The Physics of Parity-Doublet Nucleons in Dense Matter

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Outline

- Toward the observation of partial restoration of chiral sym via chiral mixing at J-PARC

  with R. Ejima, P. Gubler & K. Shigaki

- Superfluids of nucleon parity-doublet in neutron stars

  with S. Yasui & M. Nitta

Ref. Ejima, Gubler, Sasaki and Shigaki, paper in preparation

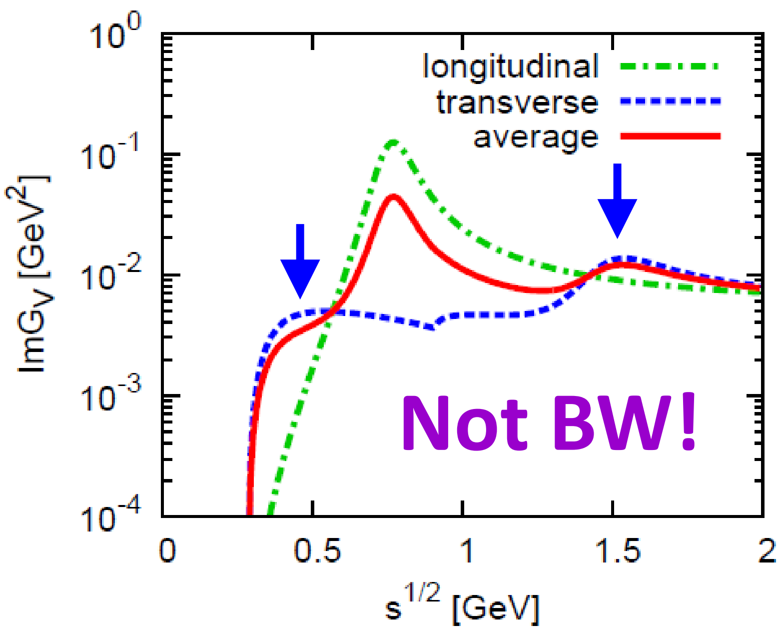
OBSERVING CHIRAL MIXING AT J-PARC E16

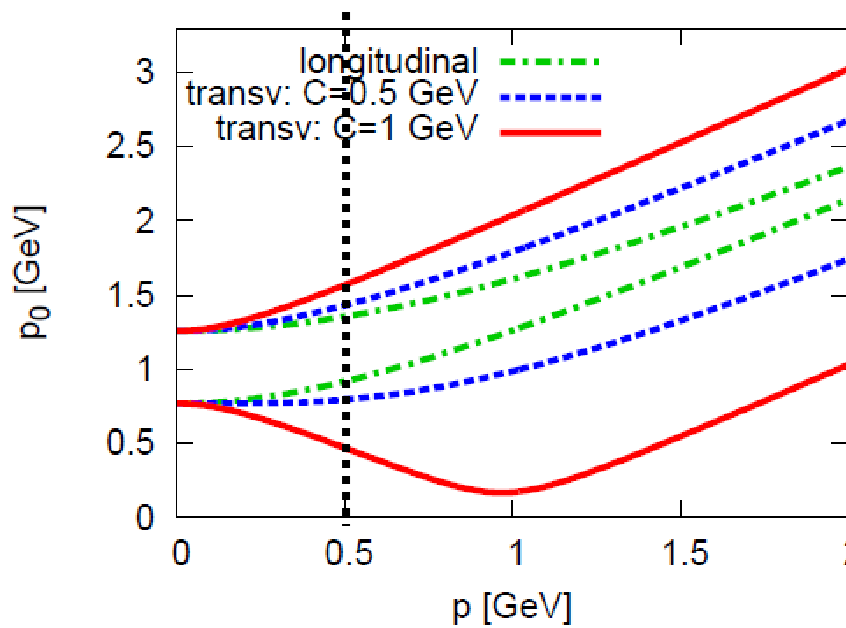
[Domokos, Harvey ('07)]

Direct V-A mixing at finite μB

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

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





φ meson in nuclear matter

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

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

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

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

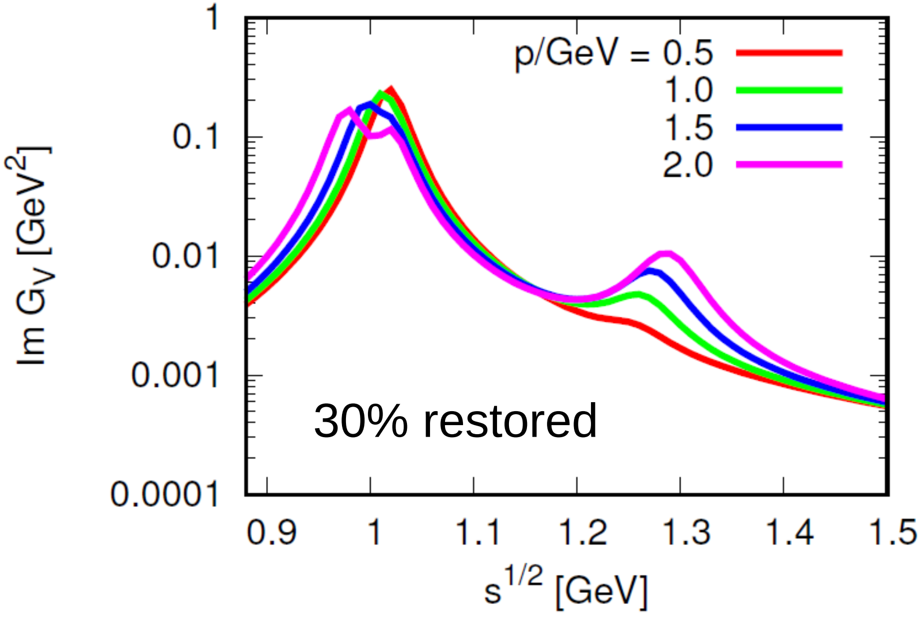
- Li, Lee, Brown (97): kaon production in Ni+Ni at 1 & 1.8 A GeV

