Theoretical Connections between Dileptons and chiral symmetry restoration

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Outline

I. Introduction

II. Sum Rule Analysis

  A. Setup

  B. Vacuum

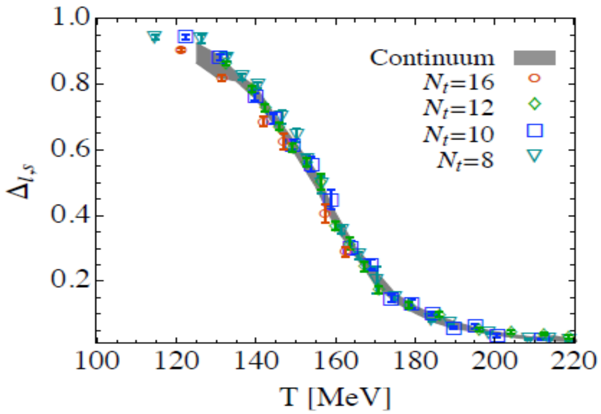
  C. Finite Temperature

III. Summary

I. Introduction

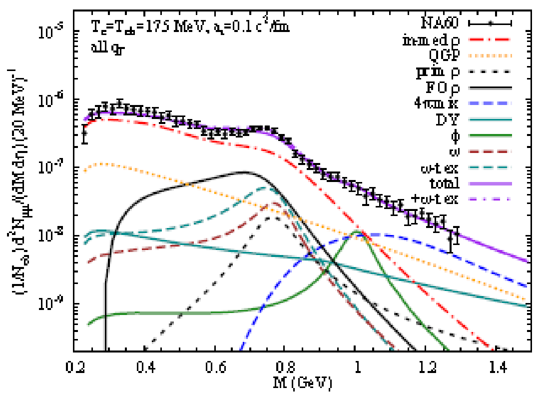
Goal: Observe chiral symmetry restoration experimentally

On the lattice:
Wuppertal-Budapest Collaboration
Borsanyi et al. (2010)



In-In (17.3GeV)

SPS/NA60
Arnaldi et al
(2006, 2009)



- Ideal probes are meson which are chiral partners
  - Iso-vector vector and axial-vector states (ρ and a_1)

$$a_1 \leftrightarrow \rho + \pi$$

  - Sensitive to chiral order parameters.

- In-medium ρ can be investigated by thermal dilepton rates $\rho \to \gamma \to l^+ l^-$

- But a1 measurements prove difficult

$$a_1 \to \gamma\pi$$

- Need theory to connect rho and a_1 properties.

II. Sum Rules
IIA. Setup

- Weinberg type sum rules:
  - Moments of the difference between vector and axial-vector SFs
  - Directly related to chiral symmetry breaking.

$$\int ds(\rho_V - \rho_A)s^n = f_n$$

$$f_{-2} = \frac{1}{3} f_\pi^2 \langle r_\pi^2 \rangle - F_A,\, f_{-1} = f_\pi^2,\, f_0 = -m_q \langle \bar{q}q \rangle,\, f_1 = -2\pi\alpha_s \langle \mathcal{O}_4^{\chi SB} \rangle$$

Weinberg, (1967); Das, Mathur, and Okubo, (1967); Kapusta and Shuryak (1994)

- QCD sum rules (with Borel transform): Shifman, Vainshtein, Zakharov, 1979
  - Constrains vector or axial-vector SFs individually.

$$\frac{1}{M^2}\int ds \frac{\rho_V(s)}{s} e^{-s/M^2} = \frac{1}{8\pi^2}\left(1 + \frac{\alpha_s}{\pi}\right) + \frac{m_q \langle \bar{q}q \rangle}{M^4} + \frac{1}{24M^4}\langle \frac{\alpha_s}{\pi} G_{\mu\nu}^2 \rangle - \frac{56\pi\alpha_s}{81M^6}\langle \mathcal{O}_4^V \rangle$$

