

# Fate of the $\rho - a_1$ mixing in dilepton production

A. Sakai et al., [arXiv:2308.03305](https://arxiv.org/abs/2308.03305)



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JAEA<sup>D</sup>, Hiroshima Univ. WPI-SKCM2<sup>E</sup>, University of Wroclaw<sup>F</sup>

# Outline

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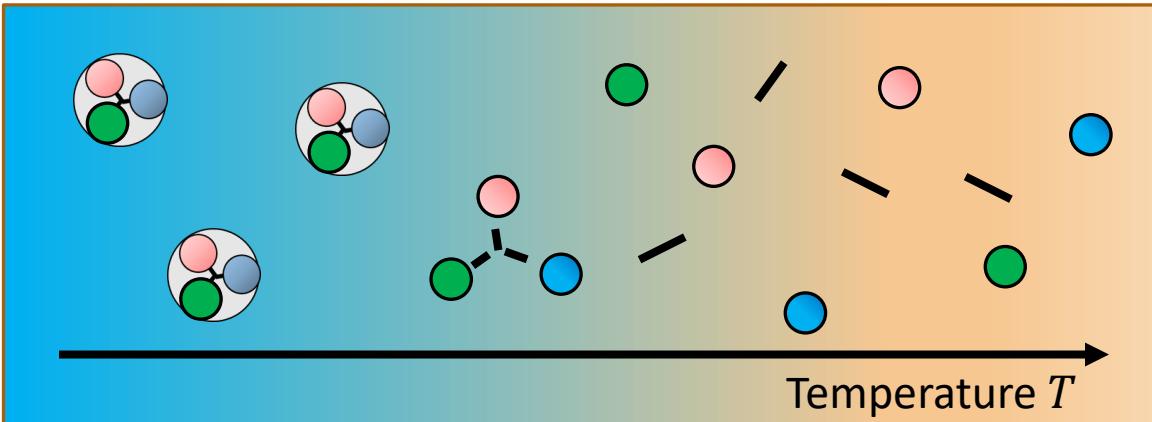
- Introduction
- Model
- Results
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# Probing the chiral symmetry restoration



## Hadron

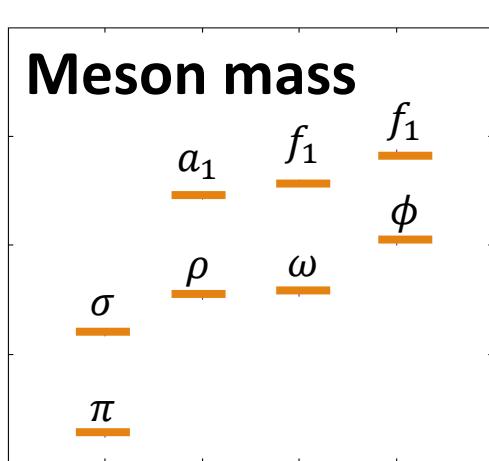
Chiral Symmetry Breaking

High temperature

QCD phase transition

## Quark gluon plasma (QGP)

Chiral Symmetry Restoration



Chiral partner:  
Same spin  
Opposite parities

**Signatures of chiral symmetry restoration**  
→ Degeneracy of the masses of chiral partners  
→  $\rho - a_1$  mixing

# Chiral mixing of $\rho$ and $a_1$ at low temperature

## Low-temperature “mixing theorem”

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

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

$$\epsilon = T^2/6f_\pi^2 \text{ valid for } \epsilon \ll 1$$

$G_{V,A}$ : current correlators

M. Dey, V. L. Eletsky, B. L. Ioffe, Phys. Lett. B 252, 620 (1990)

## Extrapolation to high temperature

→ Maximal mixing  $\epsilon = \frac{1}{2}$

False CSR

→ No mass degeneration

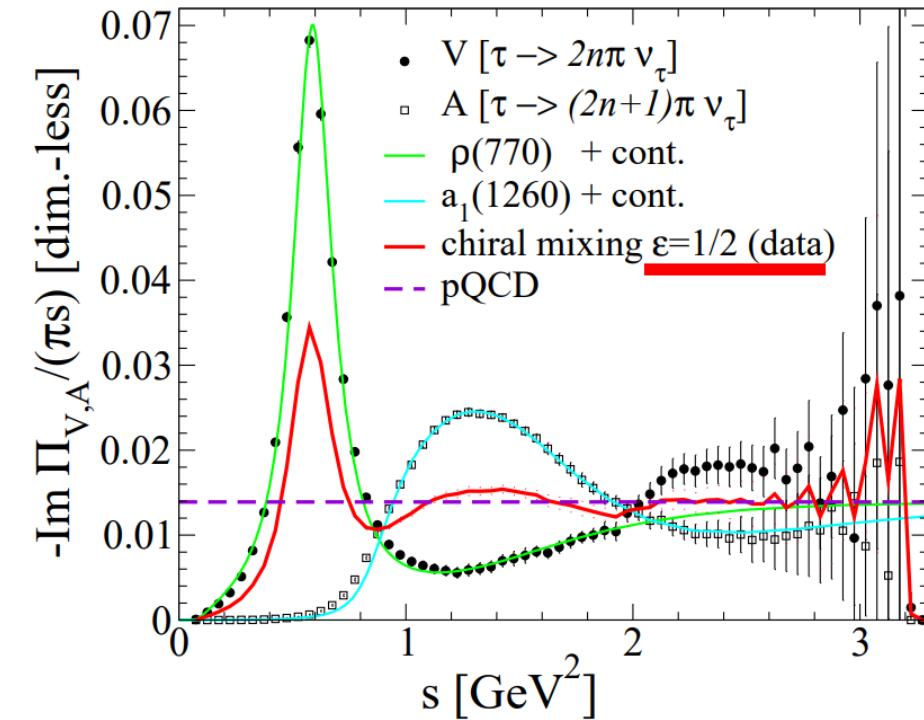


Fig. Spectral function

R. Rapp, Acta Phys. Polon. B 42, 2823 (2011)

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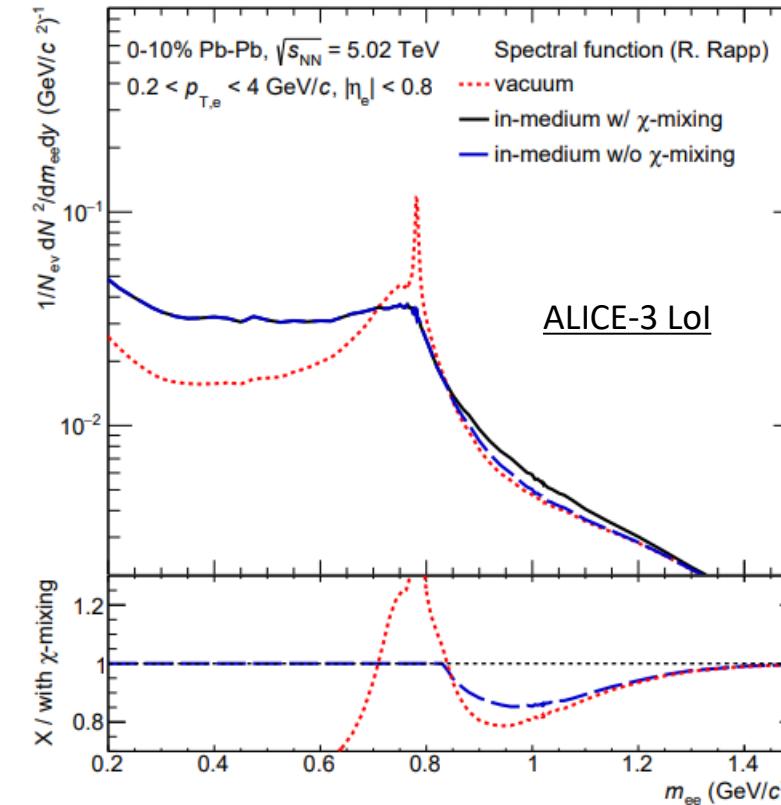


Fig. Thermal dilepton mass spectra

Increase the dilepton yield by 20-30%  
→ Overestimate?

