(Axial) Vector meson spectral functions and chiral symmetry restoration

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Thermal photons and dileptons workshop
BNL
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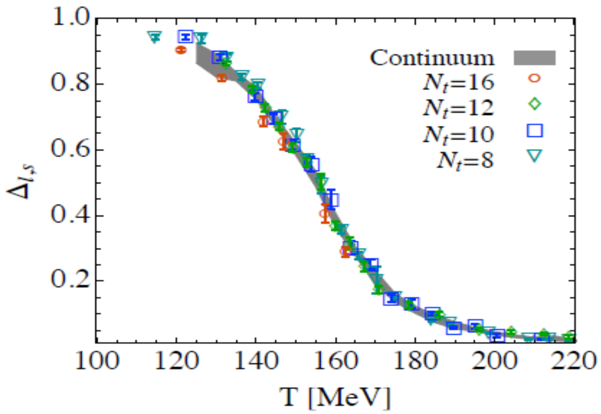
Outline

I. Motivate VSF and chiral symmetry restoration
II. Sum Rule Analysis
III. Hadronic Effective Field Theory –MYM
  A. What is Massive Yang-Mills?
  B. Calculation Scheme
  C. Vacuum
  D. Finite Temperature
IV. Summary

I. Motivation

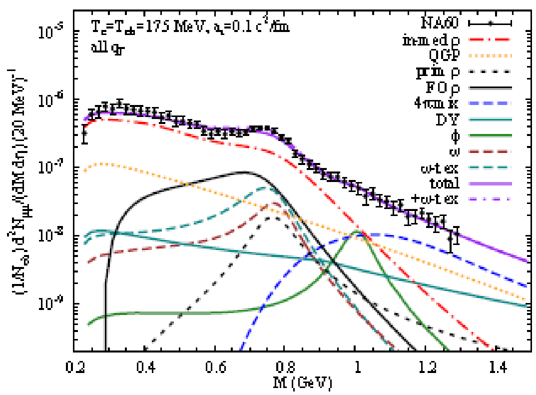
Goal: Search for chiral symmetry restoration experimentally

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 spectra $\rho \rightarrow \gamma \rightarrow l^+ l^-$

- But a_1 measurements prove difficult

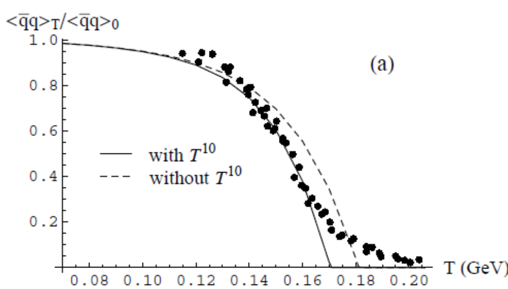
$$a_1 \rightarrow \gamma \pi$$

- Need theory to connect rho and a_1 properties.

II. Sum Rules: (A phenomenological approach)

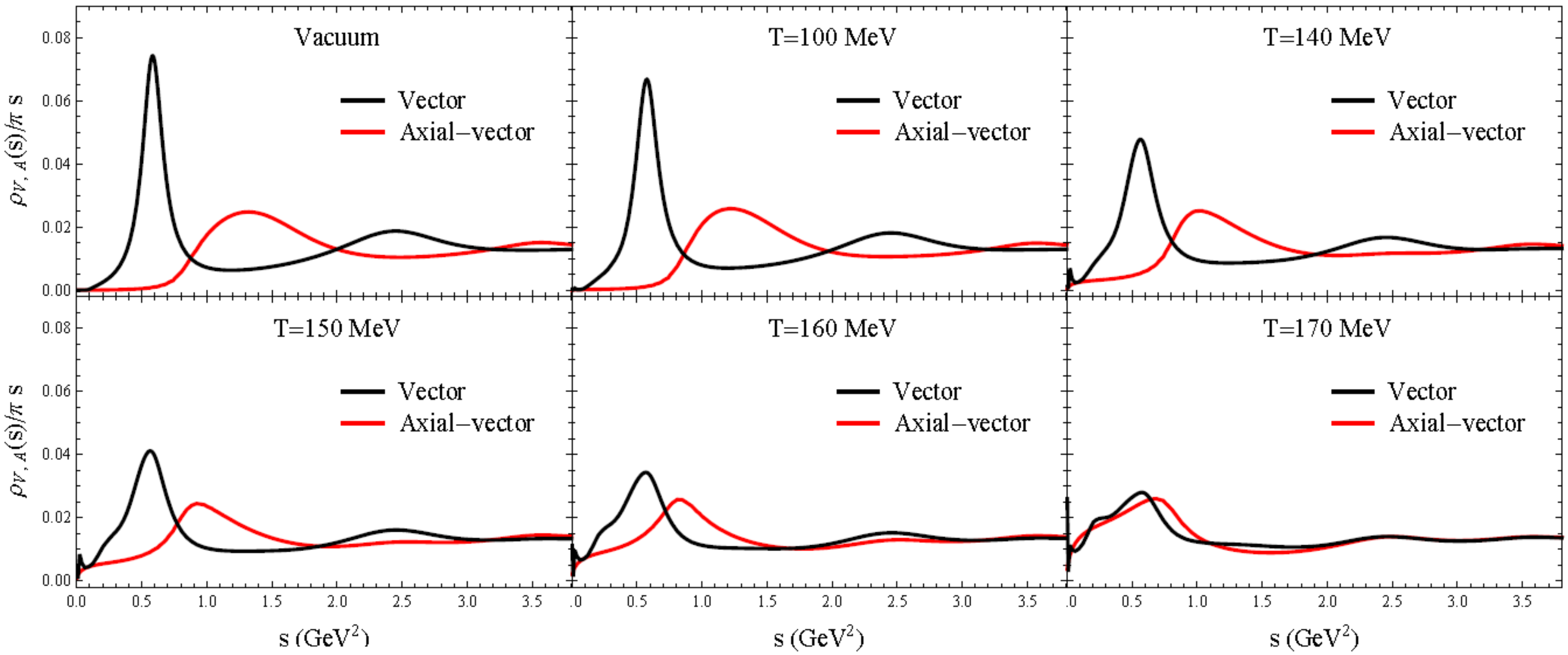
Relate dispersion integrals to condensates → connection between V and A

