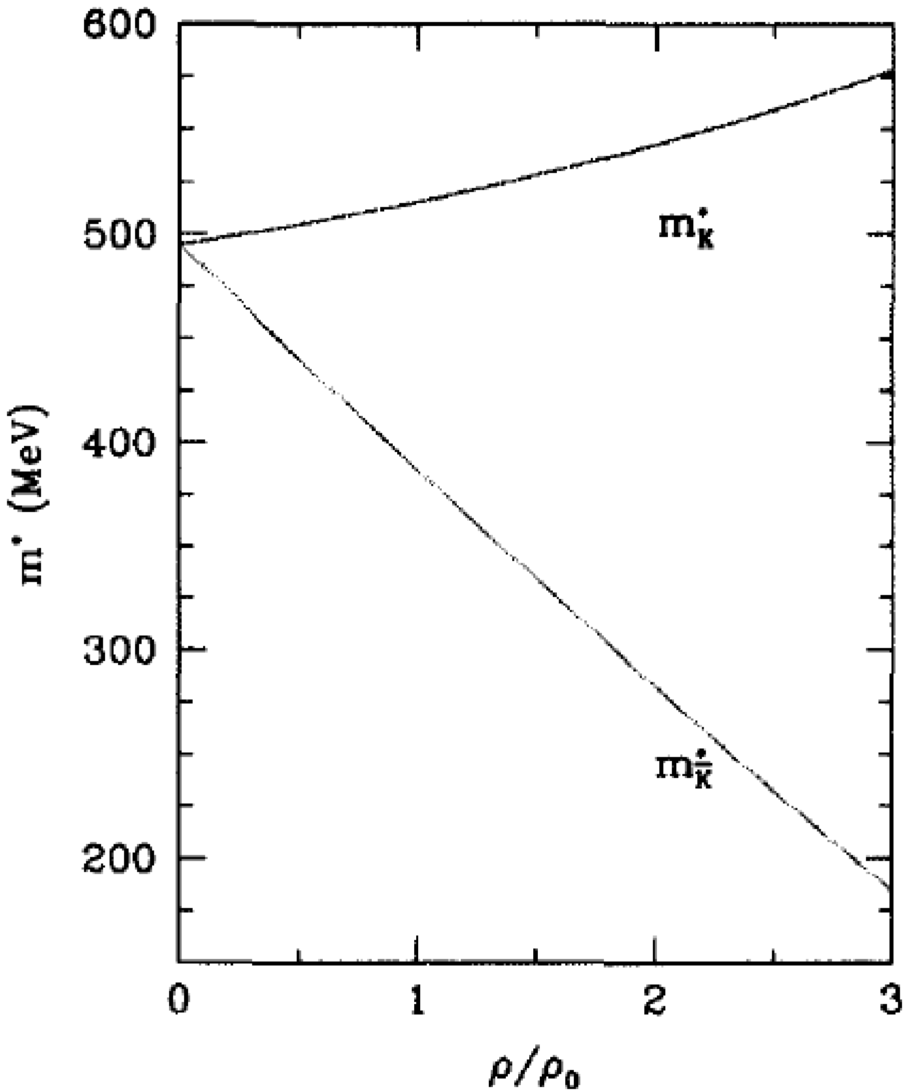
[Kim, Lee ('21): QCDSRs, mrho = 500-600 MeV]