# Chiral mixing of $\rho$ and $a_1$ at finite temperature

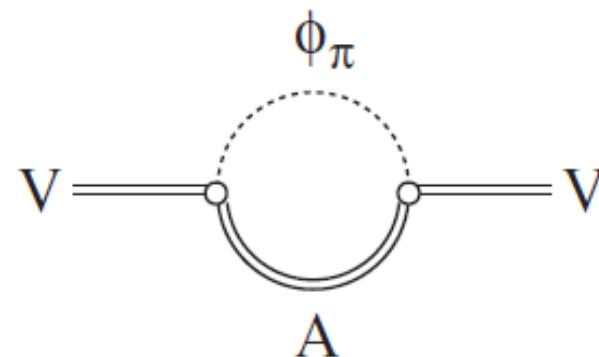
## Chiral perturbation theory with generalized hidden local symmetry (GHLS)

M. Harada, C. Sasaki, W. Weise, Phys. Rev D 78, 114003 (2008)

### Chiral mixing

Chiral Lagrangian

One loop calculation



### Chiral symmetry restoration:

Degenerate mass  $\delta M = m_\rho - m_{a_1} \rightarrow 0$

$\delta M = \text{const.}$  w/o CSR

$\delta M \rightarrow 0$  (dropping  $a_1$  mass)

w/ CSR

Chiral mixing vanishes ( $= 0$ )

# Dilepton production in heavy ion collisions

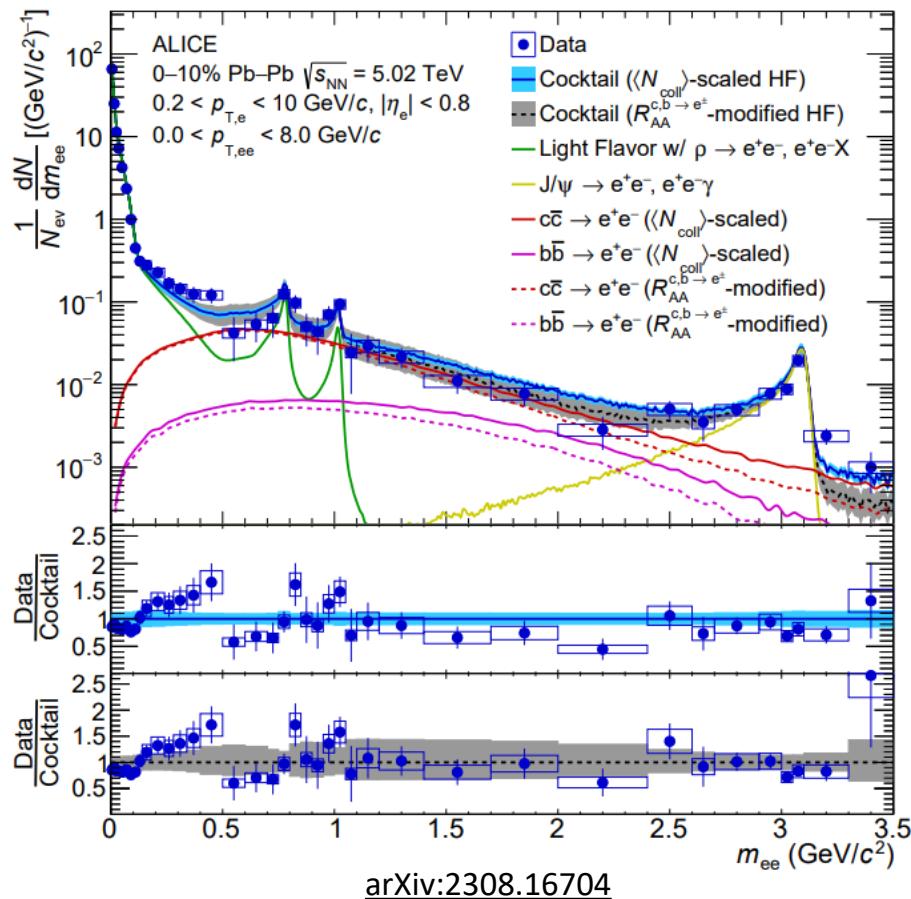


Fig. Invariant mass spectra

Lepton emitted at all stages of a collision

Observable:

Integrated over space-time evolution

Dynamical model:

Improvement in hydrodynamics

Upcoming measurements:

NA60+, CBM, ALICE 3

Purpose of study:

Study the effect of chiral symmetry restoration on dilepton invariant mass spectra

- **Spectral function (Chiral symmetry restoration)**
- **Hydrodynamic model**

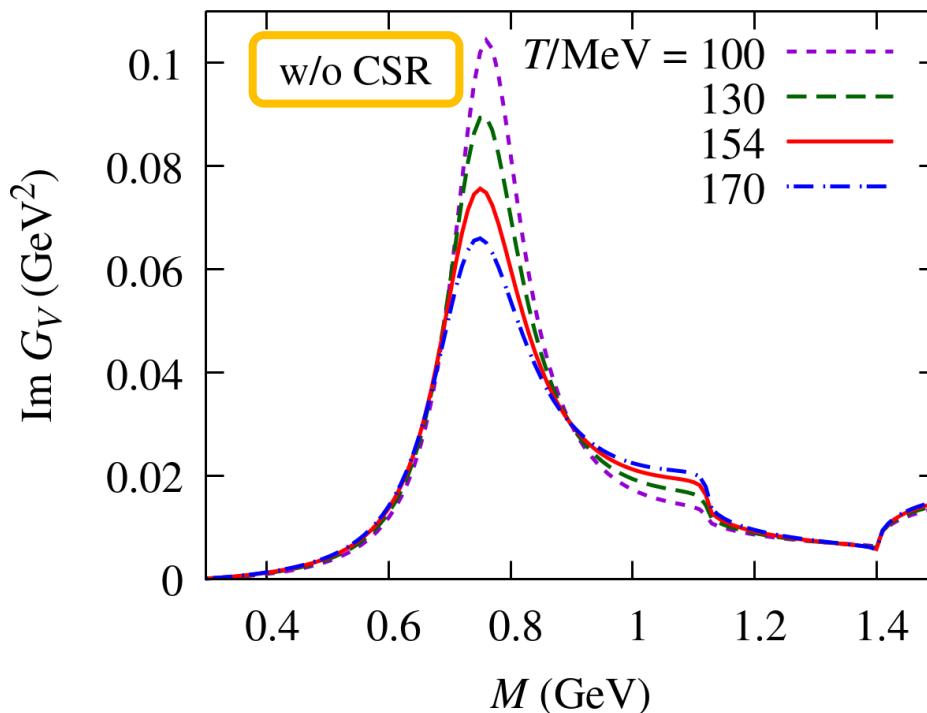
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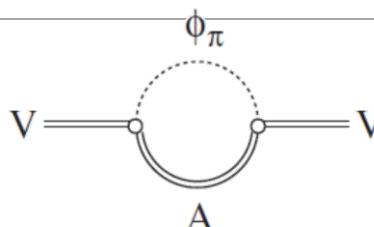
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# Model: Spectral function