- Weinberg type sum rules: $\int ds(\rho_V - \rho_A)s^n = f_n$
  - Moments of the difference between vector and axial-vector SFs
  - Directly related to chiral symmetry breaking.
- QCD sum rules: $\frac{1}{M^2}\int ds \frac{\rho_{V/A}(s)}{s} e^{-s/M^2} = \sum_n C_n \langle \mathcal{O}_n \rangle$
  - Constrains vector or axial-vector SFs individually.
- Input
  - Vector SF from RW → link to dilepton experiments
  - Condensate T dependence from Lattice and HRG
  - Excites states with "chiral mixing"
  - Degenerate high-E continua (T independent)

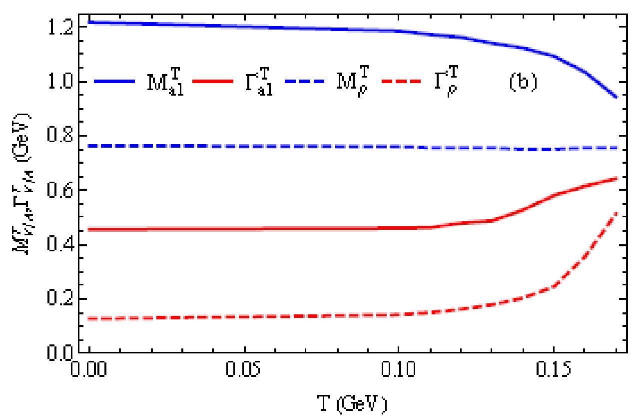


  - Phenomenological a_1 SF with parameters determined by satisfying SRs

Temperature evolution of SFs shows approach toward degeneracy



PMH and Rapp (2014)



V - AV mass degeneracy → Chiral symmetry

Resonance melting → Deconfinement

HI dileptons ⇨ Rho melting ⇨ a1 mass reduction and broadening

III. Hadronic Effective Field Theory
III.A. What is Massive Yang-Mills?

Extensive history

Chiral EFT with ρ, a_1, and π d.o.f.

- Consider a chiral non-linear sigma model to describe pions.
  - Theory has chiral phase transition
- Apply local gauging procedure
  - Physical vector and axial vector mesons = gauge bosons.
- Include "non-minimal" terms.
- Break symmetries by an explicit mass term for the mesons.

Amounts to a derivative expansion in chiral fields (but not gauge fields)

Lagrangian has 4 free parameters: m_0, g, σ, ξ or m_ρ, m_a, $g_{\rho\pi\pi}$, $g_{\rho\pi\pi}^{(3)}$.

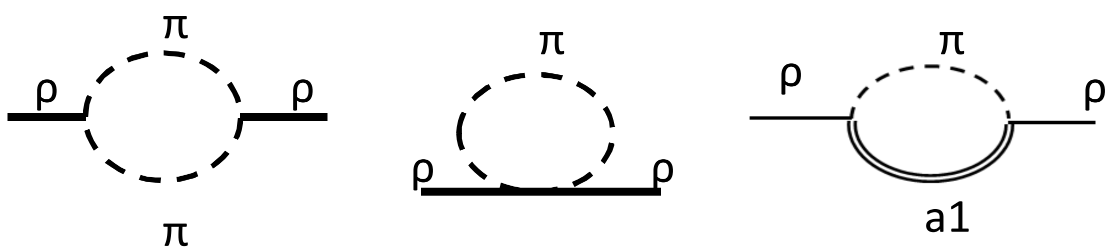
III.B. General procedure

III.B1. Diagrams

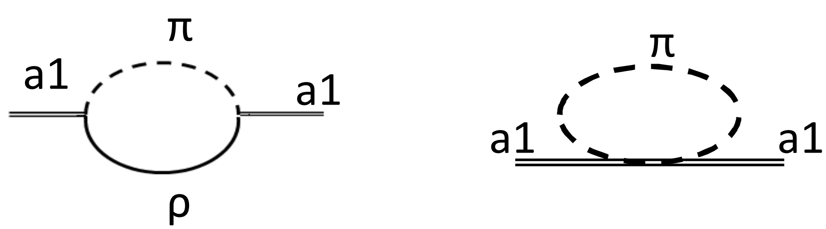
- Calculate vector and axial vector current-current correlators (self energies)

  with fewest number of diagrams to preserve symmetries

ρ:



a_1:

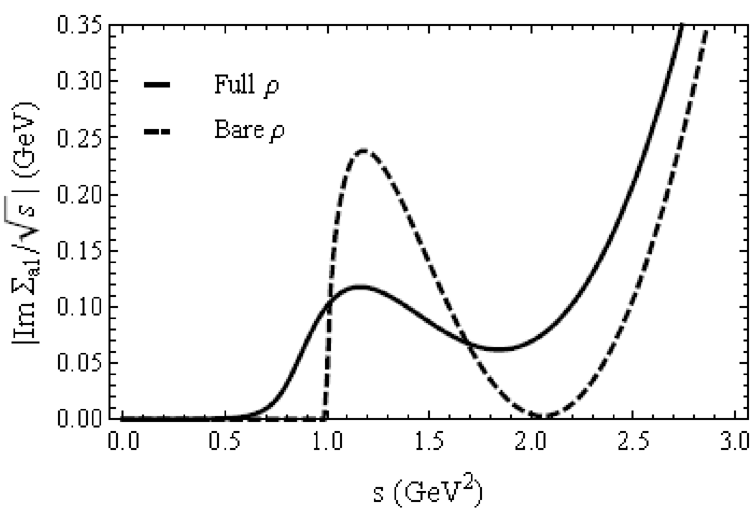


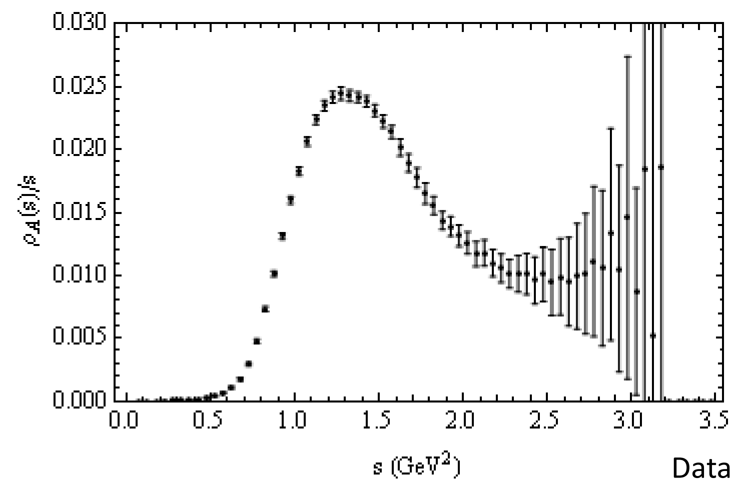
Regularized by dim-reg and counter terms.

8 additional free parameters (3 for V and 5 for AV).

III.B2. Problems and Solutions

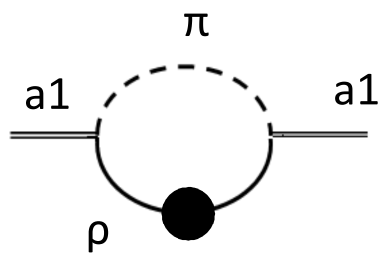
- Problems to overcome
  - a_1 width develops a zero followed by rapid growth at high energies
  - EW coupling too weak to produce necessary strength.
  - **Prevent fits to vacuum data (AV SF).**
- Solutions
  - Include a fully dressed rho propagator in a_1 loops.
    - **Need vertex correction diagrams to preserve chiral symmetry.**
  - Include a chirally invariant continuum.





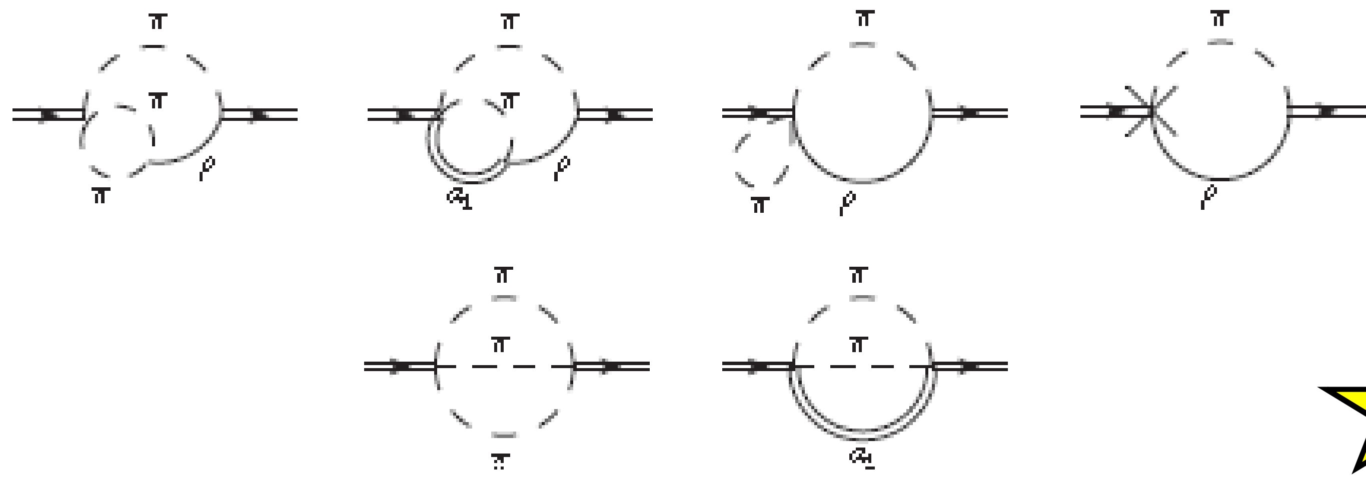
Data: ALEPH

III.B3. Broad rho and Vertex Corrections



Partial resummation of rho propagator via self energy.