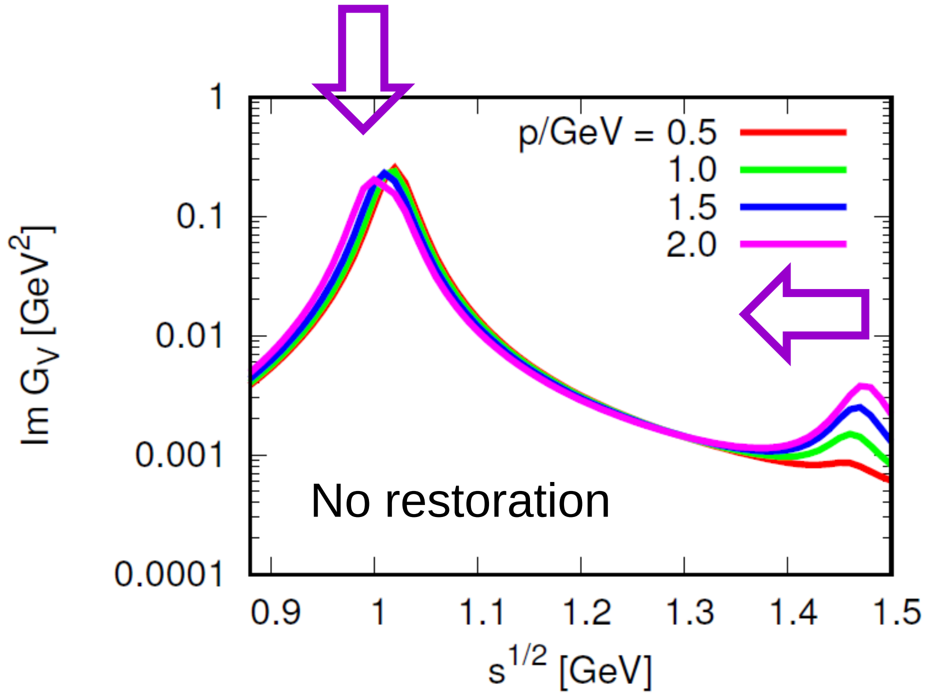
$a_K \approx 0.22\ \mathrm{GeV}^2\ \mathrm{fm}^3$ and $a_{\bar{K}} \approx 0.45\ \mathrm{GeV}^2\ \mathrm{fm}^3$

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

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

ϕ meson in nuclei



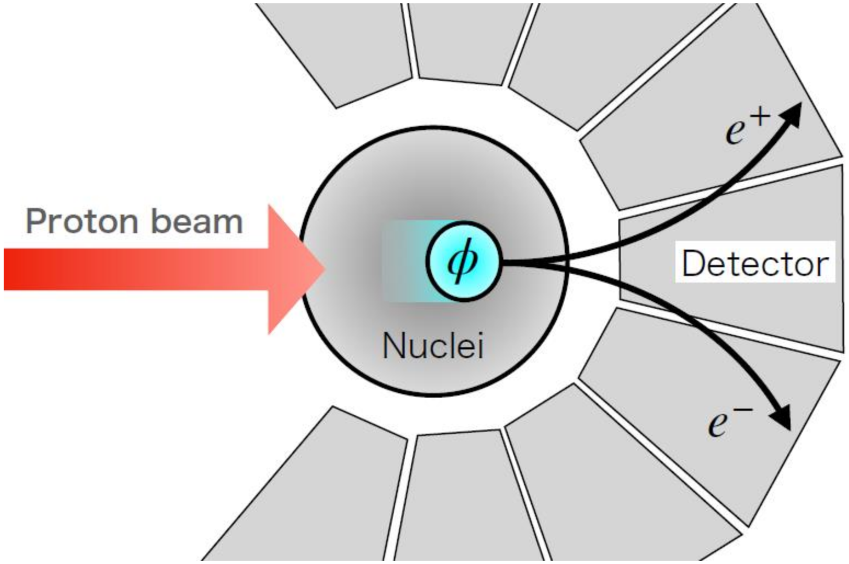


✓ Strong evidence of partial (~30%) restoration in pionic atoms [Nishi et al., Nature Physics, 2023]

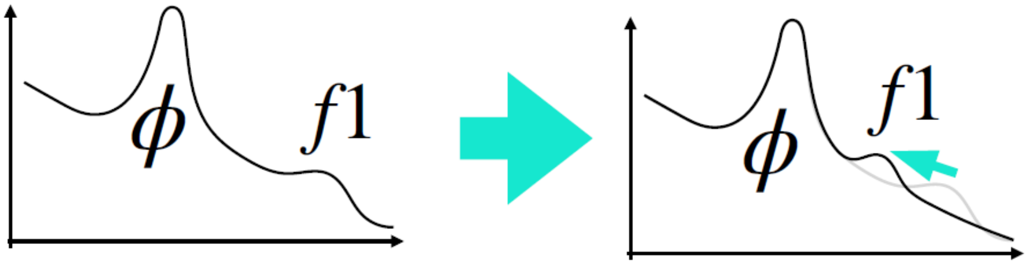
❑ Density-induced chiral mixing in broken phase