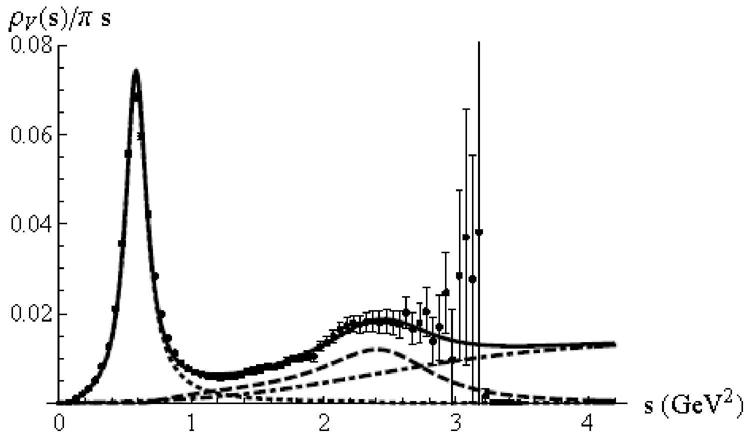
(plus non-scalar operators at finite T)

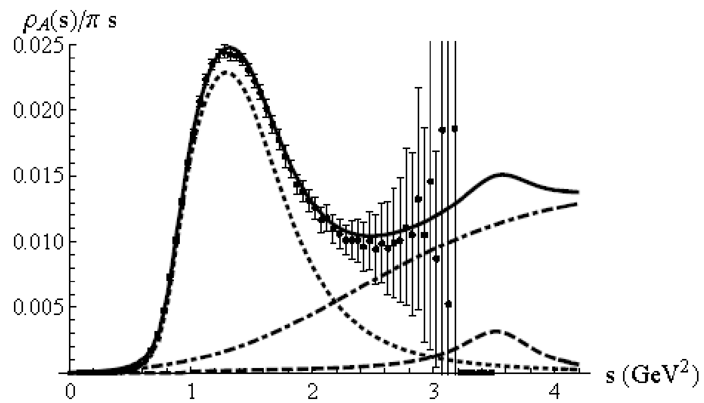
$$\frac{1}{M^2}\int ds \frac{\bar{\rho}_A(s)}{s} e^{-s/M^2} = \frac{1}{8\pi^2}\left(1 + \frac{\alpha_s}{\pi}\right) + \frac{m_q \langle \bar{q}q \rangle}{M^4} + \frac{1}{24M^4}\langle \frac{\alpha_s}{\pi} G_{\mu\nu}^2 \rangle + \frac{88\pi\alpha_s}{81M^6}\langle \mathcal{O}_4^A \rangle$$

IIB. Vacuum

Serves as foundation for finite temperature studies.

PMH and Rapp, (2012,2013)





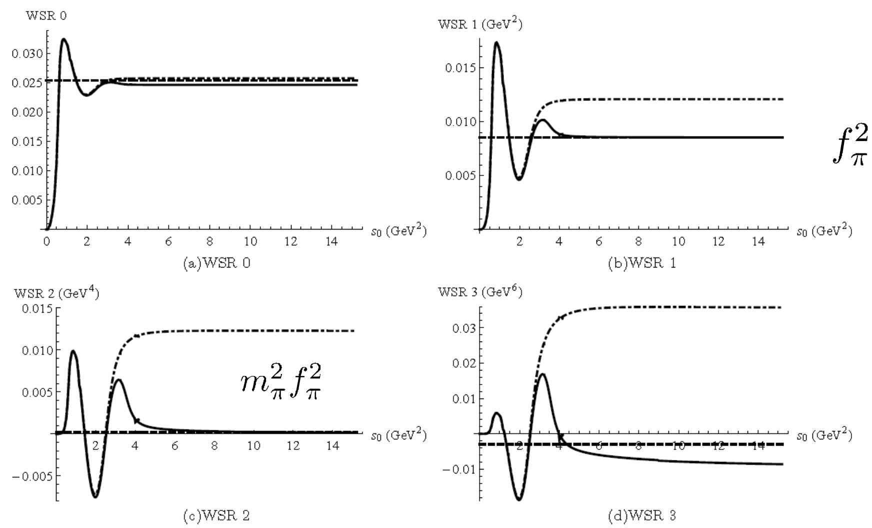
Data from ALEPH (Barate et al. 1998)

- Considered phenomenological SFs – Fit to tau decay data.
  - ρ SF from effective field theory approach. Rapp and Wambach (1999)
  - Other resonances are phenomenological (Breit-Wigner for a1 and ρ’).
  - Same perturbative continuum for both channels.

WSRs call for an excited axial vector state, a1’(1800)!