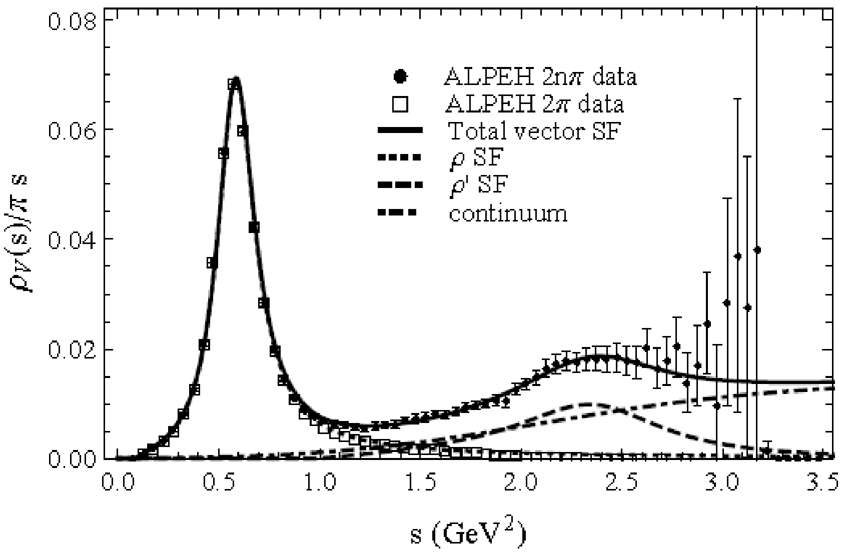
Violates chiral symmetry (PCAC) → Need vertex corrections.

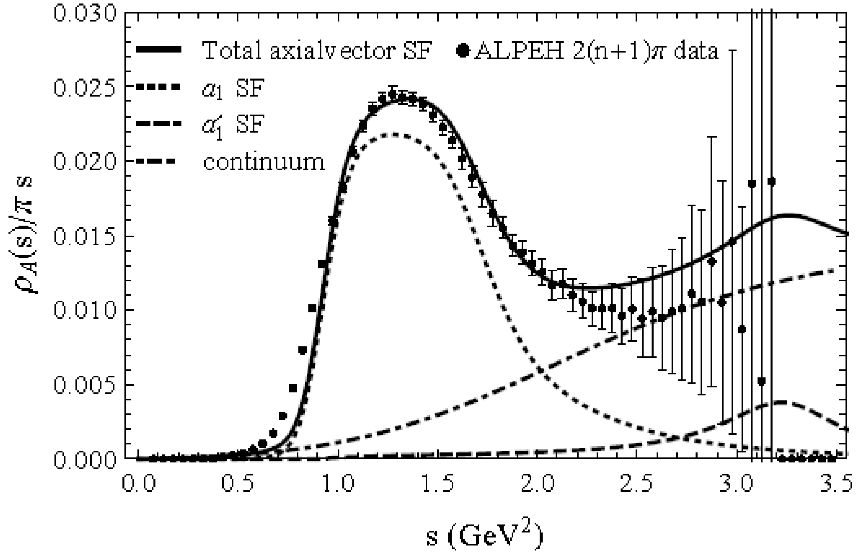


- Identify relations between Σ_{aa}, $\Sigma_{a\pi}$, and $\Sigma_{\pi\pi}$ which preserve chiral symmetry
- Include subset of vertex corrections consistent with partial resummation and symmetry.
- Control high energy behavior of vertex corrections with symmetry preserving cut-off

III.C. Vacuum Results

PMH and Rapp, (2014)





Data from ALEPH, (1998)

- For Vacuum, fit parameters to tau-decay

$m_\rho = 860\text{MeV}$ $m_a = 1200\text{MeV}$ $g_{\rho\pi\pi} = 6.01$ $g^{(3)}_{\rho\pi\pi} = 0.02\text{GeV}^{-2}$