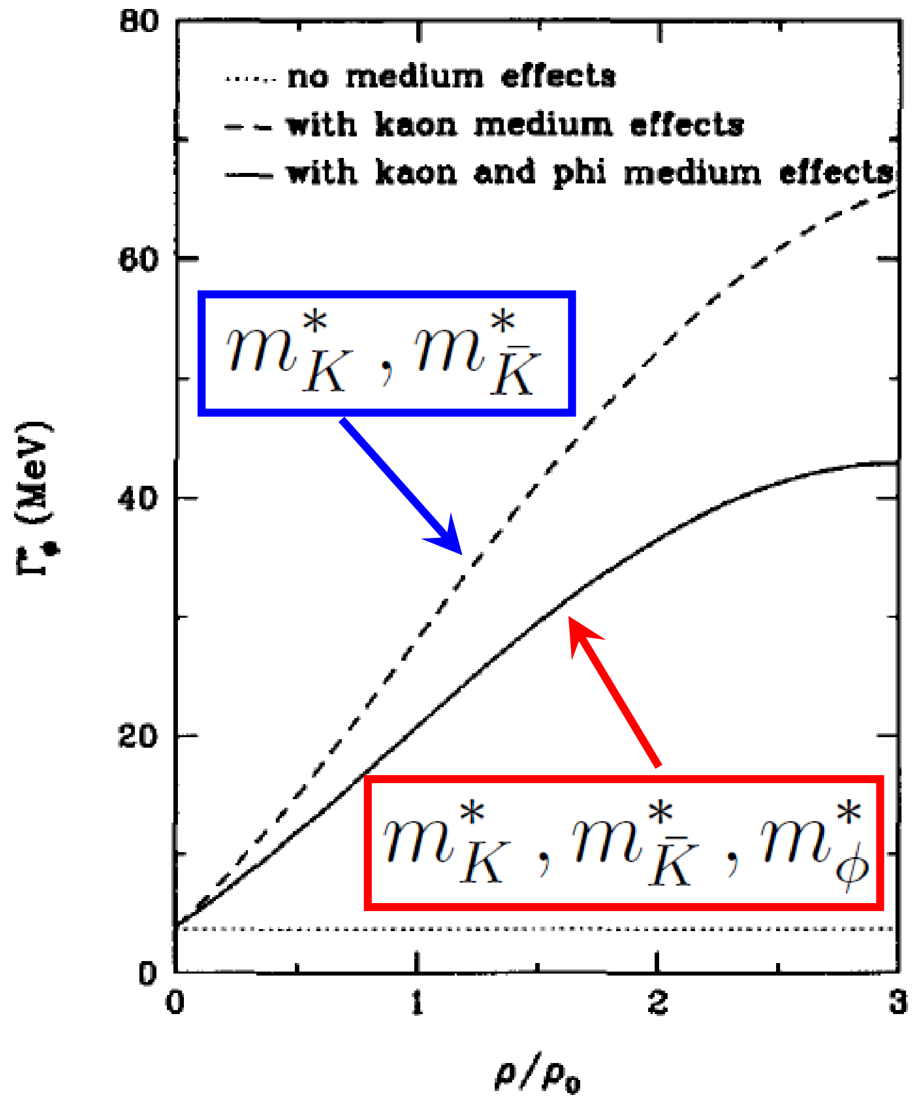
Signals diminished by p-wave states



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

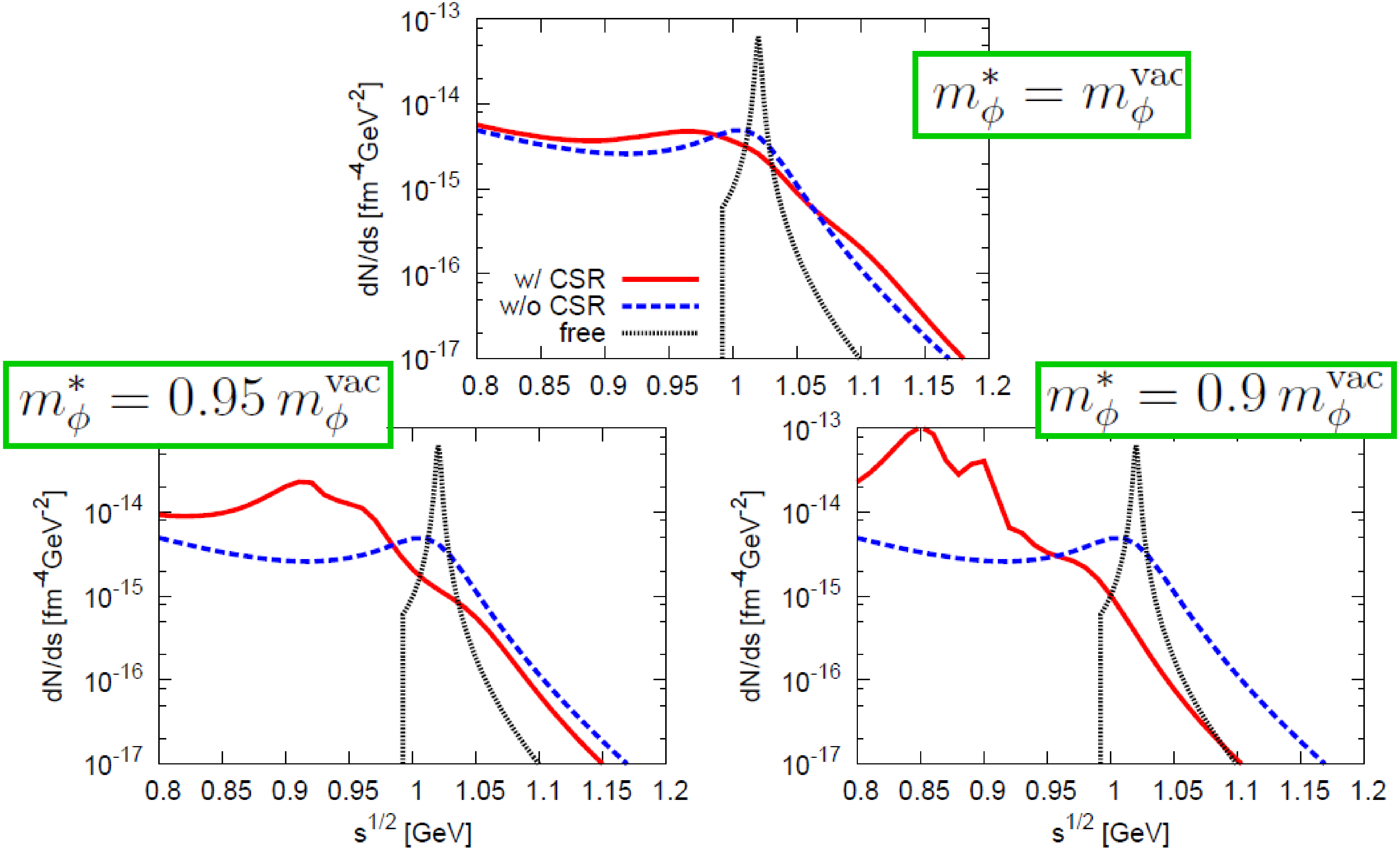
Kaon and anti-kaon