❑ 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

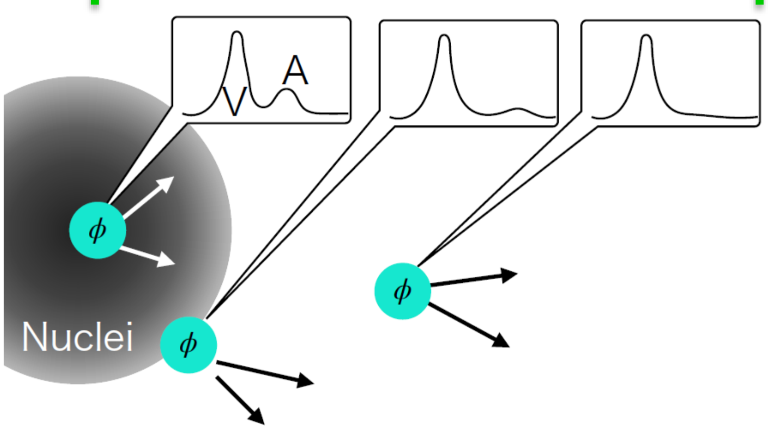


Run 1 (Dec 2024):
15k ϕ mesons
Run 2 (?):
69k ϕ mesons

Dilepton production

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

Spectral Fx   Kinematic dist   Background   Detector responce

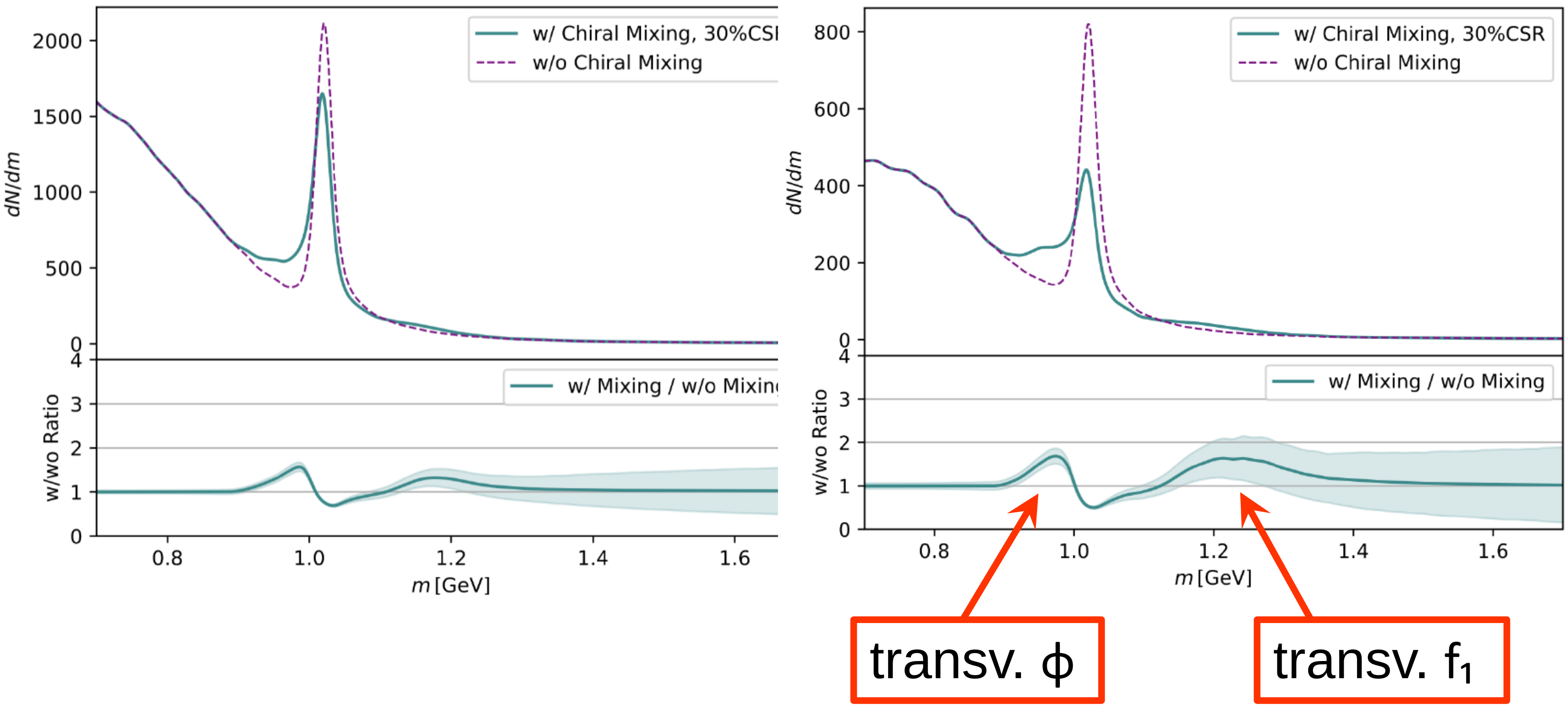


PHSD for p+Pb at 30 GeV

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

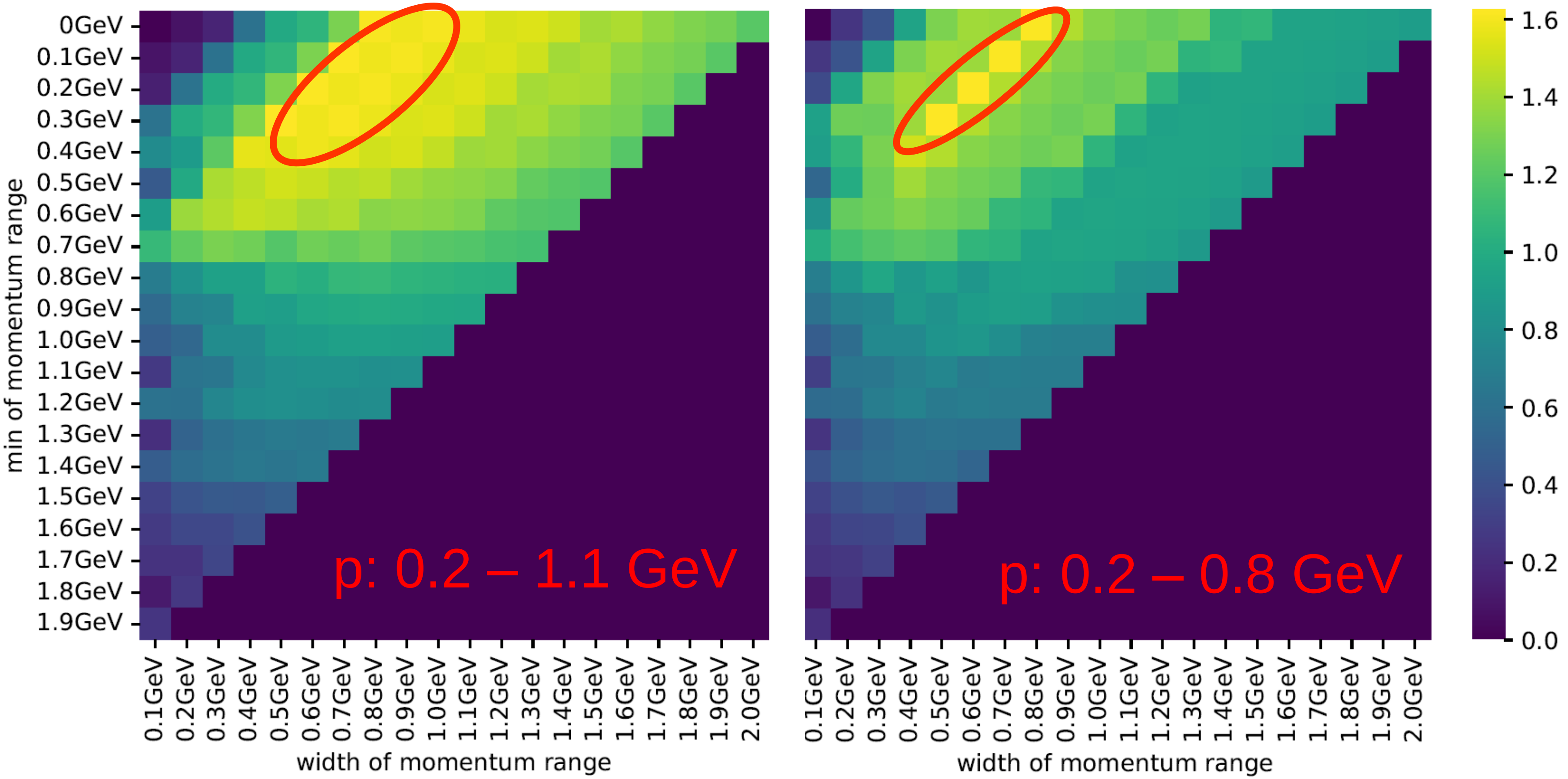
Dilepton production

p+Pb, Run-2 statistics, c = 0.2, 0.5 GeV at ρ_0



Dilepton production

c = 0.2 GeV at ρ_o c = 0.5 GeV at ρ_o



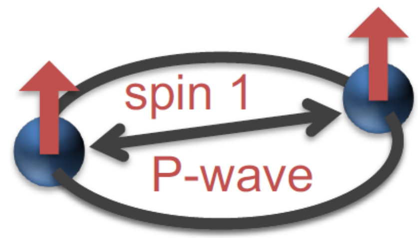
Signatures with < 1σ

Ref. Yasui, Nitta and Sasaki, in preparation

SUPERFLUID IN NEUTRON STARS

Superfluidity in neutron stars

- ❑ s-wave superfluid by $^1S_0$ [Migdal, '60]
- ❑ p-wave superfluid by $^3P_2$ at $\rho/\rho_0 > 1/2$ [Tabakin, '68]
  - ✓ Pulser glitches
  - ✓ Rapid cooling