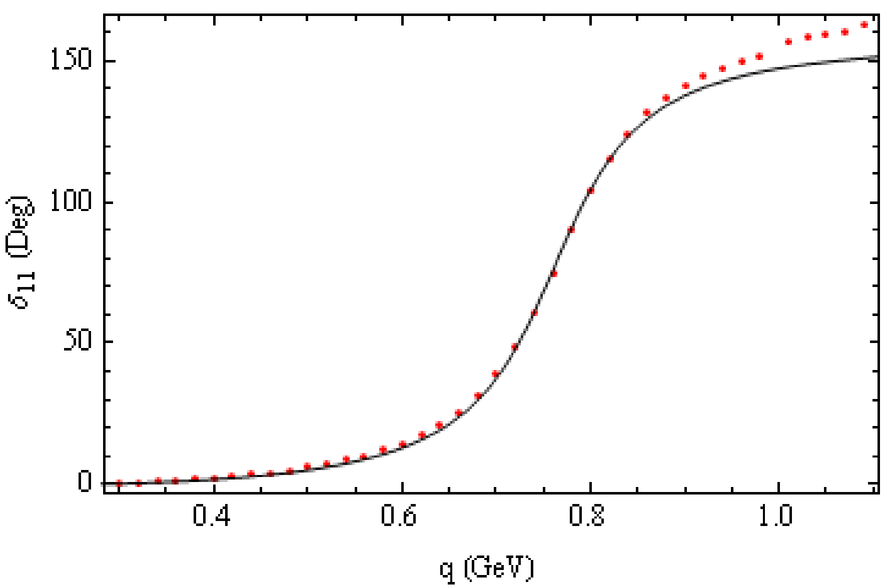
Continuum parameters are similar to sum rule study.

	Calc.	Expt.
$\Gamma_{a_1 \to \pi\gamma}$	244 keV	640±246 keV
$D/S\vert_{\sqrt{s}=1.23\text{GeV}}$	-0.125	-0.062±0.020

Vacuum "Predictions"

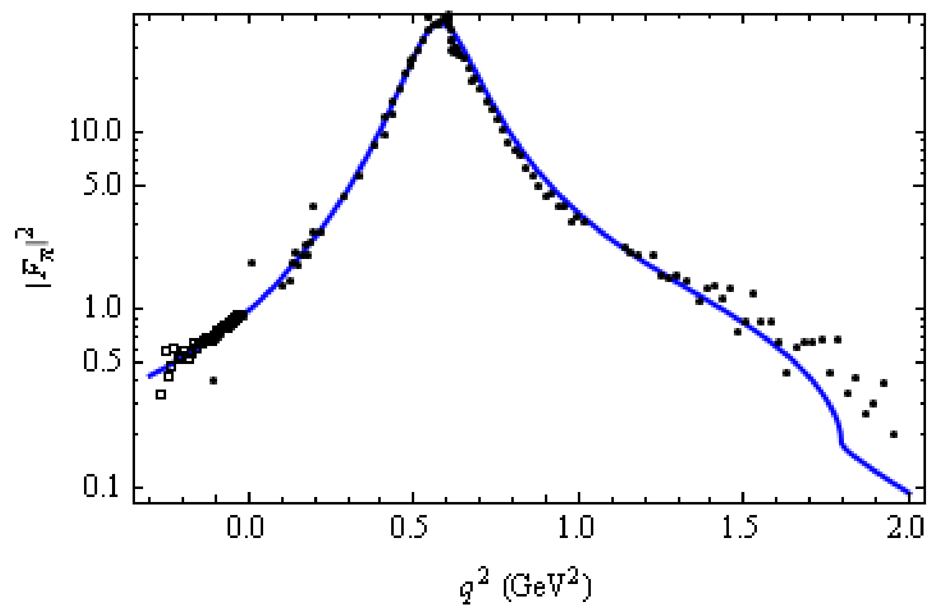
Not used in fitting procedure

ππ-phase shift



Data: Froggatt and Petersen, 1977

Pion Form factor



Data: NA7 and OLYA and CMD

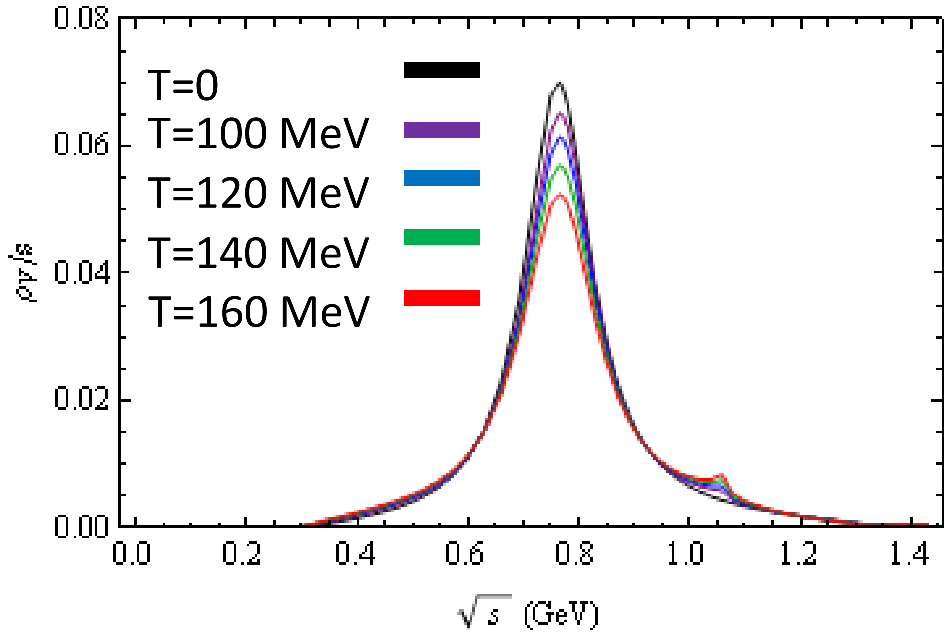
Both show satisfactory agreement with experimental data.

Vacuum V and AV SFs which agree with experiments can be constructed with aid of a broad rho and a chirally invariant continuum

Re-establishes MYM as a viable model to study chiral restoration.

