

# Theoretical Connections between Dileptons and chiral symmetry restoration

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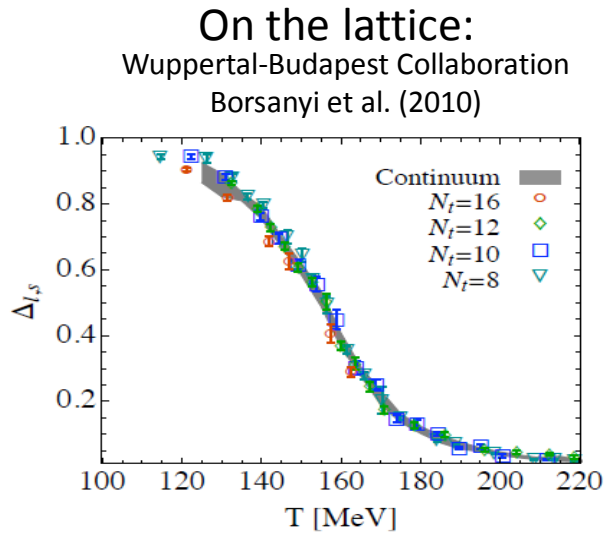
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# Outline

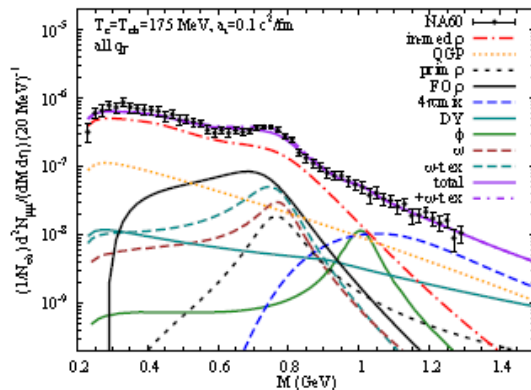
- I. Introduction
- II. Sum Rule Analysis
  - A. Setup
  - B. Vacuum
  - C. Finite Temperature
- III. Summary

# I. Introduction

Goal: Observe chiral symmetry restoration experimentally



In-In (17.3 GeV)



SPS/NA60  
Arnaldi et al  
(2006, 2009)

- Ideal probes are meson which are chiral partners
  - Iso-vector vector and axial-vector states ( $\rho$  and  $a_1$ )
 
$$a_1 \leftrightarrow \rho + \pi$$
  - Sensitive to chiral order parameters.
- In-medium  $\rho$  can be investigated by thermal dilepton rates
 
$$\rho \rightarrow \gamma \rightarrow l^+ l^-$$
- But  $a_1$  measurements prove difficult
 
$$a_1 \rightarrow \gamma \pi$$
- 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.