$^{2S+1}L_J$

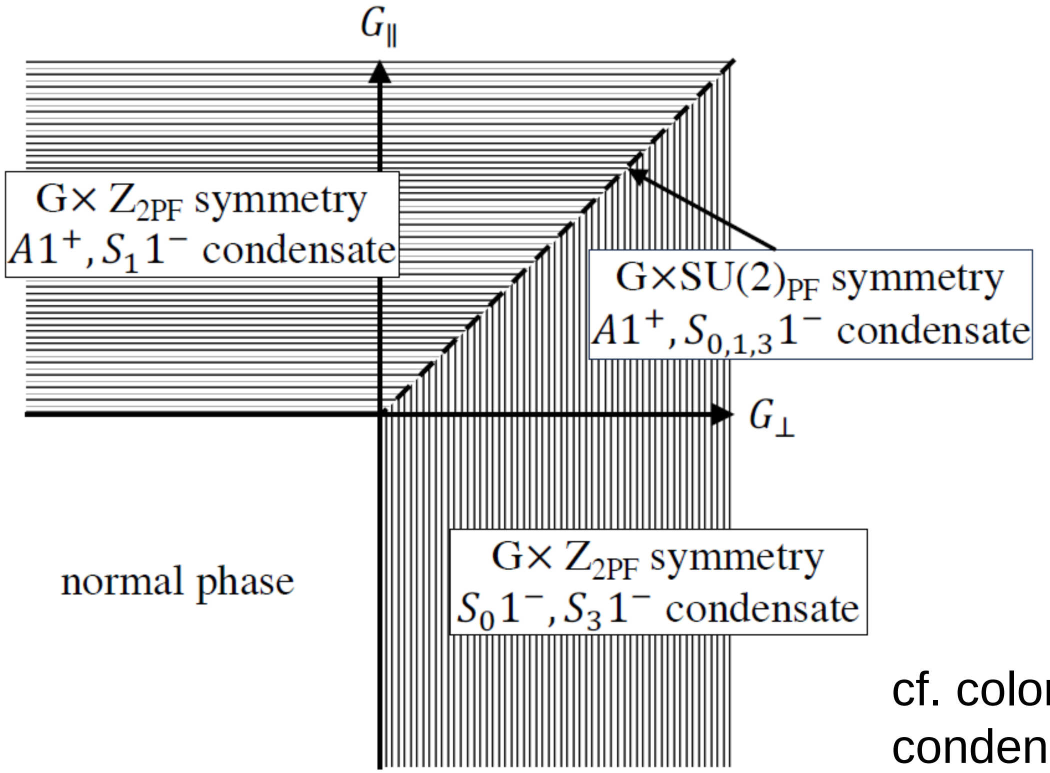
S: spin
L: angular momentum
J: spin+angular momentum

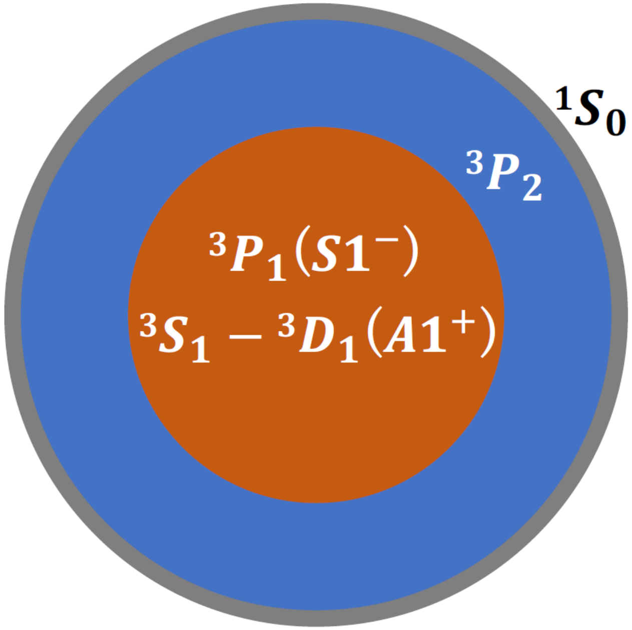
- ❑ This study: Cooper pairing of neutron parity-doublet at high density → the role of N*
  - Extended chiral sym G such that G ⊃ naïve&mirror
    $$G = U(1)_{1L} \times U(1)_{1R} \times U(1)_{2L} \times U(1)_{2R}$$
  - $\psi_1 \leftrightarrow \psi_2$ symmetry? Extra Z_2 or SU(2) introduced
  - Common operators to the naïve & mirror assign.

Phase diagram

Cooper pairings: NN, NN*, N*N*

- Phase structure: two vector-type condensates



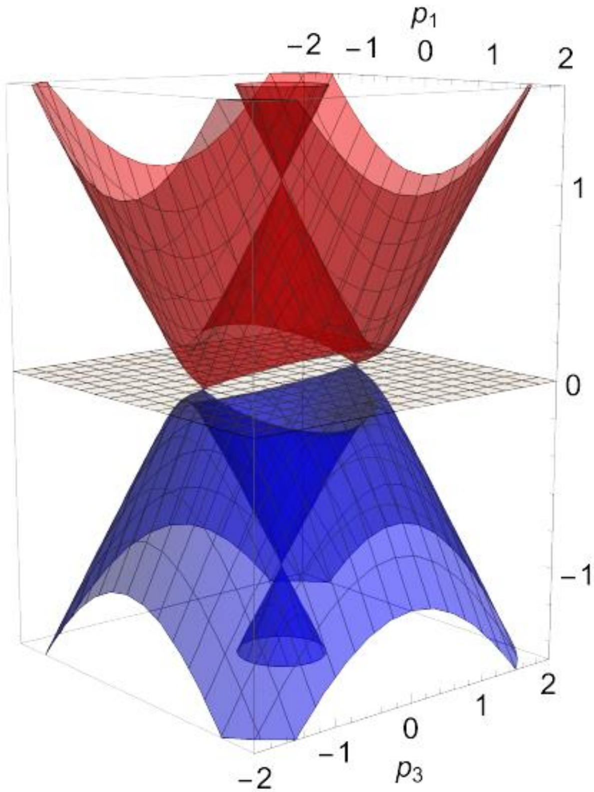


cf. color-spin locking by spin-1 diquark condensate in Nf=2 quark matter

Aguilera et al., 2005

Dirac points

- Spatial anisotropy → both rotational & chiral sym. broken → type-II NG mode



cf. type-I NG mode in ordinary matter

$$\vec{\delta} = (0,0,\delta)$$

Dirac points at $p_3 = \pm\sqrt{\mu^2 + \delta^2}$

$$\varepsilon_q \cong \sqrt{\frac{q_1^2 + q_2^2}{1 + \frac{\mu^2}{\delta^2}} + q_3^2}$$