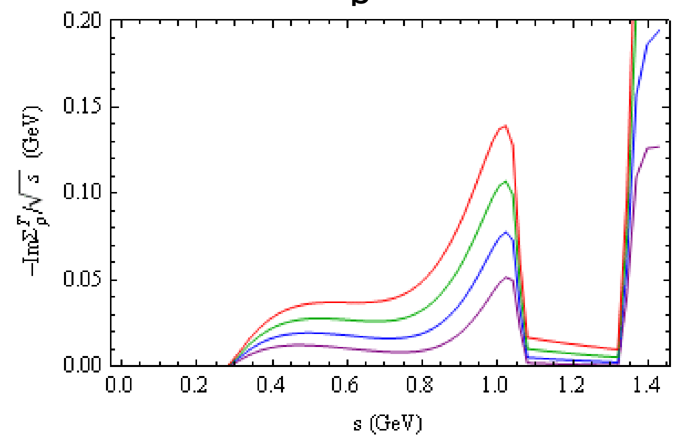
III.D. Finite Temperature
III.D1. Vector Spectral Function

Width broaden with no mass shift.

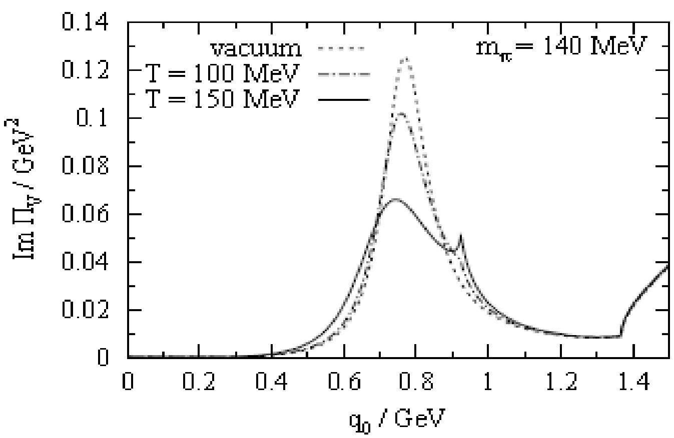


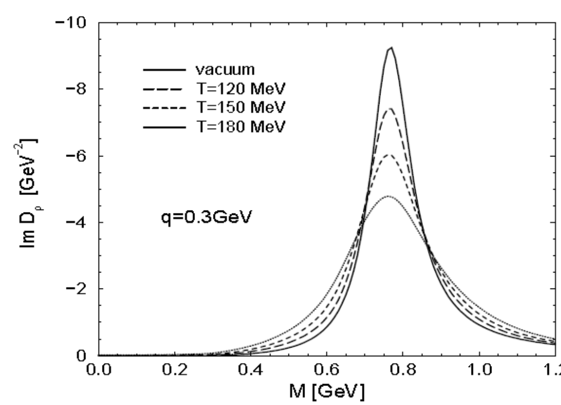
Urban et al 2001

Γ_ρ^T



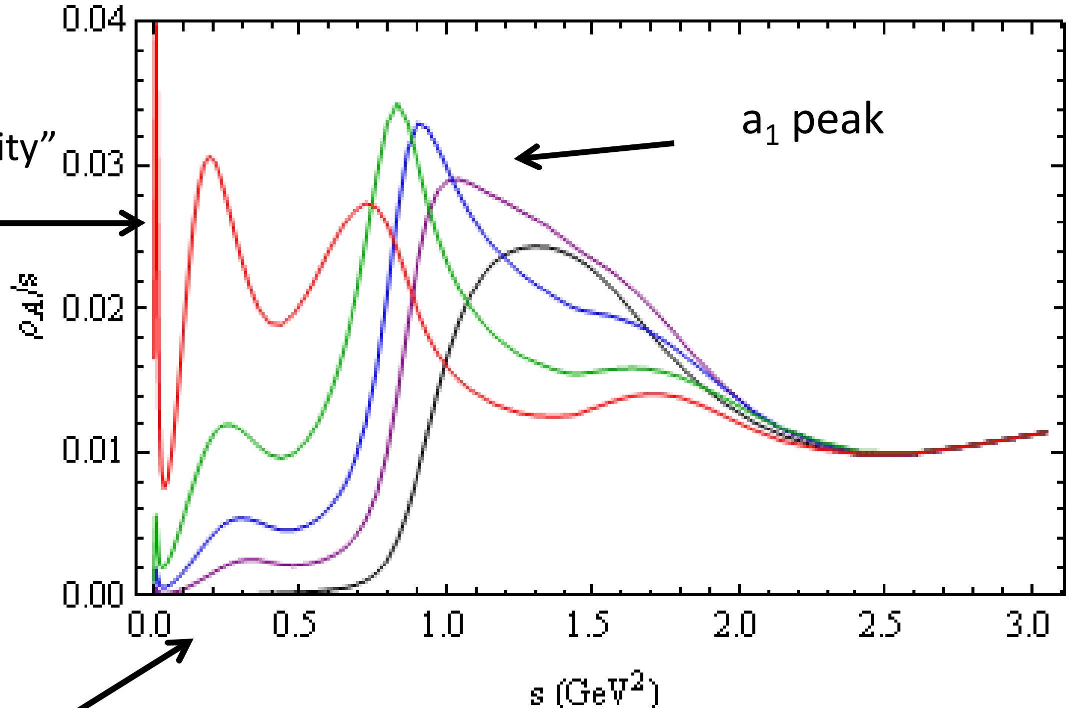
Gale and Rapp 1999





(Includes higher resonances)