Int.over p > 0.5 GeV

Dilepton rates at T=50 MeV



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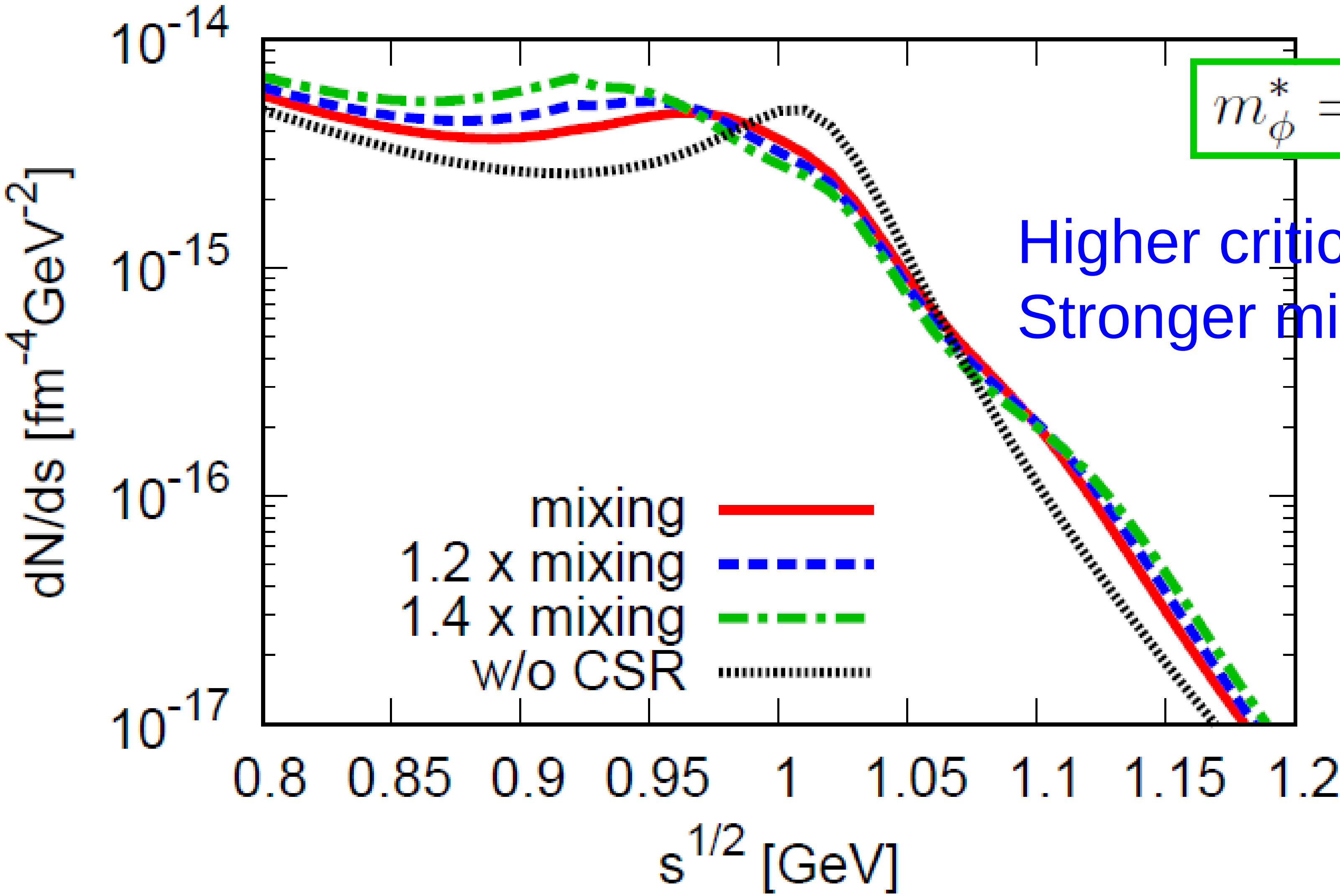

Higher critical ρ?
Stronger mixing?