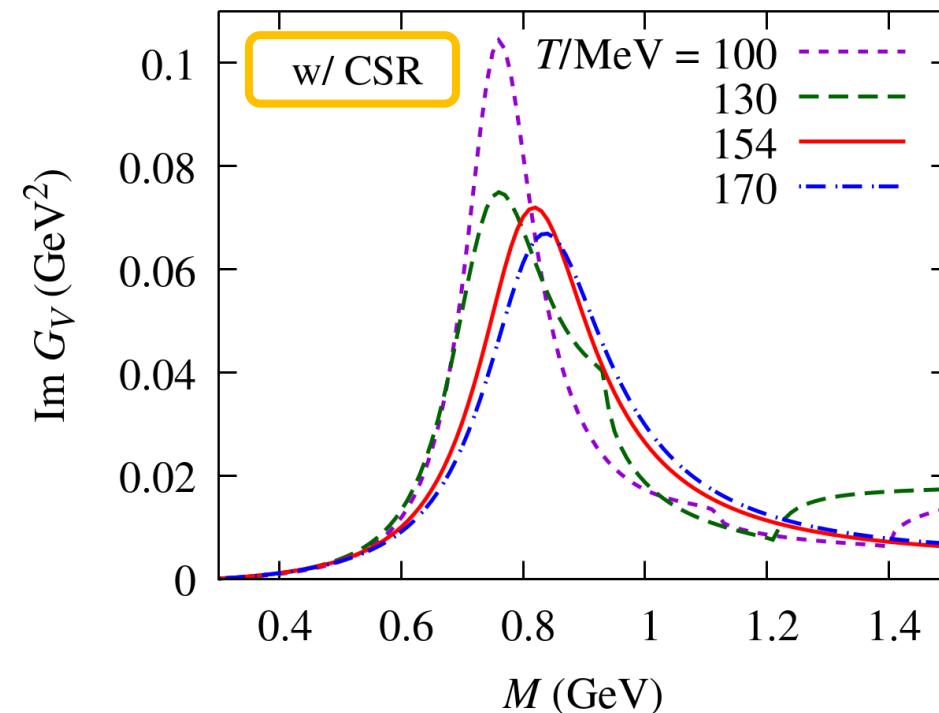
Chiral mixing: One loop calculation



Without chiral symmetry restoration:  
Constant  $\rho, a_1$  mass     $\delta M = \text{const.}$



Reactions:  $a_1 + \pi \rightarrow \rho, a_1 \rightarrow \rho + \pi$   
M. Harada, et al., Phys. Rev D 78, 114003 (2008)



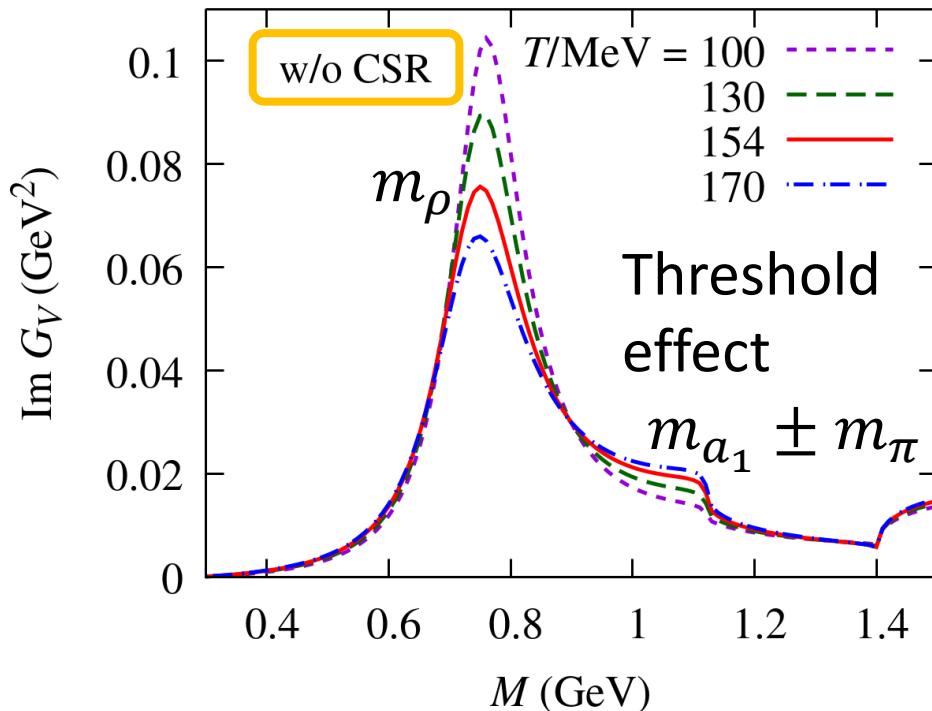
With chiral symmetry restoration:  
Dropping  $m_{a_1}$      $\delta M \sim 0$  at  $T_c = 154 \text{ MeV}$

Y. Aoki, et al., JHEP 06, 088 (2009)

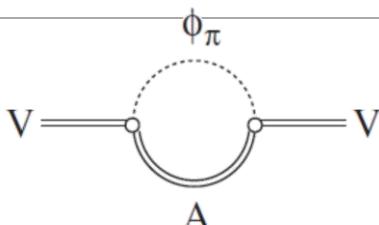
A. Bazavov, et al., Phys. Rev. D 85, 054503 (2012)

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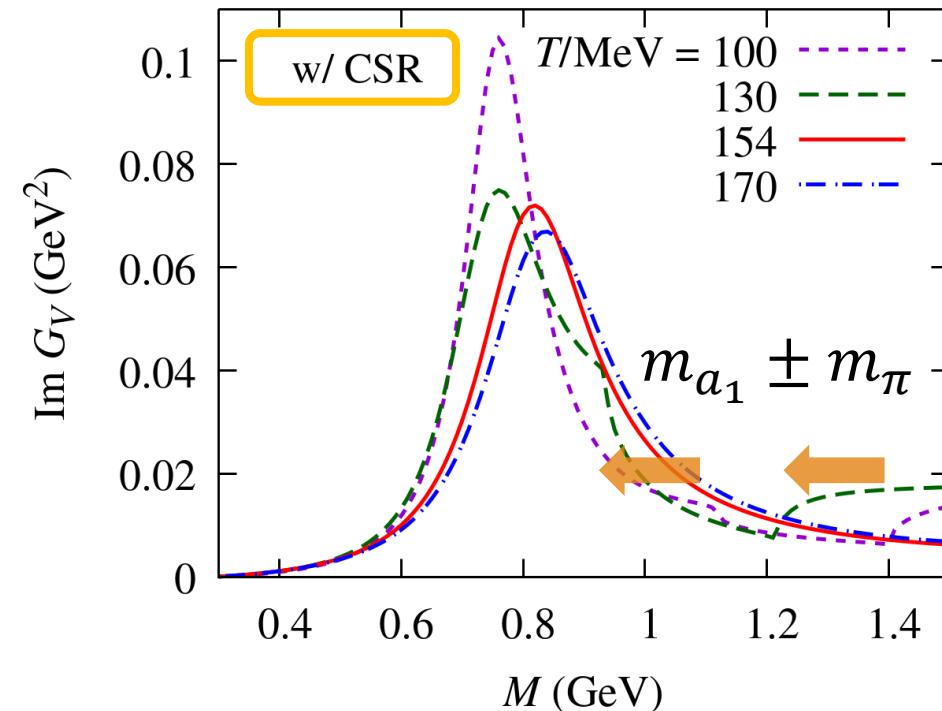
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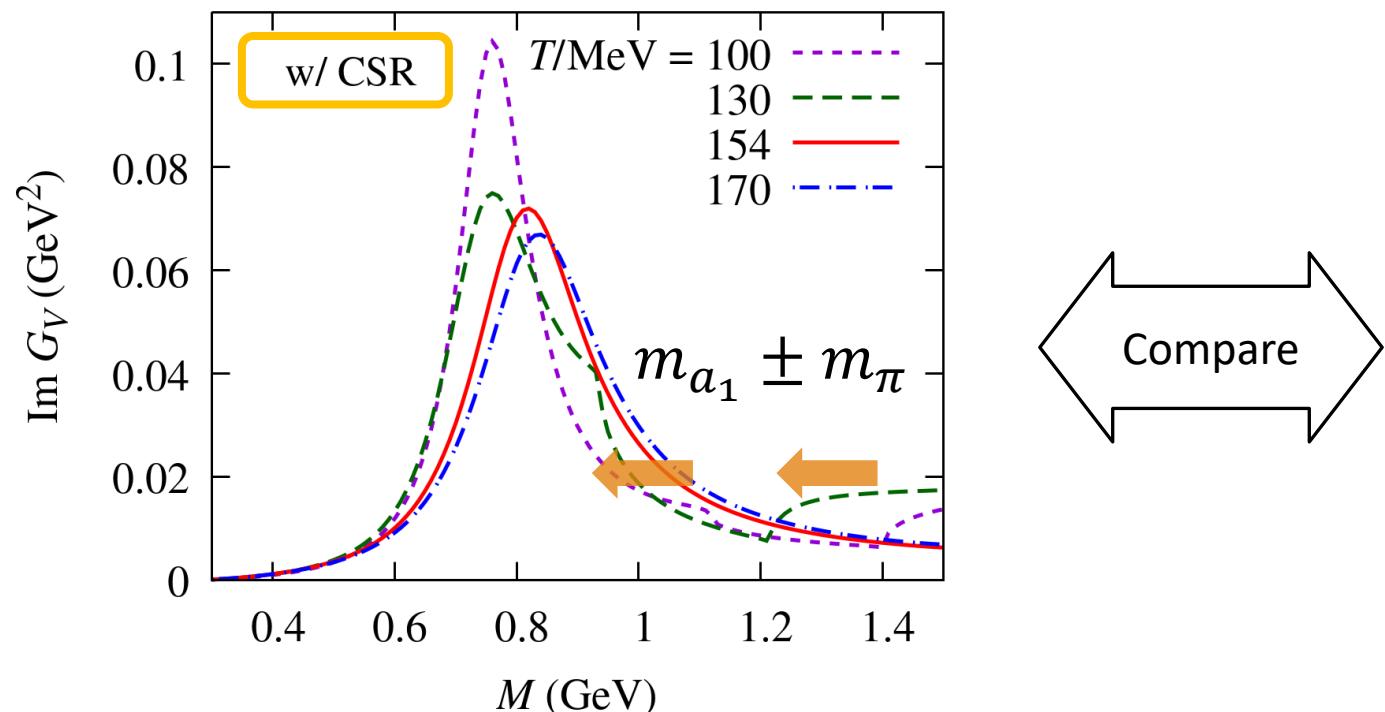
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# Model: Spectral function