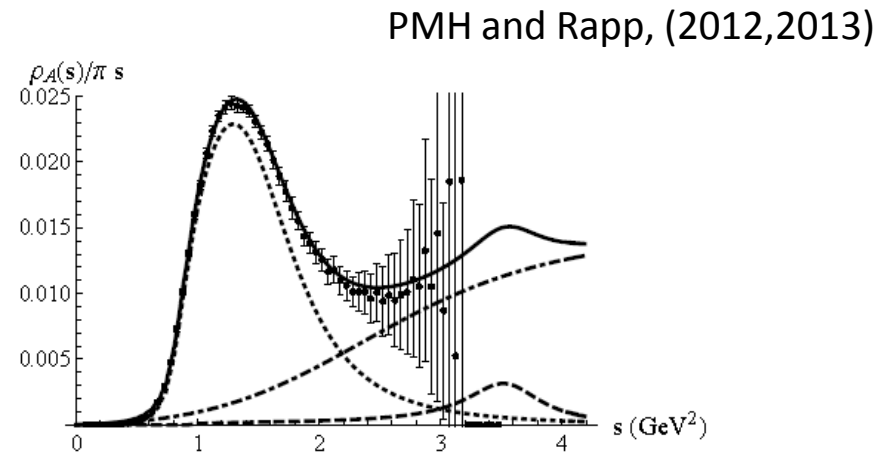
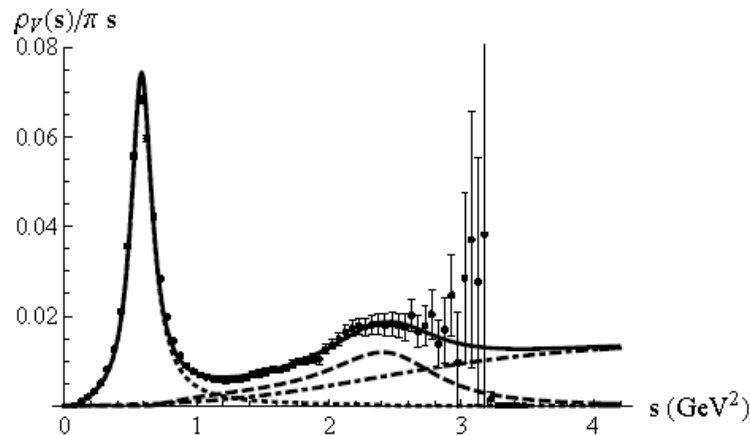
$$\frac{1}{M^2} \int ds \frac{\rho_V(s)}{s} e^{-s/M^2} = \frac{1}{8\pi^2} \left(1 + \frac{\alpha_s}{\pi}\right) + \frac{m_q\langle \bar{q}q \rangle}{M^4} + \frac{1}{24M^4} \left\langle \frac{\alpha_s}{\pi} G_{\mu\nu}^2 \right\rangle - \frac{56\pi\alpha_s}{81M^6} \langle \mathcal{O}_4^V \rangle$$

(plus non-scalar operators at finite T)

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

## IIB. Vacuum

Serves as foundation for finite temperature studies.



Data from ALEPH (Barate et al. 1998)

- Considered phenomenological SFs – Fit to tau decay data.
  - $\rho$  SF from effective field theory approach. Rapp and Wambach (1999)
  - Other resonances are phenomenological (Breit-Wigner for  $a_1$  and  $\rho'$ ).
  - Same perturbative continuum for both channels.

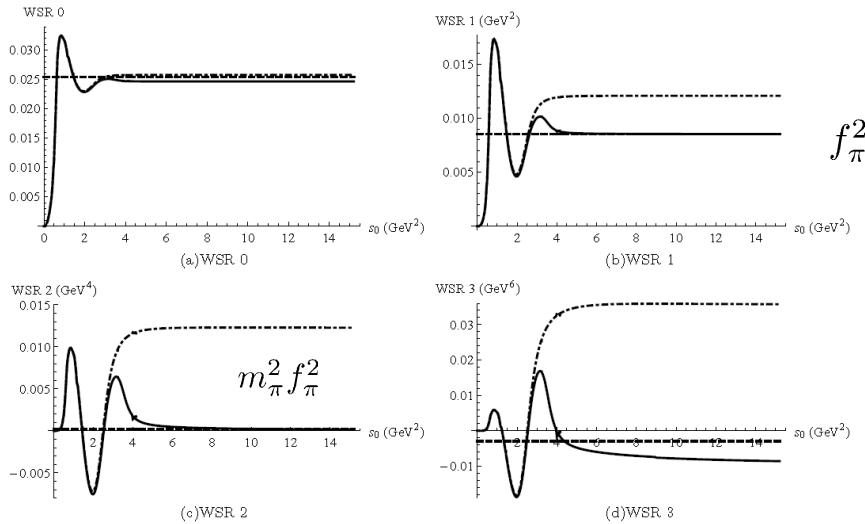


WSRs call for an excited axial vector state,  $a_1'(1800)$ !



