Low Mass Dileptons and Chiral Symmetry Restoration

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Outline

- Chiral symmetry of QCD; dynamical breaking
- restoration in the medium
- Dileptons and vector correlator
- in-medium spectral function of vector mesons
- theoretically convincing signatures of chiral symmetry restoration
- summary and outlook

Chiral symmetry of QCD

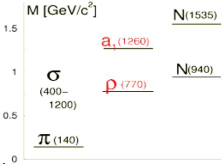
- In terms of chiral quark fields $(\gamma^5 q_{R,L} = \pm q_{R,L})$

$$\mathcal{L}_{QCD} = i\overline{q}_R \not{D} q_R + i\overline{q}_L \not{D} q_L - \frac{1}{4} G_{\mu\nu} G^{\mu\nu} \qquad q_{L,R} = \begin{pmatrix} u_{L,R} \\ d_{L,R} \end{pmatrix}$$
$$- m_q(\overline{q}_R q_L + \overline{q}_L q_R)$$

- for massless quarks no mixing of L and R (chiralities) $m_q \ll 1$ GeV fairly good approximation
- invariant under separate isospin rotations of left and right handed components $q_L \to U_L q_L$, $q_R \to U_R q_R$
- $\implies \mathcal{L}_{QCD}$ is $SU(2)_L \times SU(2)_R$ symmetric
- If the ground state of QCD is also chiral symmetric so that $Q_V|0\rangle = 0$ and $Q_A|0\rangle = 0$ $\rightarrow$we should expect degenerate isospin multiplets of opposite parity in hadron spectrum

What we actually observe

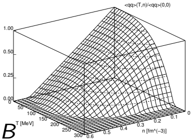
- we do see isospin multiplets (ρ^+, ρ^0, ρ^-), (p, n)
- but multiplets of opposite parity e.g (ρ, a_1) largely separated in mass ~ 500 MeV $m_q \neq 0$ unlikely reason



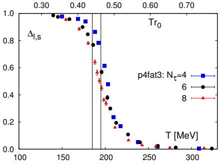
- QCD vacuum symmetric only under $SU(2)_V$ $Q_V|0\rangle = 0$ but $Q_A|0\rangle \neq 0$
- $\Longrightarrow$ hypothesis: $SU(2)_L \times SU(2)_R$ dynamically broken to $SU(2)_V$
- with the pion multiplet (π^+, π^0, π^-) as the (approximately) massless Goldstone bosons
- existence of the chiral condensate: $\langle 0|\bar{q}q|0\rangle \sim -(250\ MeV)^3$
  - QCD vacuum is a BE condensate of quark anti-quark pairs
  - induces $L \leftrightarrow R$ transitions
  - imparts dynamical (constituent) quark mass

Restoration of chiral symmetry

- heating/compression of hadronic matter leads to a non-trivial modification of the QCD vacuum leading to possible restoration of chiral symmetry
- ChPT calculations show a decrease of the chiral condensate with T



- linear density expansions show decrease with μ_B
  $\Longrightarrow$ to lowest order $\langle \overline{q}q \rangle \simeq \langle 0|\overline{q}q|0\rangle \left(1 - \dfrac{T^2}{8F_\pi^2} - \dfrac{\rho_N}{3\rho_0}\right)$
- lattice show $\langle \bar{q}q \rangle \to 0$ around $T \sim 170$ MeV
- an order parameter of χSR
  (not measurable experimentally)
  conjectured: $\dfrac{m_V^*}{m_V} \simeq \dfrac{\langle \overline{q}q \rangle}{\langle \overline{q}q \rangle_0}$ *Brown-Rho, Harada*



Bazavov (2009)

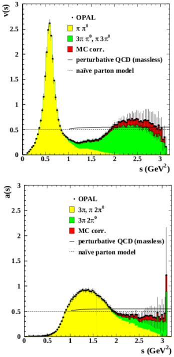
Current Correlators (in vacuum)

- modification of the vacuum is conveniently studied using current correlators

$$\Pi_V^{\mu\nu}(q) = i\int d^4x e^{iq\cdot x}\langle T V^\mu(x) V^\nu(0)\rangle$$

$$\Pi_A^{\mu\nu}(q) = i\int d^4x e^{iq\cdot x}\langle T A^\mu(x) A^\nu(0)\rangle$$

- $V^\mu = \overline{q}\gamma^\mu\tau_i q/2$ and $A^\mu = \overline{q}\gamma^\mu\gamma^5\tau_i q/2$ are chiral currents of QCD
- at low energies, these are dominated by ρ and a_1 resonances: very different spectral shapes $\rightarrow$ broken chiral symmetry
- $\Pi^{V,A}$ expanded in terms of quark and gluon condensates (QSR) $\Longrightarrow$ behaviour of resonances reflects the vacuum structure of QCD