How well are the sum rules satisfied?

Weinberg-type sum rules



WSR 0	WSR 1	WSR 2	WSR 3
-3.0%	~0%	~0%	200%

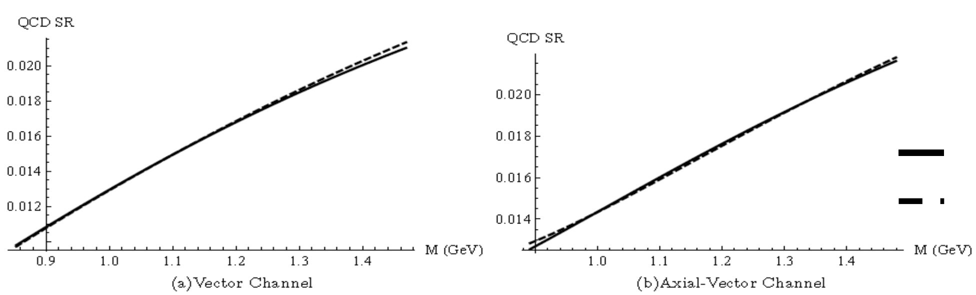
QCD sum rules

Leupold, Peters, Mosel (1998)
Leinweber (1997)

Selection criterion: d-value (average deviation over Borel window)

$$d_V = 0.59\%$$

$$d_A = 0.49\%$$



LHS
RHS

$$\langle \frac{\alpha_s}{\pi} G^2_{\mu\nu} \rangle = 0.425 \mathrm{GeV}^2 \mathrm{fm}^{-2}$$

$$\langle \mathcal{O}_4^{V/A} \rangle = \kappa_{V/A} \langle \bar{q} q \rangle^2$$

$$\kappa_V = \kappa_A = 2.1$$

IIC. Finite Temperature

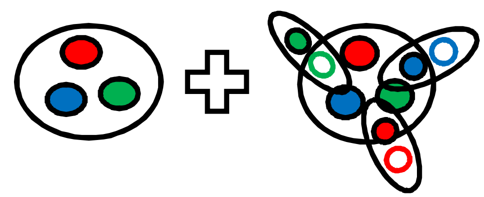
Two major ingredients: Condensates and Spectral functions

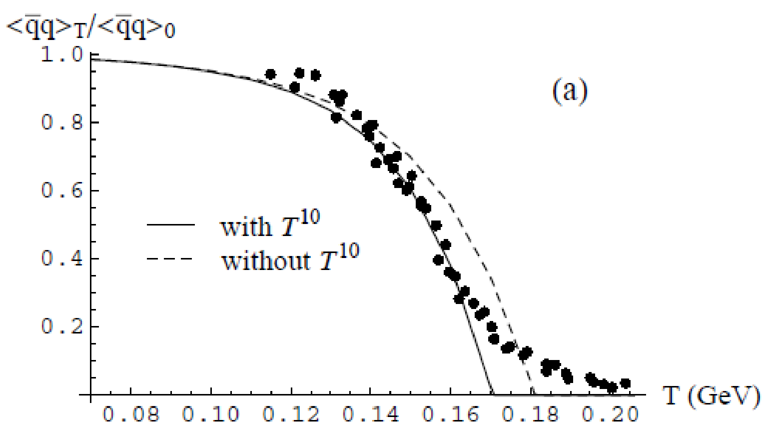
- Condensates:
  - Use a hadron resonance gas model for temp dependence.

$$\frac{\langle \bar{q}q\rangle_T}{\langle \bar{q}q\rangle_0} = 1 - \sum_H \frac{\sigma_H}{f_\pi^2 m_\pi^2}\varrho_s^H - \alpha T^{10}$$