# How well are the sum rules satisfied?

## Weinberg-type sum rules



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

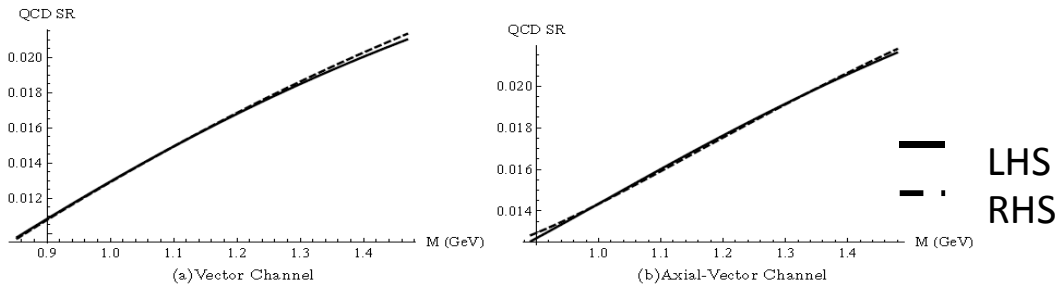
## QCD sum rules

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

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

$$d_V = 0.59\%$$

$$d_A = 0.49\%$$



$$\left\langle \frac{\alpha_s}{\pi} G_{\mu\nu}^2 \right\rangle = 0.425 \text{GeV}^2 \text{fm}^{-2}$$

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

$$\kappa_V = \kappa_A = 2.1$$

# IIC. Finite Temperature

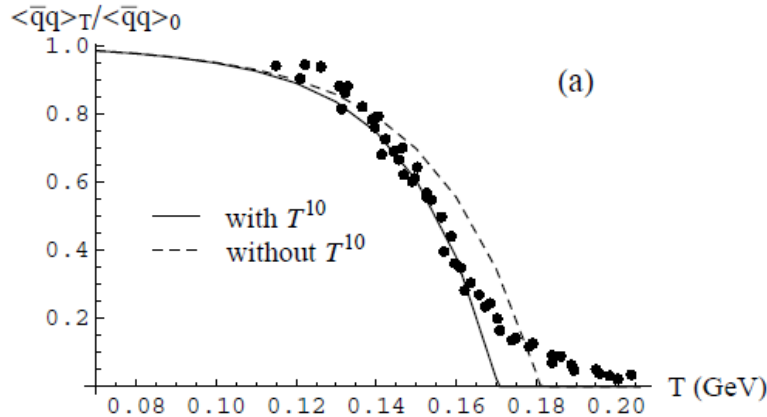
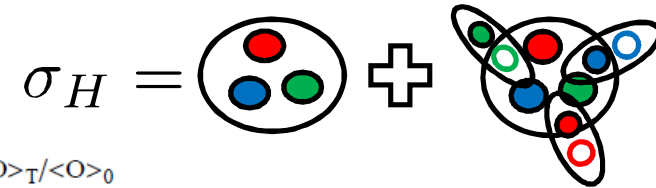
Two major ingredients: Condensates and Spectral functions

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

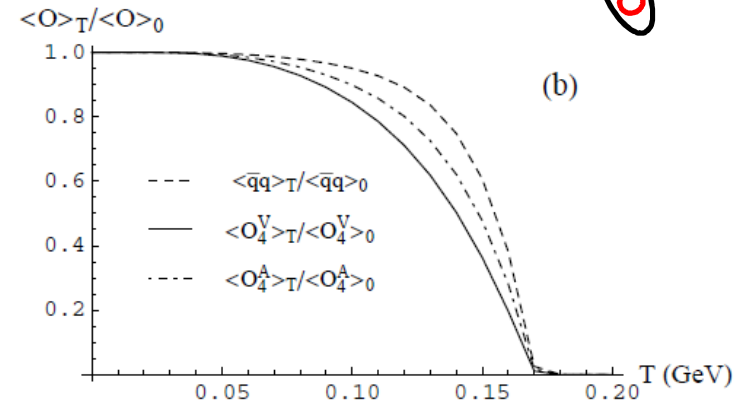
$$\frac{\langle \bar{q}q \rangle_T}{\langle \bar{q}q \rangle_0} = 1 - \sum_H \frac{\sigma_H}{f_\pi^2 m_\pi^2} \rho_s^H - \alpha T^{10}$$