## Chiral mixing: One loop calculation

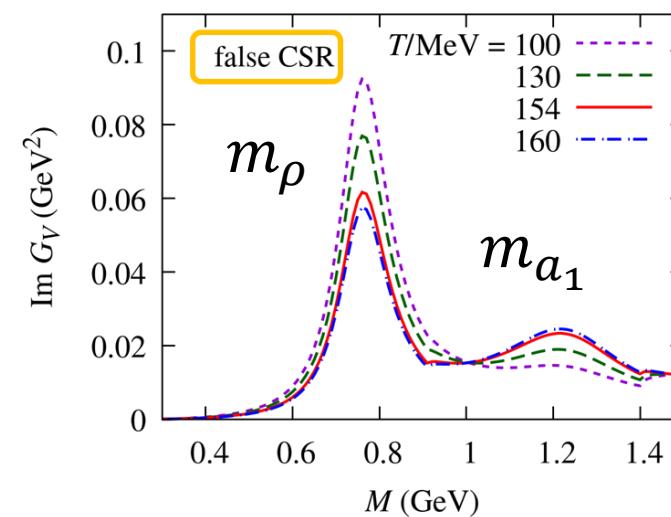


With chiral symmetry restoration:

Chiral mixing  $\sim 0$

Dropping  $m_{a_1}$   $\delta M \sim 0$  at  $T_c = 154$  MeV

## Chiral mixing: Low-temperature mixing theorem

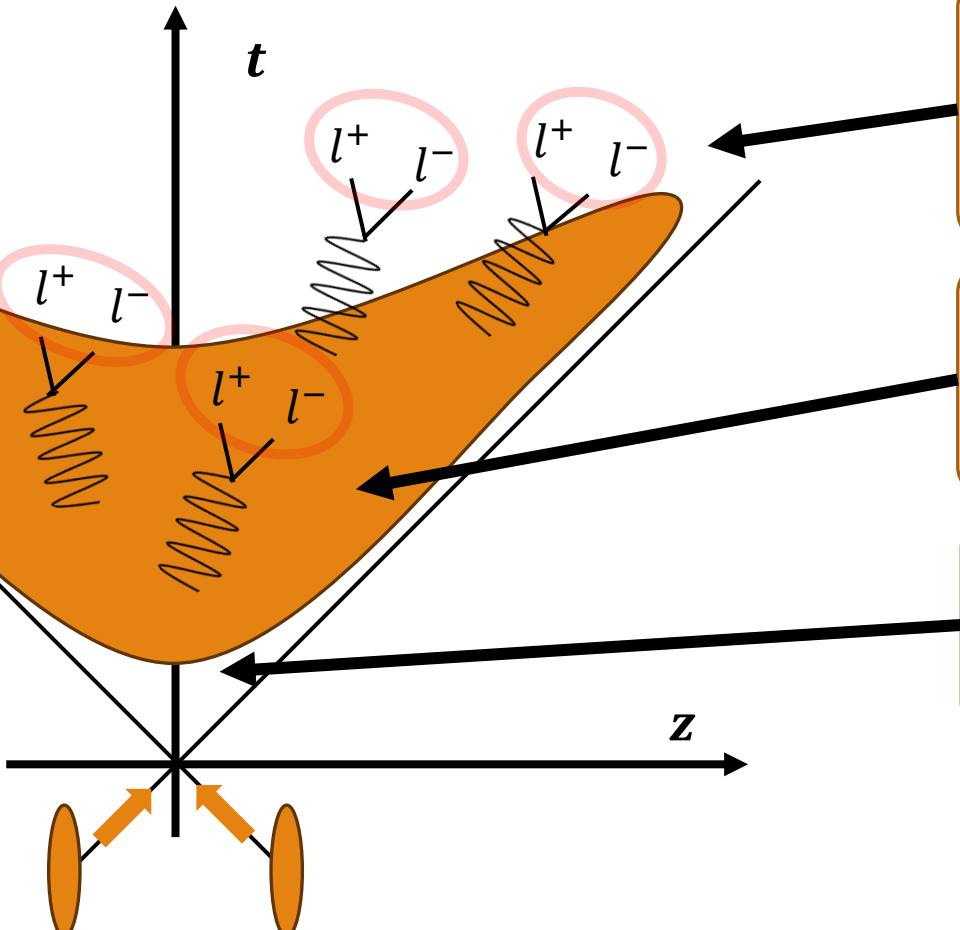


False chiral symmetry restoration:

Maximal mixing  $\epsilon = 1/2$

No mass degeneration

# Model: hydrodynamic model



Observable: Dilepton yield  
Integrate the dilepton production rate  
over **space-time evolution**

**Viscous hydrodynamic model with  $\frac{\eta}{s}(T)$  and  $\zeta(T)$**   
[K. Okamoto and C. Nonaka, Phys. Rev. C 98, 054906 \(2018\)](#)  
[H. Fujii, K. Itakura, K. Miyachi, and C. Nonaka, Phys. Rev. C 106, 034906 \(2022\)](#)

Initial condition: TRENTO  
[J. S. Moreland, et al., Phys. Rev. C 92, 011901 \(2015\)](#)

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# Results: Invariant mass spectrum