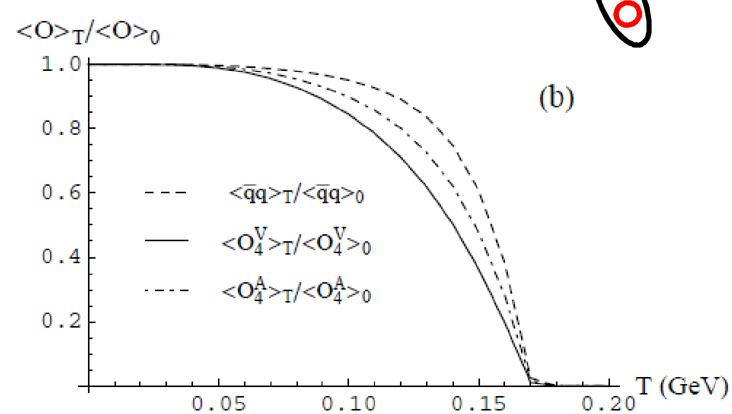
$$\sigma_H = \langle H|\bar{q}q|H\rangle$$

$$\sigma_H = \sigma_{\rm core} + \sigma_{\rm pioncloud}$$

$\sigma_H =$ 

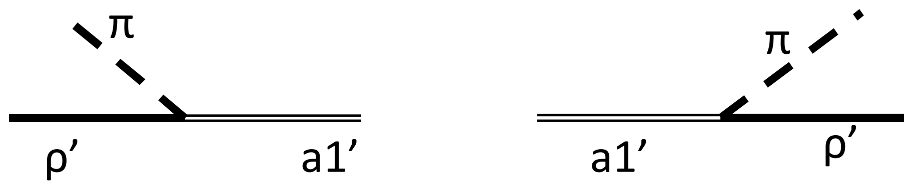


Quark condensate



- Spectral functions:
  - ρ :
    - in medium SF from EFT approach.
    - **Known to be consistent with experimental dilepton data.**
  - Excited state:
    - Use “chiral mixing” with thermal/cloud pions

Chanfray, Delorme, Ericson (1998)
Krippa (1998)