III.D2. Axial Vector Spectral Function

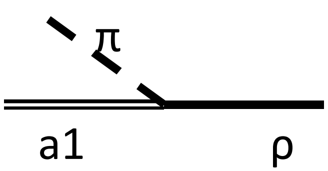


Axial-"conductivity"

T=0
T=100 MeV
T=120 MeV
T=140 MeV
T=160 MeV

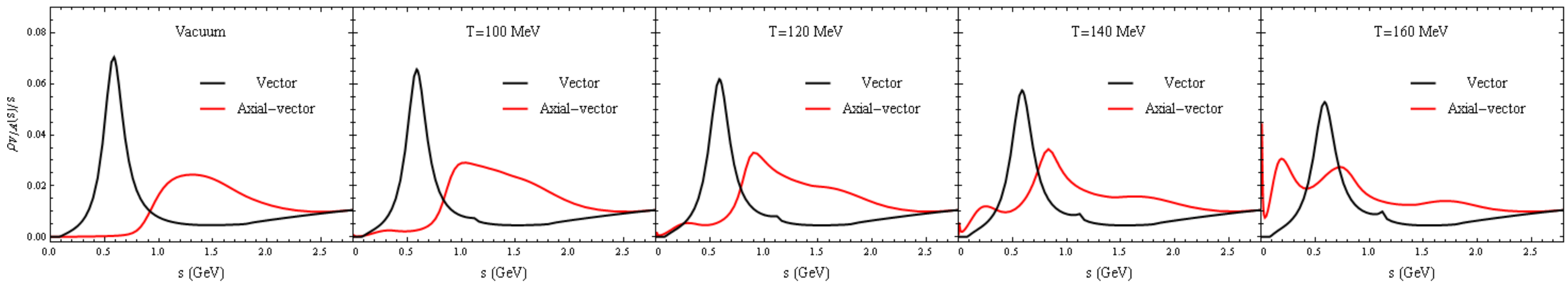
Thermal pion scattering

Mass shift towards lower energies.



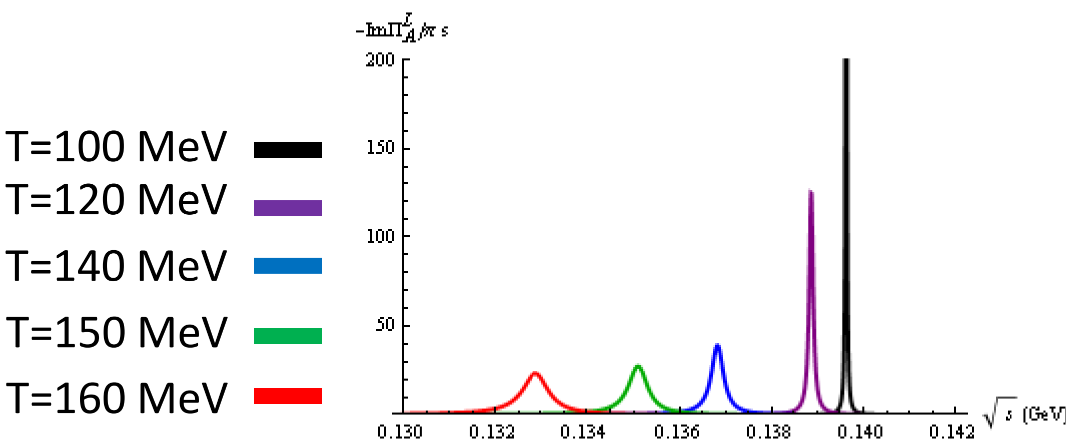
Suggests possible trend toward spectral degeneracy

III.D3. Chiral Symmetry Restoration?



Trend toward spectral degeneracy, but clearly not there.