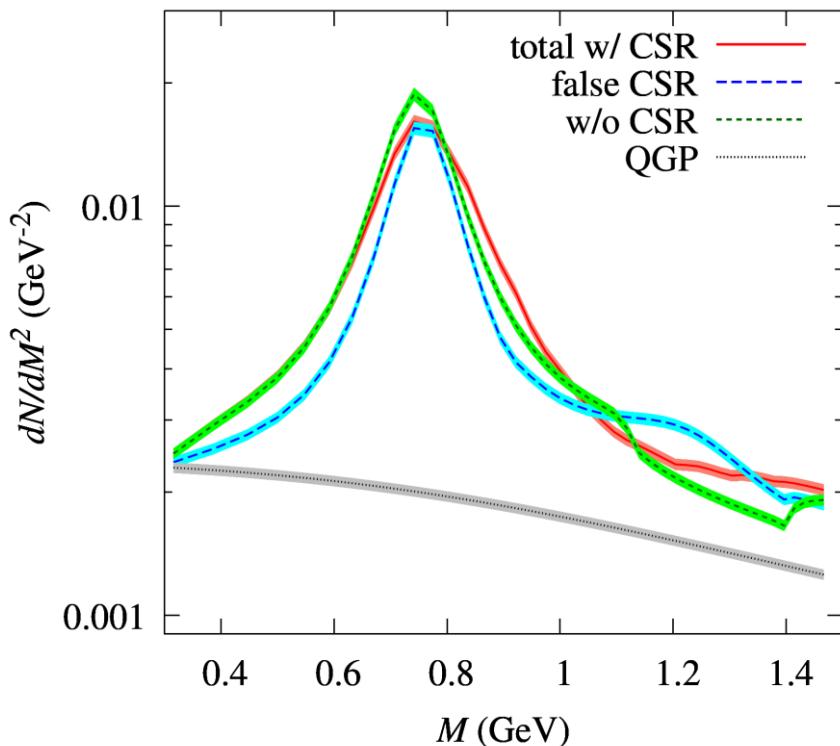


Fig. Dilepton yield

Settings:

Pb-Pb 2.76 TeV, Centrality 0-5 %

$0.2 < p_t < 5.0$  GeV,  $|\eta| < 0.8$

# Results: Invariant mass spectrum

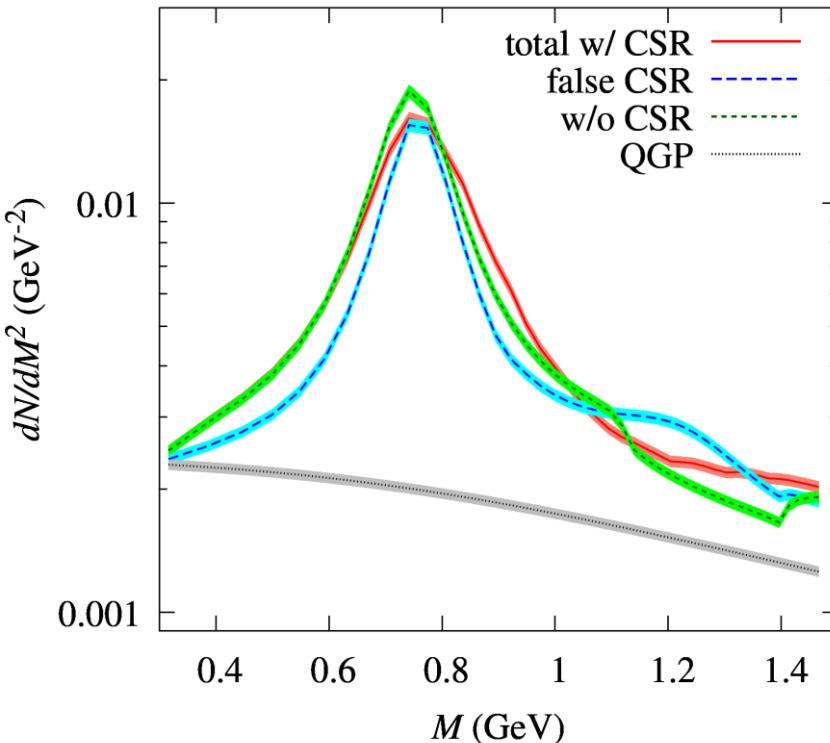


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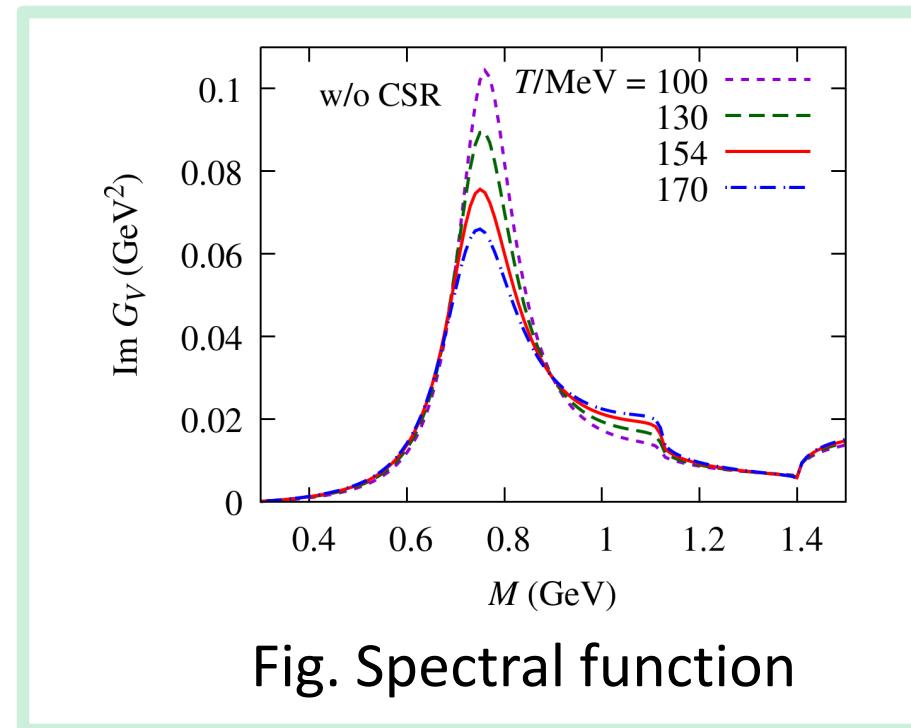