- Propagation along 1&2 directions in v << c=1
- Propagation along 3 direction in v = c =1

→ Anisotropy in transport phenomena, NS cooling

SUMMARY

Final remarks

Parity doubling of hadrons as signatures of chiral symmetry restoration in a medium

❑ Density-induced chiral mixing

- Estimated signatures at J-PARC E16 experiment (p+Pb) via dilepton production, Run-2 adequate

❑ Superfluidity in neutron stars

- 2 kinds of vector condensates, strong anisotropy, type-II NGB
- Specific in mirror scenario? Vortices? QM?

BACKUP

Vector-current correlator

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

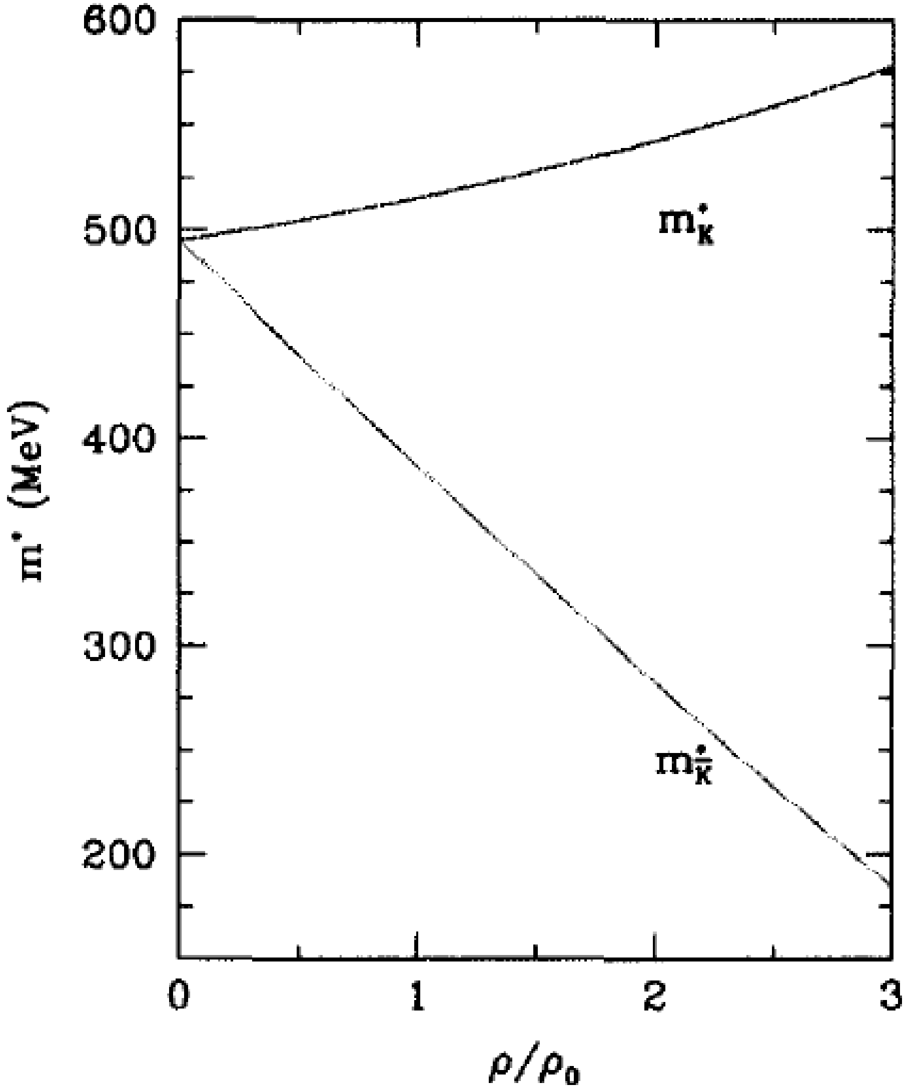
$$D_{V,A} = s - m_{\rho,a_1}^2 + i m_{\rho,a_1}\Gamma_{\rho,a_1}(s),$$