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

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



Quark condensate



- Spectral functions:

- $\rho$ :

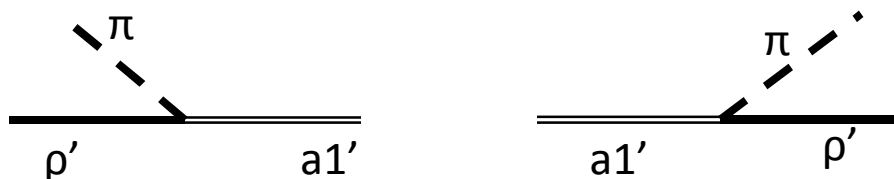
- in medium SF from EFT approach.
    - **Known to be consistent with experimental dilepton data.**



- Excited state:

- Use “chiral mixing” with thermal/cloud pions

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



- Continuum - temperature independent

- $a_1$ :

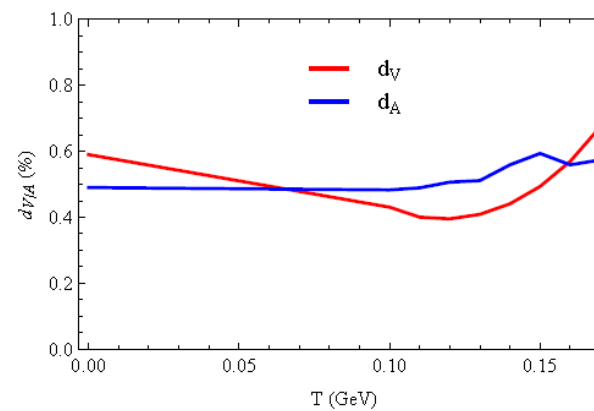
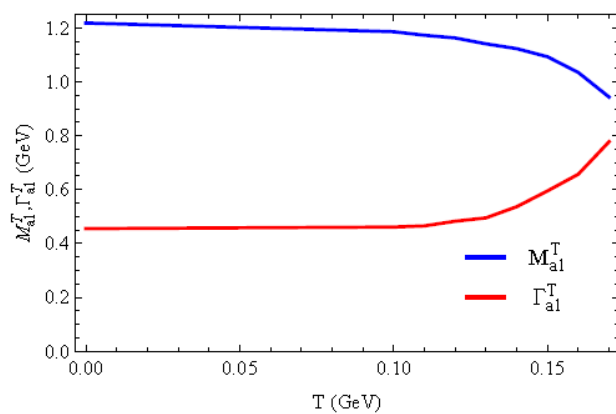
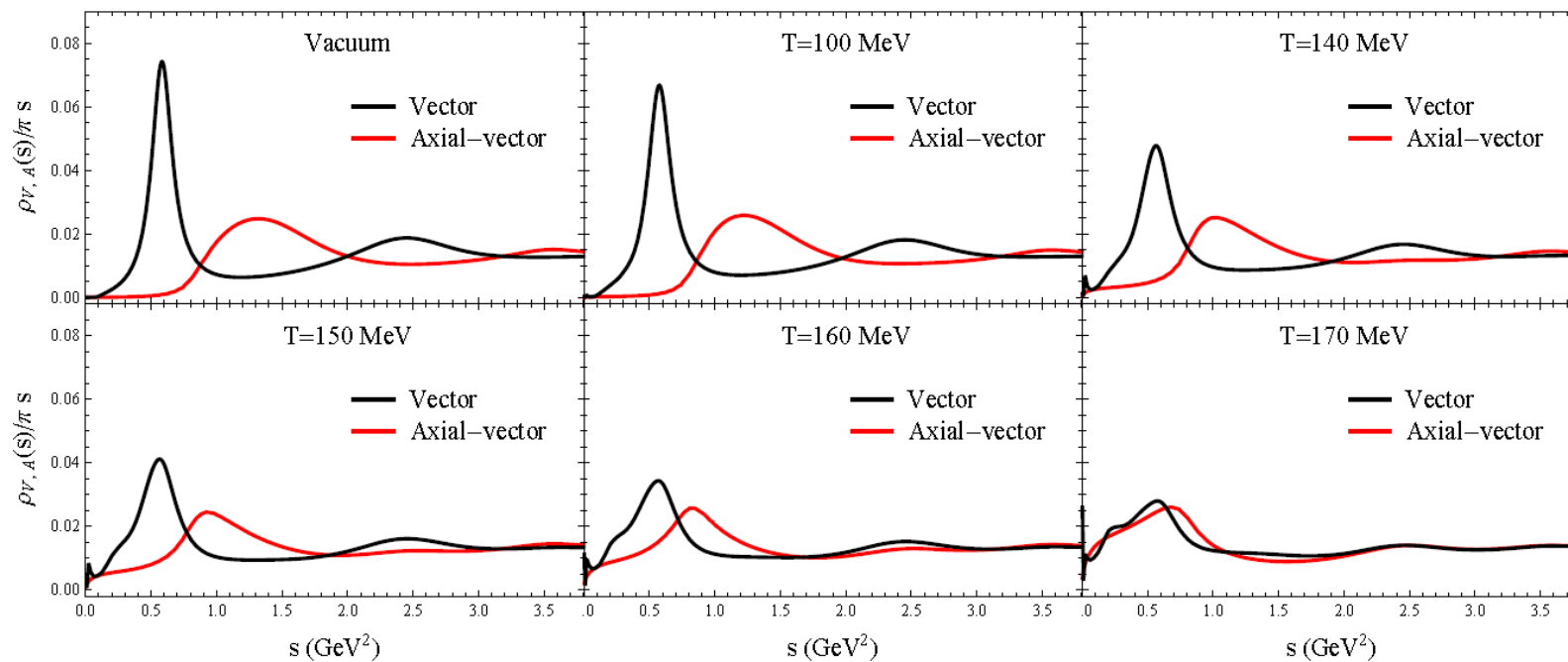
- 4 parameters controlling in-medium mass, width and axial-current coupling.