ALEPH and OPAL τ *decays* $\rightarrow$ *even*(*odd*) *no. of* π'*s* V (A)

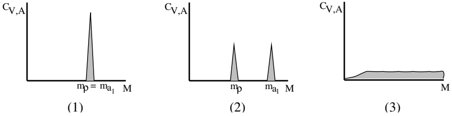
observing χSR through in-medium correlators

- at $T \geq T_\chi$ chiral symmetry demands that Π^V and Π^A are identical (not only mass and width but entire spectral shape)

- guidelines from Weinberg Sum Rules : relates difference of V and A correlators to vacuum parameters e.g.

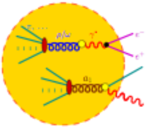
$$\int \frac{ds}{s} \left[\mathrm{Im}\Pi^V(s) - \mathrm{Im}\Pi^A(s) \right] = F_\pi^2$$

- three possibilities of observing χSR: Kapusta and Shuryak (1994)

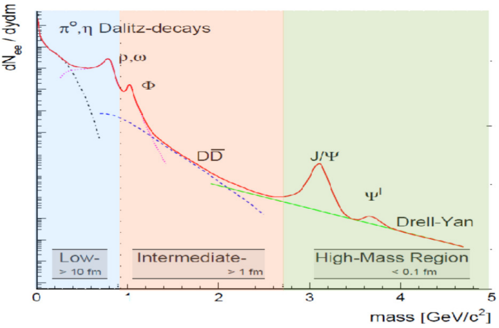


Koch(1997)

- $\mathrm{Im}\Pi^V$ is accessible from dilepton spectra
  $\mathrm{Im}\Pi^A$ not so because of final state interactions in $\pi\gamma$ invariant mass



$\mathrm{Im}\Pi^V$ from Dileptons: HICs



We will look at thermal dilepton production in the low mass region

- Low Mass Region: Dalitz decays and thermal radiation from low mass hadrons
- Intermediate Mass Region: thermal radiation from QGP and hadronic matter, semi-leptonic decays of heavy quarks
- High Mass Region: Drell-Yan, decays of heavy quarkonia

Dilepton Emission Rate

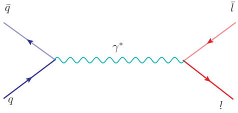
- Dilepton emission rate is given by the thermal expectation value of the correlator of EM currents *McLerran & Toimela*

$$\frac{dN_{l^+l^-}}{d^4x\ d^4q} = -\frac{\alpha^2}{3\pi^3\ q^2}\frac{L(m_l)}{e^{\beta q_0}+1}\,g^{\mu\nu}W_{\mu\nu}(q_0,\vec{q})$$

$$W_{\mu\nu}(q_0,\vec{q}) = \mathrm{Im}\int d^4x\ e^{iq\cdot x}\langle TJ^{em}_\mu(x)J^{em}_\nu(0)\rangle$$

- EM current of quarks

$$J^{em}_\mu = \sum_f e_f\overline{q}_f\gamma_\mu q_f$$



- gives the Born rate for emission from QGP

$$g^{\mu\nu}W_{\mu\nu}(q_0,\vec{q}) \simeq \sum_f e_f^2\frac{3q^2L(m_f)}{4\pi}\coth(\beta q_0/2)$$

Dileptons:Hadronic Matter

- Consider e.g. iso-vector projection of the EM current J_μ^{em}

$$J_\mu^{em} \rightarrow \frac{1}{2}(\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d)$$
$$= V_\mu$$

$\Longrightarrow$ coincides with the vector current of chiral symmetry

- use field-current identity (Sakurai); replace currents by fields - in this case the vector-isovector ρ meson

$$j_\mu^{em} \rightarrow F_\rho m_\rho \rho_\mu$$

- so that, EM correlator $\langle T\ j^{em}(x) j^{em}(0)\rangle \propto \langle T\ \rho(x)\rho(0)\rangle$ ρ -propagator

- imaginary part $\rightarrow W_{\mu\nu} = F_\rho^2 m_\rho^2\ \mathrm{Im}\, G^\rho_{\mu\nu} \ \propto\ \rho$ sp. fn.