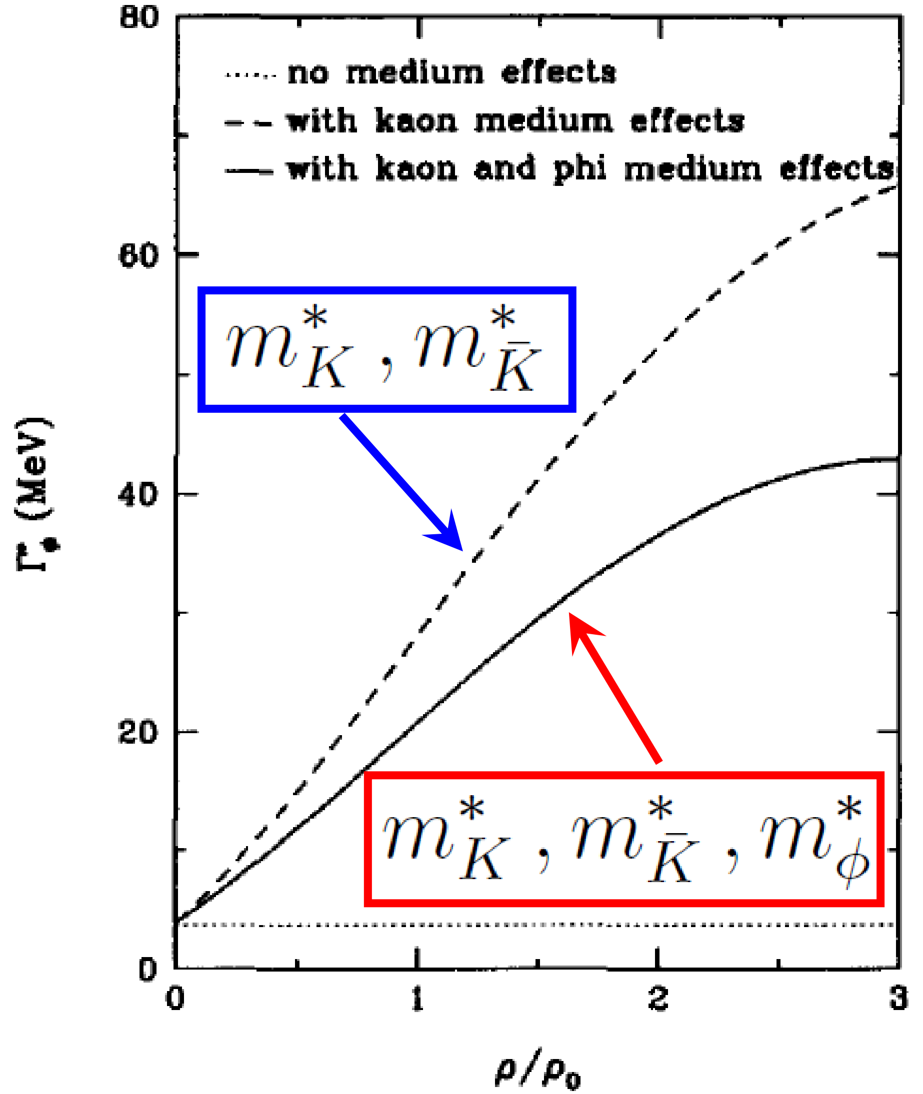
- m and Γ: ***in-medium*** masses and widths
- Strategy of an illustrative computation:
  - Modify only mass and width of axial-vector states.
  - Set G_A equal to G_V at CSR, according to

    Γ_a1 = Γ(a1→ρπ) + δΓ(f_pi) → Γ_ρ

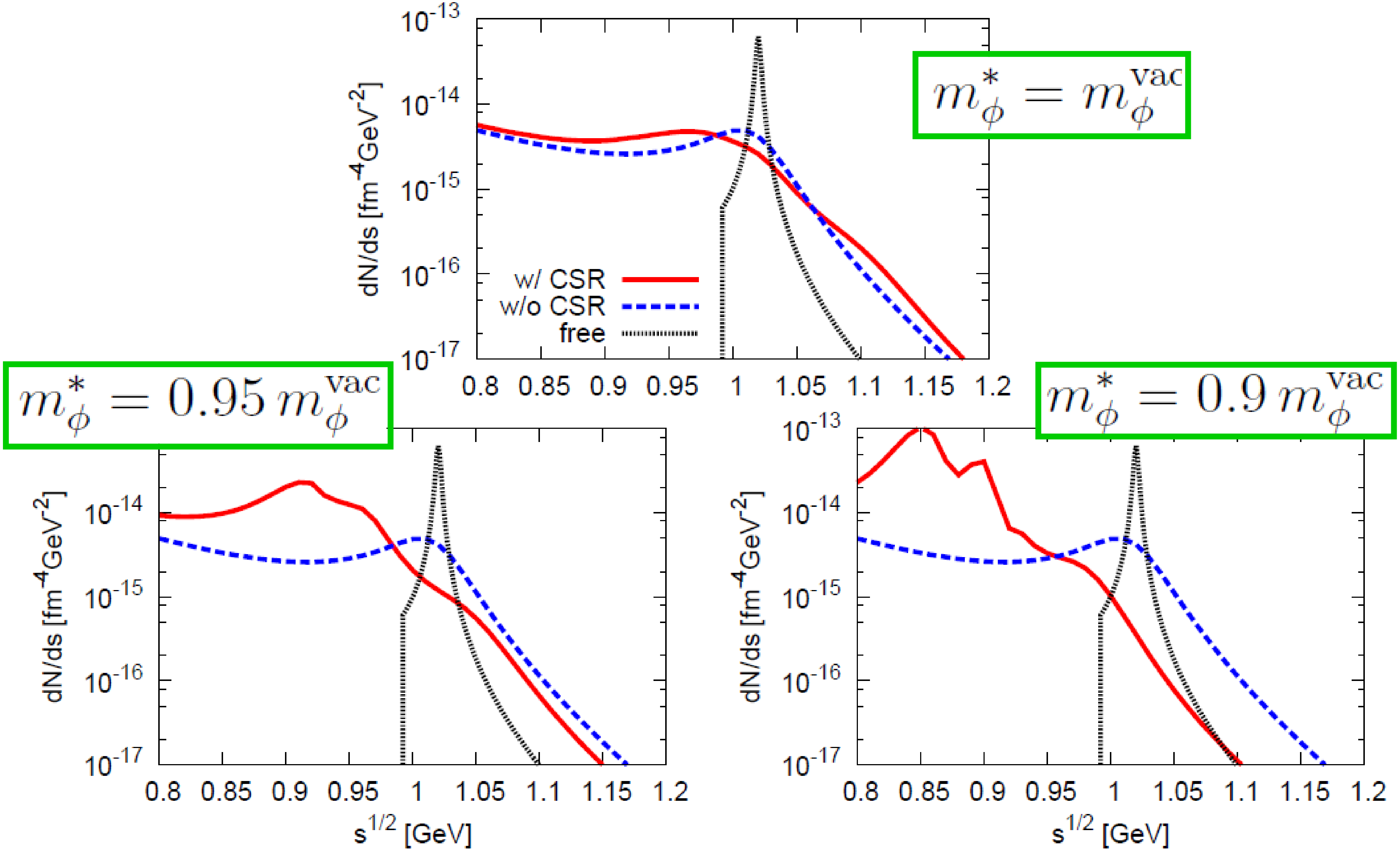
[Li, Lee, Brown (97)] [Chung, Ko, Li (98)]