Fig. Spectral function

w/o CSR

Reflects the structure at  $m_{a_1} \pm m_\pi$

# Results: Invariant mass spectrum

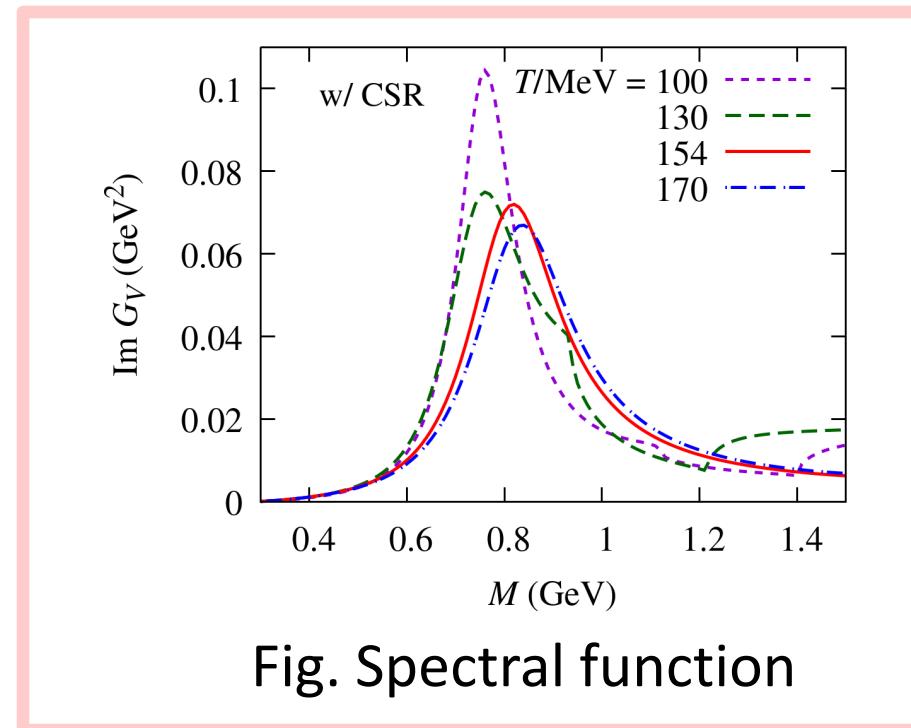
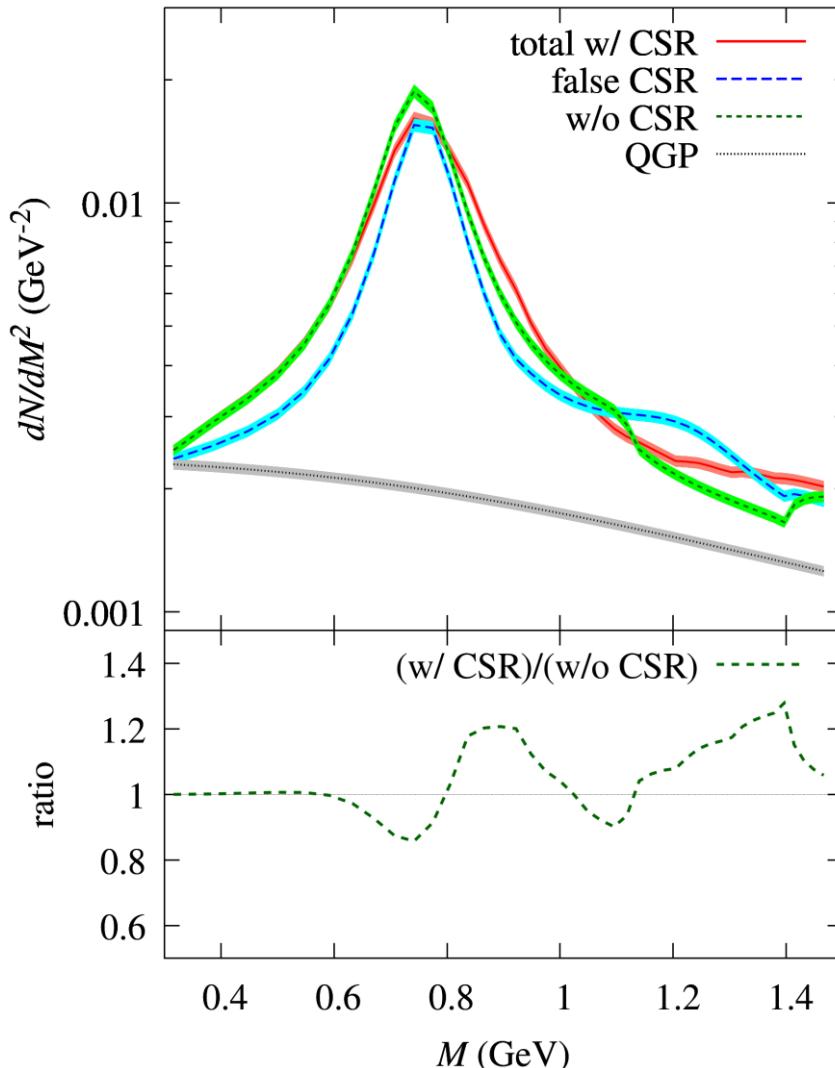


Fig. Spectral function

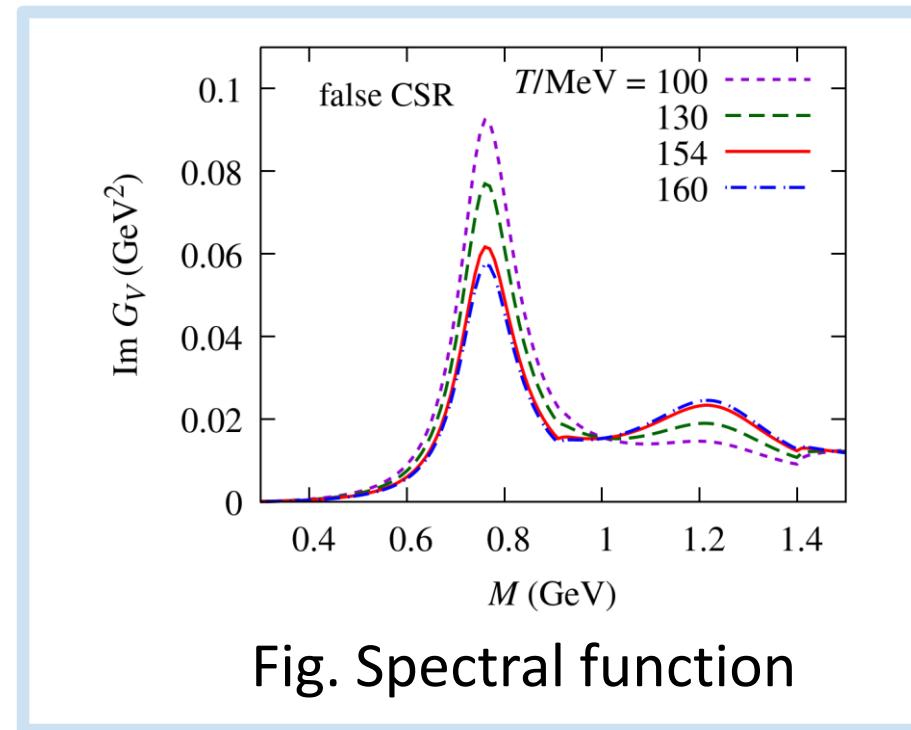
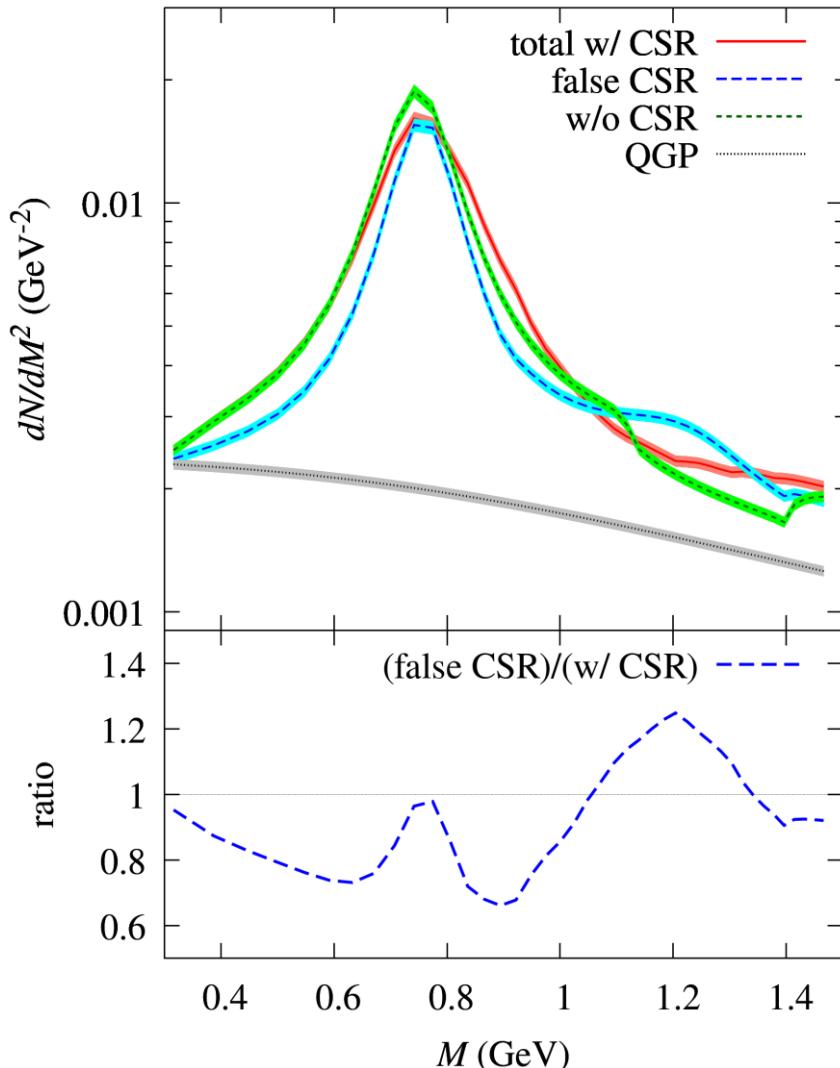
w/ CSR