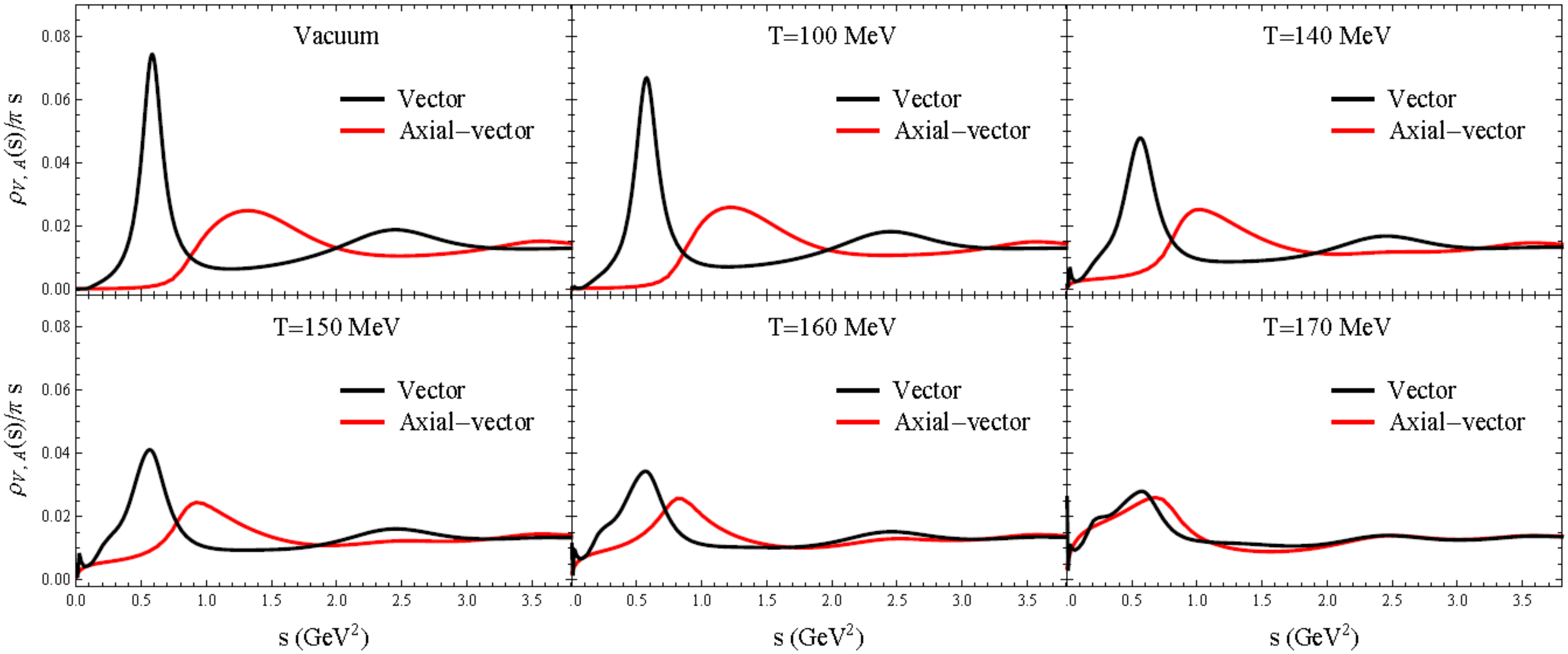


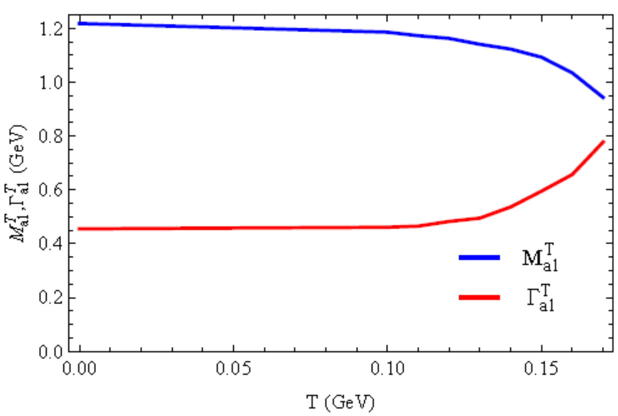
  - Continuum - temperature independent
  - a_1:
    - 4 parameters controlling in-medium mass, width and axial-current coupling.

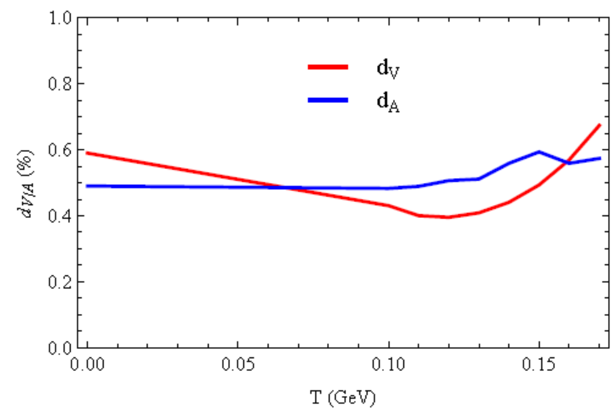
Search for parameters satisfying QCDSRs and WSRs.

Results

PMH and Rapp (2013)







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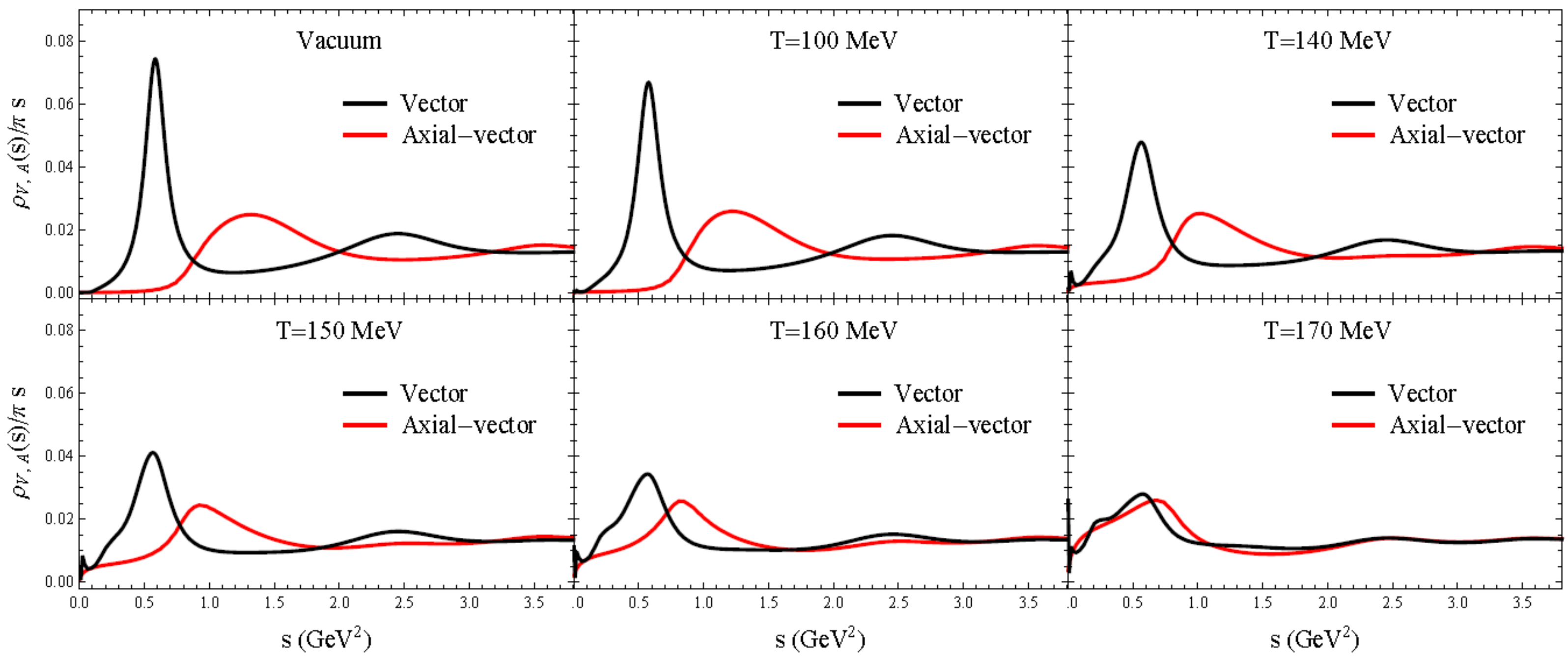