Kaon and anti-kaon



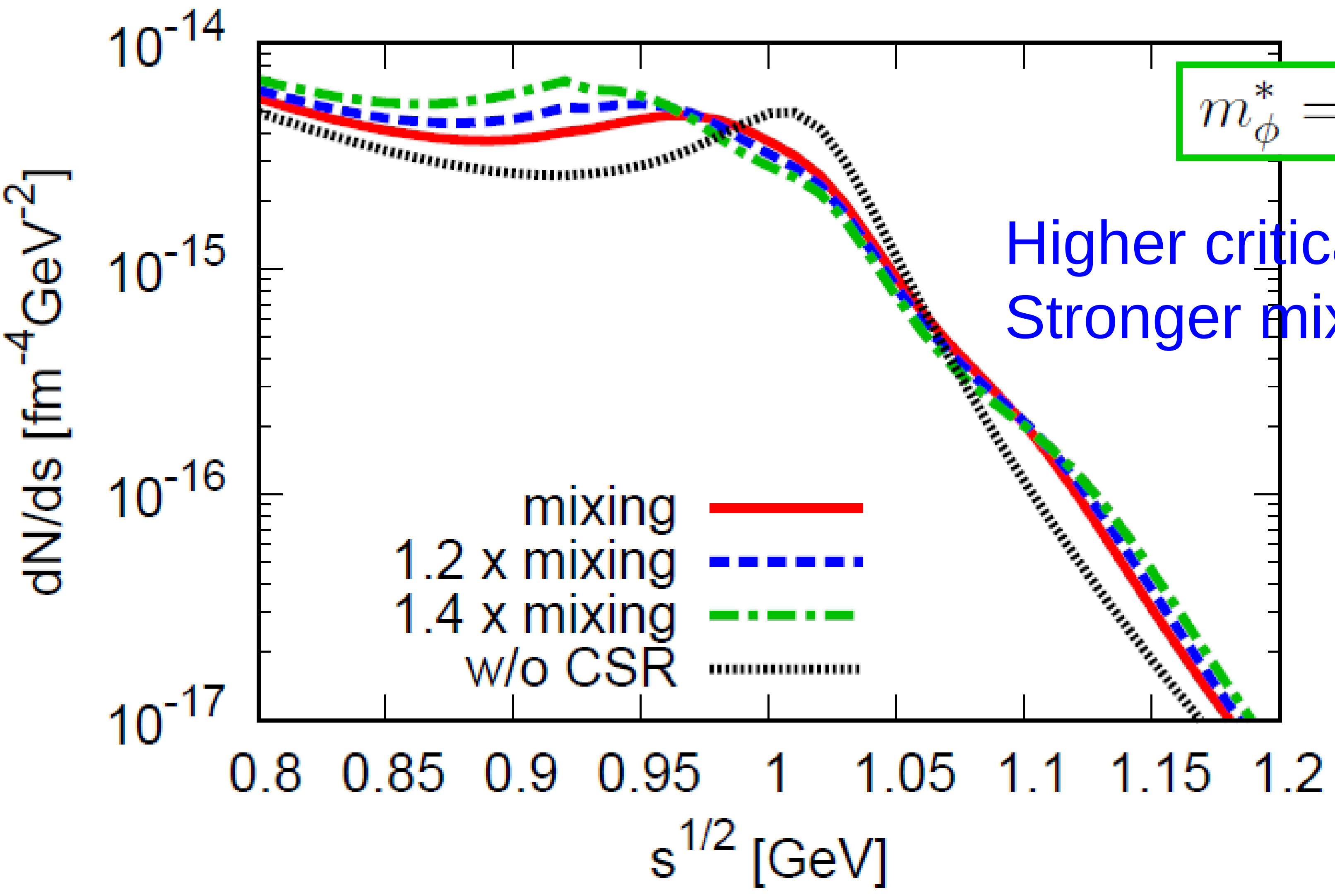


Dilepton rates at T=50 MeV



Int.over p > 0.5 GeV

Dilepton rates at T=50 MeV



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

Higher critical ρ?
Stronger mixing?