Search for parameters satisfying QCDSRs and WSRs.



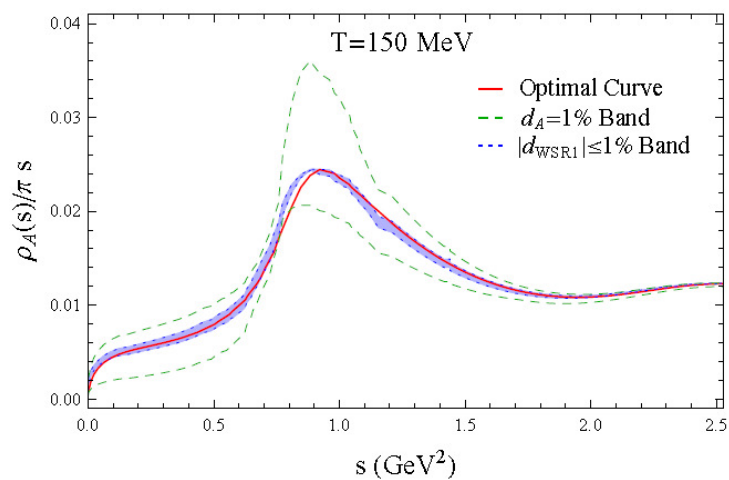
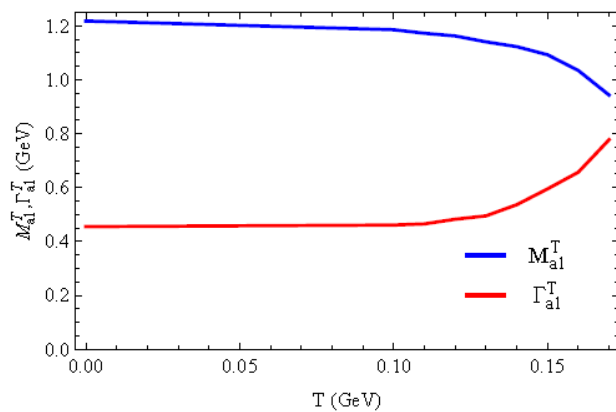
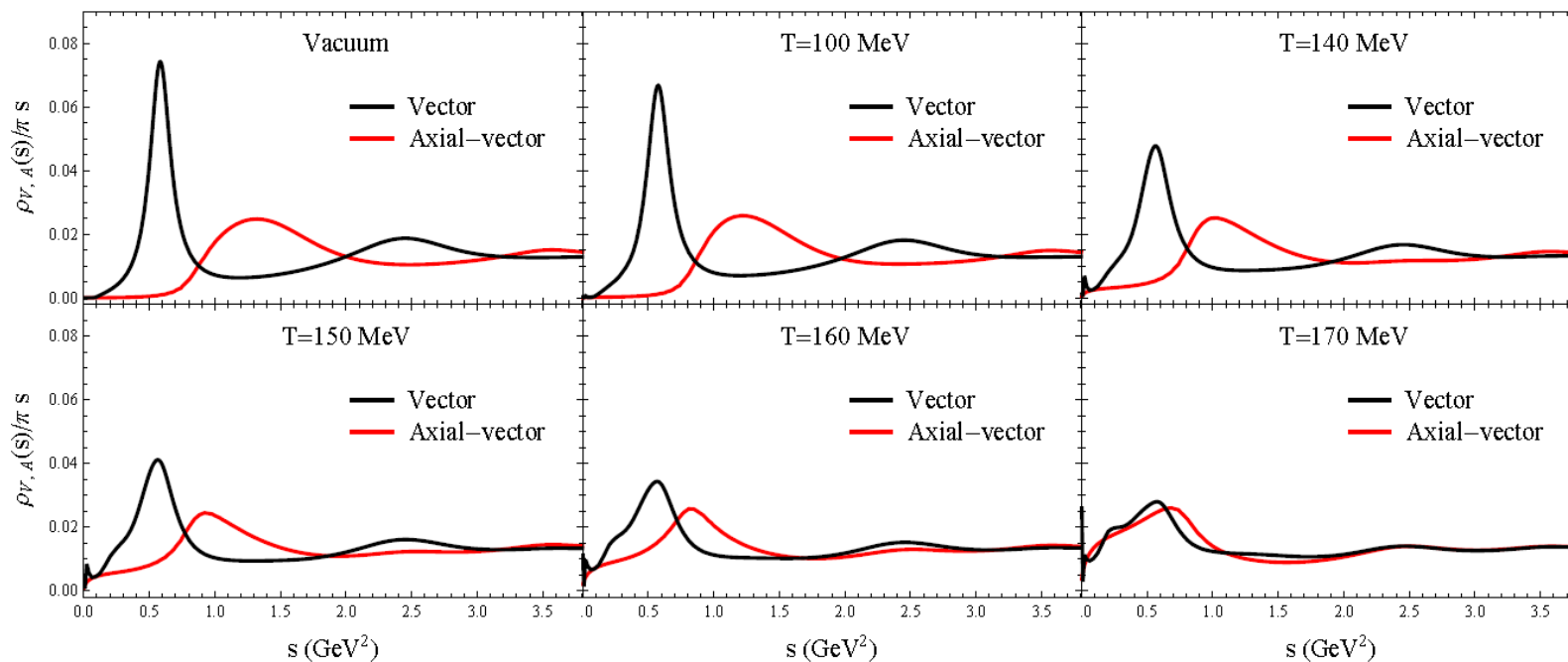
# Results

PMH and Rapp (2013)



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PMH and Rapp (2013)



## 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.

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

New!!

Thus  $\rho$  melting is compatible with restoration.