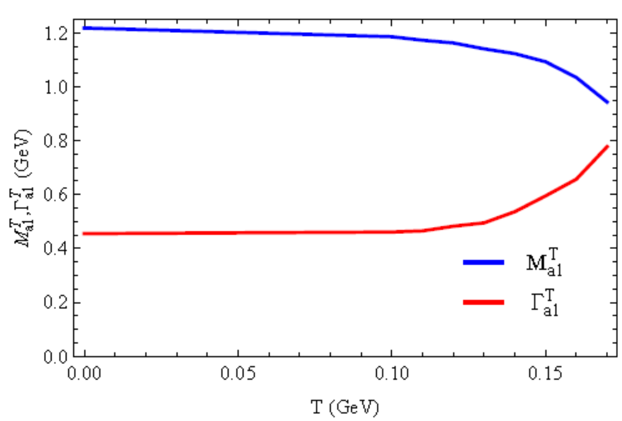

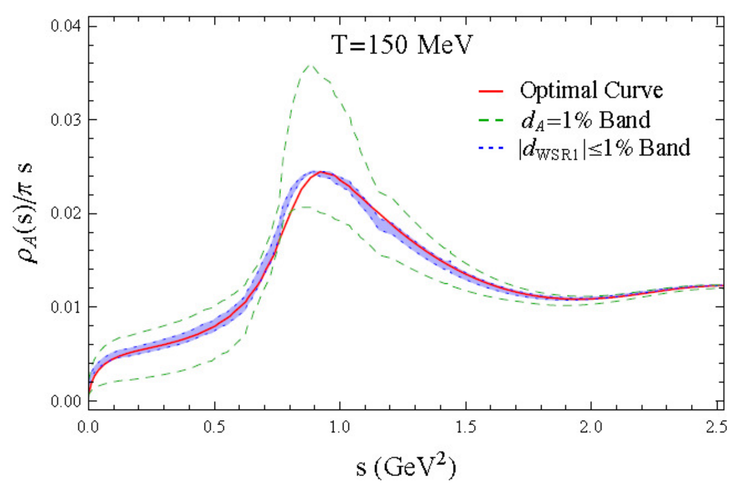

VI. Summary

Tested the existence of in-medium axial-vector SFs consistent with the sum rules.

- Vector SF which quantitatively describe dilepton data.
- Input from lattice for condensates
- Constraining power of using both QCDSR and WSR.
- Vacuum studies serve as foundation.

Reveals a systematic temperature progression indicative of chiral restoration.

New!!

HI dileptons $\Longrightarrow$ Rho melting $\Longrightarrow$ a1 mass reduction and broadening

Thus ρ melting is compatible with restoration.