Smooth enhancement in  $1.1 < M < 1.4$  GeV

→ Due to lighter  $a_1$

Chiral symmetry restoration signal

# Results: Invariant mass spectrum



## False wCSR

Overestimate in  $1.1 < M < 1.3$  GeV

→ Comes from extrapolation to high temperature

**FALSE CSR signal**

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# Summary and Outlook

Analyzed the dilepton production with:

Spectral function with different chiral symmetry restoration scenario

Taking account of space-time evolution with viscous hydrodynamic model

Invariant mass spectra:

With chiral symmetry restoration (w/ CSR): Chiral mixing  $\sim 0$

→ Smooth enhancement in  $1.1 < M < 1.4$  GeV ← Dropping  $a_1$  mass fills in this region

False CSR scenario: Maximal mixing  $\epsilon = 1/2$

→ Overestimate in  $1.1 < M < 1.3$  GeV ← Extrapolation of low-temperature theorem

Outlook:

Spectral function with  $\omega$  meson and  $\phi$  meson

Chiral mixing in a dense medium

# Backup

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# Model: Dilepton rate

Integrate the dilepton production rate over space-time evolution → Dilepton yield

Initial condition: TRENTO

[J. S. Moreland, et al., Phys. Rev. C 92, 011901 \(2015\)](#)

Viscous hydrodynamic model with  $\frac{\eta}{s}(T)$  and  $\zeta(T)$

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[H. Fujii, K. Itakura, K. Miyachi, and C. Nonaka, Phys. Rev. C 106, 034906 \(2022\)](#)

Time

Dilepton production rate:

$$\frac{dR}{d^4q} = \frac{1}{2} \left( 1 - \tanh \frac{T - T_c}{\Delta T} \right) \boxed{\frac{dR_{\text{had}}}{d^4q}} + \frac{1}{2} \left( 1 + \tanh \frac{T - T_c}{\Delta T} \right) \boxed{\frac{dR_{\text{QGP}}}{d^4q}}$$

$$T_c = 154 \text{ MeV}$$

$$\Delta T = T_c \times 0.1$$

$$T_f = 116 \text{ MeV}$$

Dilepton emission rate from hadronic matter

$$\frac{dR_{\text{had}}}{d^4q} = \frac{\alpha_{EM}^2}{\pi^3 s} \frac{\text{Im}G_V(q; T)}{e^{q_0/T} - 1}$$

$\text{Im}G_V$  : Spectral function (w/ and w/o CSR)

Dilepton emission rate from QGP medium

$$\frac{dR_{\text{QGP}}}{d^4q} = \frac{\alpha_{EM}^2}{6\pi^4} \frac{1}{e^{q_0/T} - 1} \left\{ 1 - \frac{2T}{|\mathbf{q}|} \ln \left[ \frac{n_-}{n_+} \right] \right\}$$
$$n_{\pm} = 1 + \exp \left[ -\frac{q_0 \pm |\mathbf{q}|}{2T} \right]$$

# Mass degeneration

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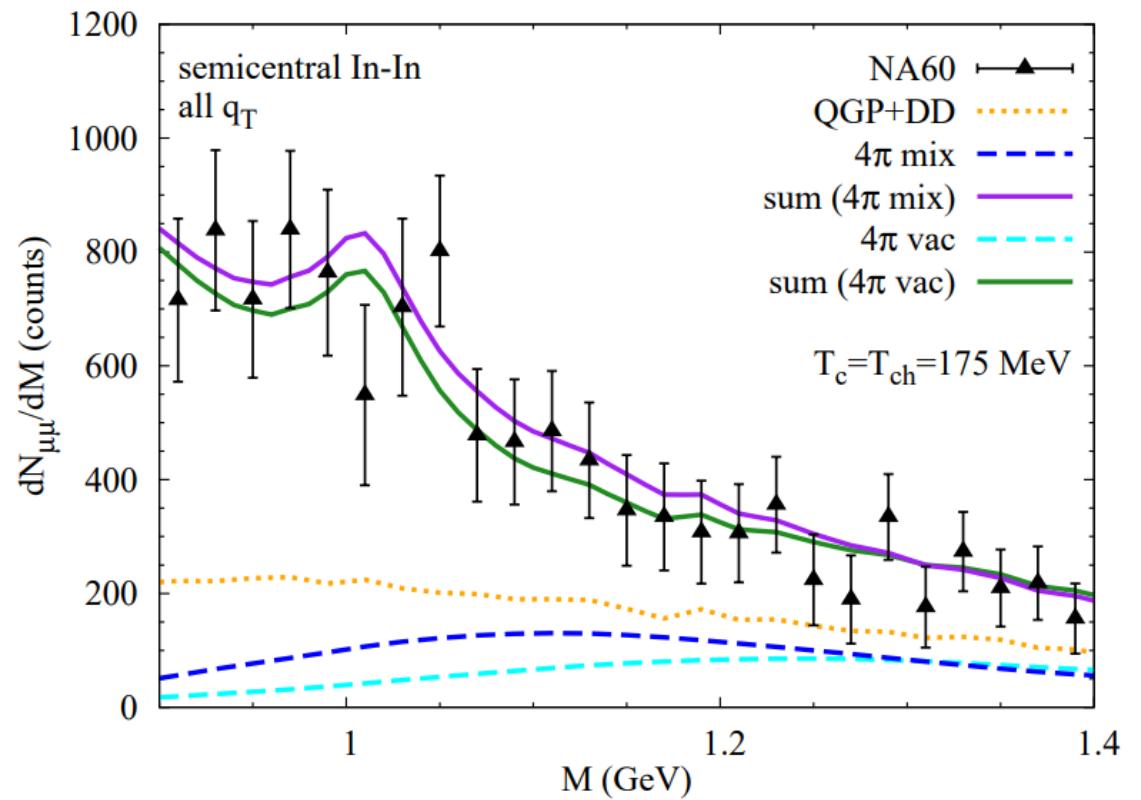
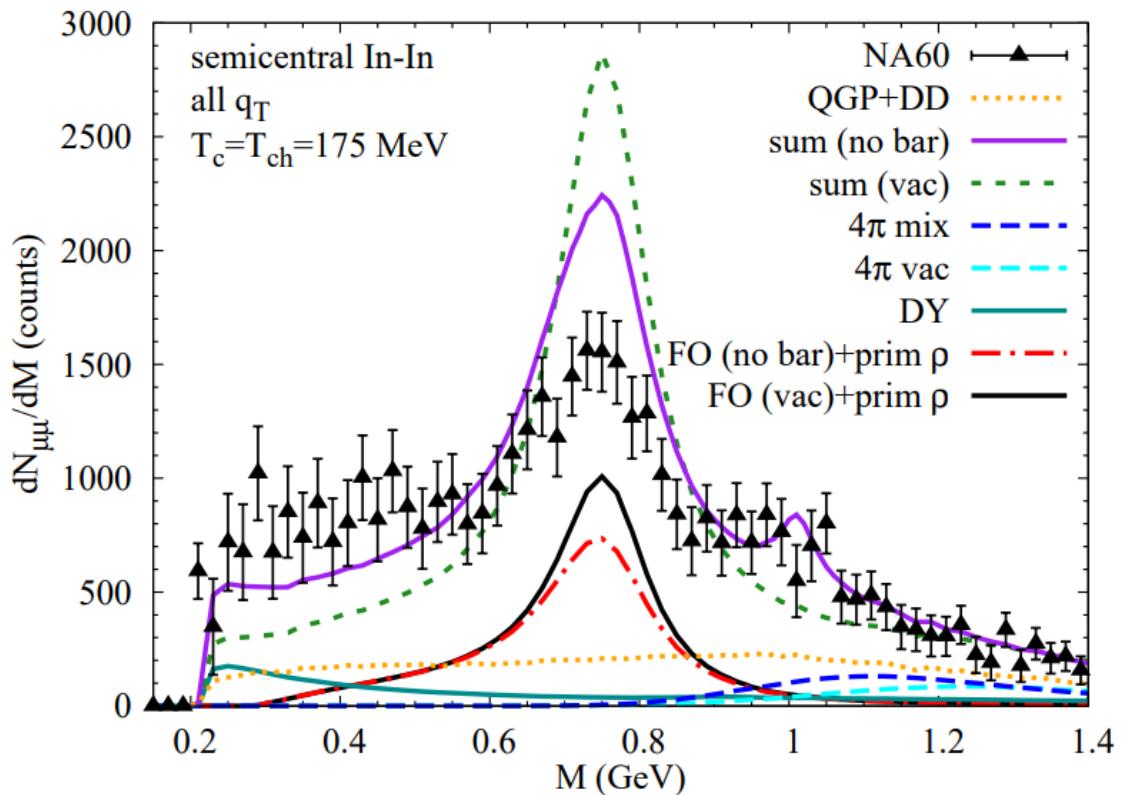
$\delta M \rightarrow 0$  (dropping  $a_1$  mass)