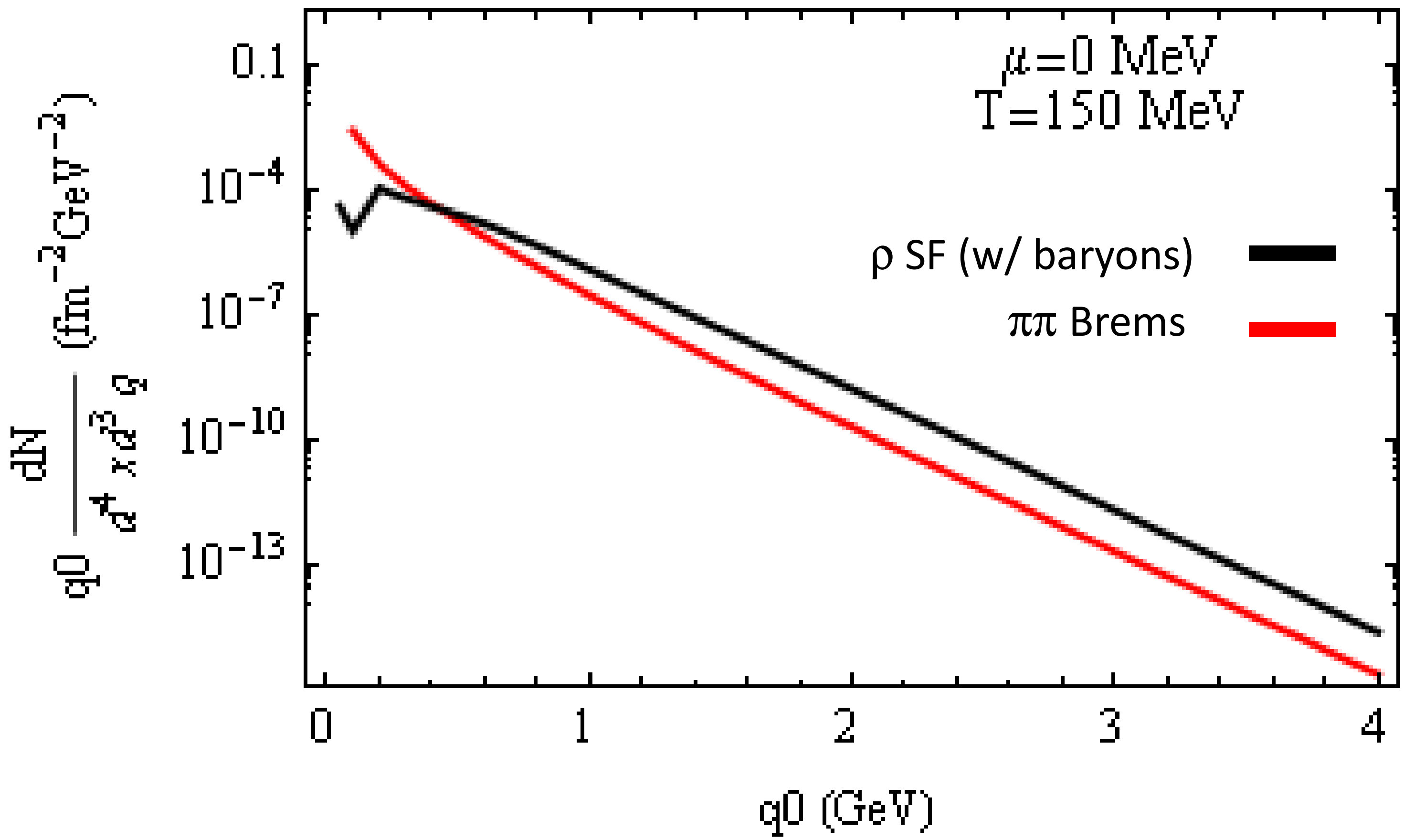
Want a quantitative measure of a chiral order parameter



Pion mass shift and marked reduction of peak strength

Extraction of f_π to be done

Photon rates from Bremsstrahlung



Bremsstrahlung ~10% contribution

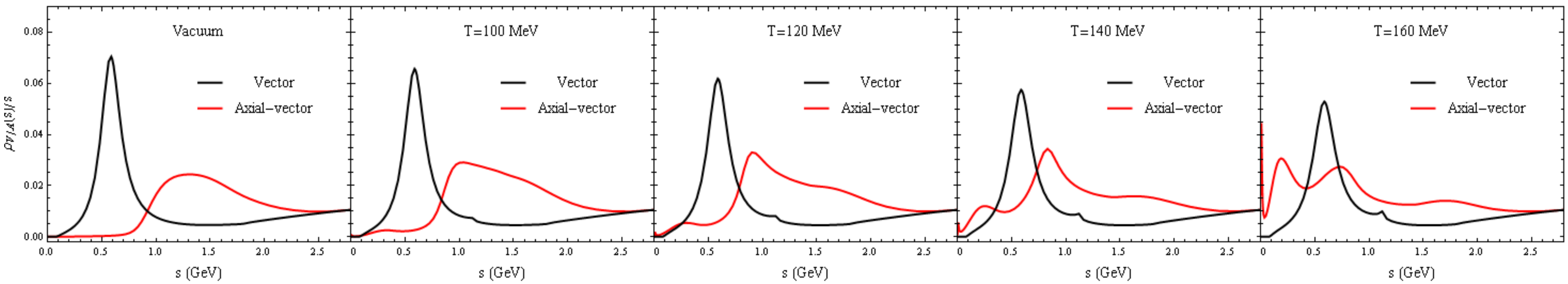
Parameterizations available soon.

IV: Summary

- **Sum Rules** (phenomenological study)
  - Found V and AV SFs which satisfied both QCDSRs and WSRs
  - Thermal evolution towards spectral degeneracy and chiral restoration
  - Characterized by the V broadening and the AV mass shift
- **Massive Yang-Mills** (microscopic calculation)
  - Vacuum:
    - Achieved agreement with vacuum spectral data
    - Included a broad rho and a chirally invariant continuum.
    - Broad rho was implemented preserving chiral symmetry
    - Re-established MYM as viable chiral model with V/AV mesons
  - Finite Temperature:
    - Vector SF consistent with only peak broadening without a mass shift
    - Axial Vector SF has mass shift toward vector
    - Quantitative chiral order parameter is still needed

A picture of chiral symmetry restoration may begin to emerge
but more work is still needed

MYM



Sum rules