$$\delta M^2(T) = c(T)g^2F^2$$

$$c(T) = c\Theta(T_f - T) + c\Theta(T - T_f) \frac{T_c^2 - T^2}{T_c^2 - T_f^2}$$

Critical temperature:  $T_c = 154$  MeV

Flash temperature:  $T_f = 0.7T_c$



H. van Hees, R. Rapp, Nucl. Phys. A806, 339 (2008)

# Hydrodynamic model

Temperature dependence of viscosity:

$$\frac{\eta}{s}(T) = \left(\frac{\eta}{s}\right)_{\min} + c_1(T_c - T)\theta(T_c - T) + c_2(T - T_c)\theta(T - T_c)$$

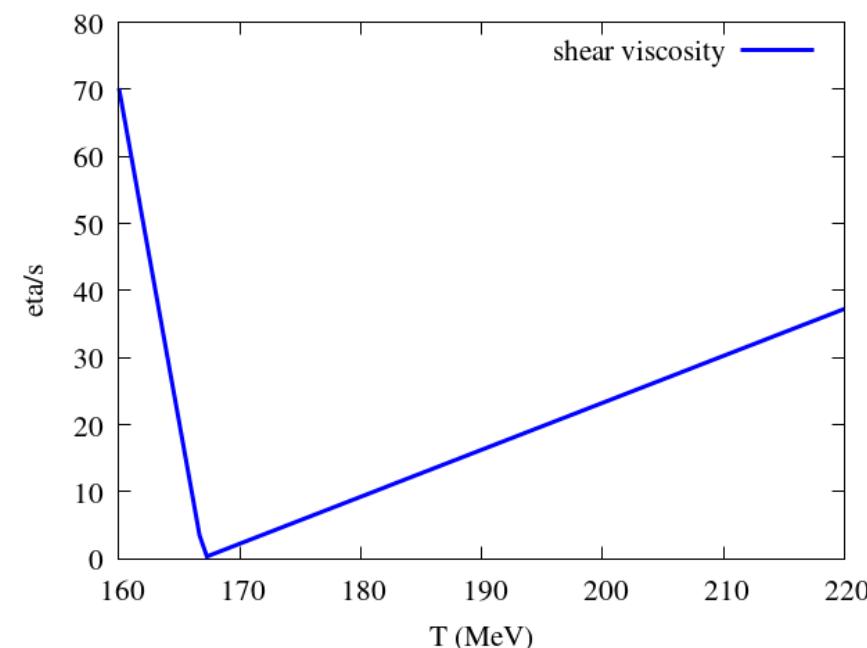
$$\frac{\zeta}{s} = b \frac{\eta}{s} \left( \frac{1}{3} - c_s^2 \right)^2$$

$$\left(\frac{\eta}{s}\right)_{\min} = 0.08$$

$$c_1 = 10$$

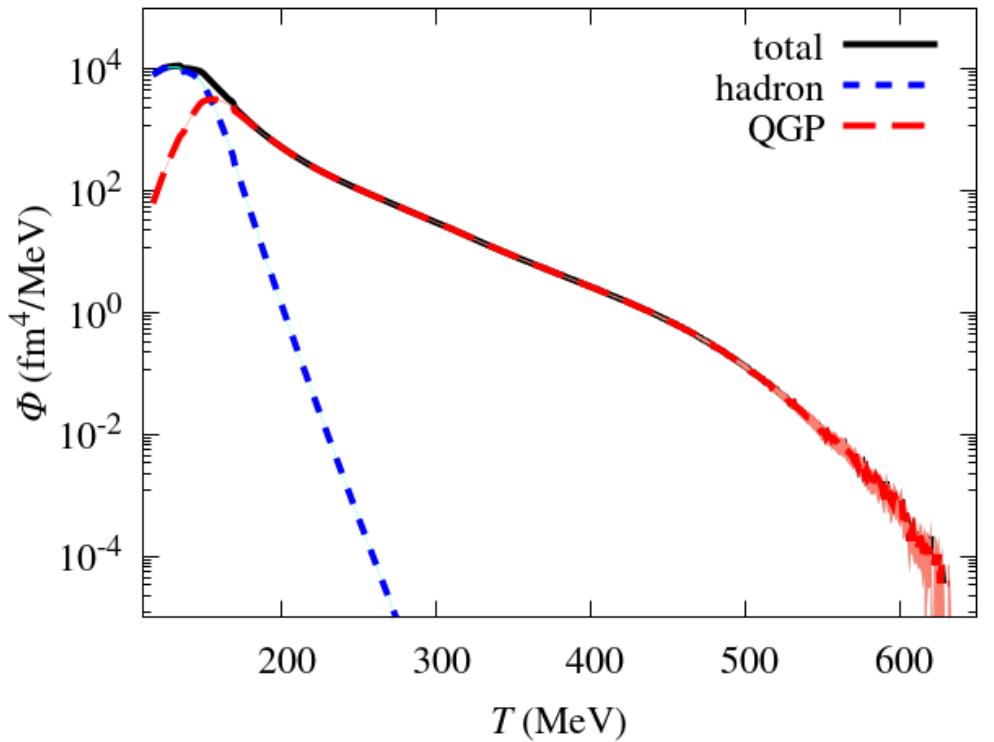
$$c_2 = 0.7$$

$$b = 10$$



H. Fujii, K. Itakura, K. Miyachi, and C. Nonaka, Phys. Rev. C 106, 034906 (2022)

# Results: Profile function



$$\int \frac{dR}{d^4q} d^4x = \int_{T_i}^{T_f} \frac{dR}{d^4q}(q; T) \Phi(T) dT$$

**Profile function:**

$$\Phi(T) = \int d^4x \delta(T(x) - T)$$

- Smooth transition between QGP phase and hadron phase
- Thermal dileptons produced in the hadronic phase amount to 70%