Dileptons:Hadronic Matter

- Adding the iso-scalar contribution and other flavours,

$$W_{\mu\nu} = F_\rho^2 m_\rho^2 \,\mathrm{Im}\, G^\rho_{\mu\nu} + F_\omega^2 m_\omega^2 \,\mathrm{Im}\, G^\omega_{\mu\nu} \; + \; \cdots$$

$$\frac{dN_{l^+l^-}}{d^4x \; d^4q} = -\frac{\alpha^2}{3\pi^3 \; q^2} \frac{1}{e^{\beta q_0} + 1} \sum_V F_V^2 m_V^2 A_V(q_0, \vec{q}, T, \mu_B)$$

$\Longrightarrow$ dilepton production is given by the imaginary part of in-medium propagators (spectral functions) of vector mesons

- low mass dilepton emission $\equiv$ vector meson spectroscopy

In-medium spectral function

- Interactions of ρ with medium is evaluated perturbatively by means of the self-energy

$$G = G^0 + G^0\,\Pi\,G^0 + G^0\Pi\,G^0\Pi\,G^0 + \cdots.$$
$$= \frac{G^0}{1+\Pi G^0} = \frac{1}{p^2 - m^2 + \Pi}$$

- spectral function

$$A = \mathrm{Im}G = \frac{\mathrm{Im}\Pi}{(p^2 - m^2 + \mathrm{Re}\Pi)^2 + (\mathrm{Im}\Pi)^2}$$

- Real part gives in-medium mass & Imaginary part relates to width

- The spectral function at finite momentum is essential to study low mass lepton pair spectra

- requires good estimation of the vector meson self-energy

estimation of the self-energy

- We need to account for interactions with mesons and baryons in the hadronic medium (mesonic & baryonic loop diagrams)

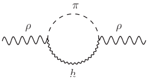
- to evaluate them we need :
  - effective interaction Lagrangian
  - Massive Yang-Mills *Song et al PRD (1996)*
  - Hidden Local Symmetry *Bando et al PRL (1985)*
  - Chiral Perturbation Theory with massive spin-1 fields *Ecker et al PLB (1989)*

- perturbative framework $\rightarrow$ thermal field theory
  - imaginary time formalism (Matsubara)
  - real time formalism

ρ self-energy: meson loops

- The one-loop self energy is given by

$$\Pi(E,\vec{q}) = i\int \frac{d^4k}{(2\pi)^4} N(q,k) D_\pi(k)\; D_h(q-k)$$



$h = \pi,\ \omega,\ h_1,\ a_1$

where $$D(k) = \frac{1}{k^2 - m^2 + i\epsilon} - 2i\pi n \delta(k^2 - m^2)$$

vacuum + medium

- The vertex factors in $N(q,k)$ are obtained from :

$$\begin{aligned}
\mathcal{L}_{int} &= -\frac{2G_\rho}{m_\rho F_\pi^2}\partial_\mu \vec{\rho}_\nu \cdot \partial^\mu \vec{\pi} \times \partial^\nu \vec{\pi} && \rho - \pi - \pi \\
&+\frac{g_1}{F_\pi}\epsilon_{\mu\nu\lambda\sigma}(\partial^\nu \omega^\mu \vec{\rho}^\lambda - \omega^\mu \partial^\nu \vec{\rho}^\lambda) \cdot \partial^\sigma \vec{\pi} && \rho - \omega - \pi \\
&-\frac{g_2}{F_\pi} h_1^\mu (\partial_\mu \vec{\rho}_\nu - \partial_\nu \vec{\rho}_\mu) \cdot \partial^\nu \vec{\pi} && \rho - h_1 - \pi \\
&+\frac{g_3}{F_\pi}(\partial_\mu \vec{\rho}_\nu - \partial_\nu \vec{\rho}_\mu) \cdot \vec{a}_1^\mu \times \partial^\nu \vec{\pi} && \rho - a_1 - \pi
\end{aligned}$$

Self-energy in medium

- In vacuum only the first diagram of (a) contributes
- in the medium there are eight possibilities

$$\mathrm{Im}\Pi(q_0,\vec{q}) = -\pi\int\frac{d^3k}{(2\pi)^3 4\omega_\pi\omega_h}\times$$

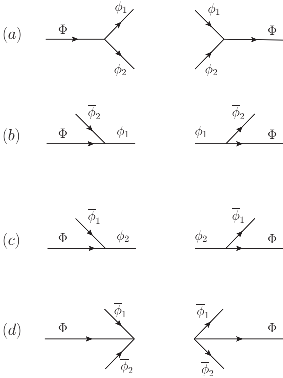
$$\Big[N_1\{\boxed{(1-f^{(0)}(\omega_\pi)-f^{(0)}(\omega_h))\delta(q_0-\omega_\pi-\omega_h)}$$

$$+(f^{(0)}(\omega_\pi)-f^{(0)}(\omega_h))\delta(q_0-\omega_\pi+\omega_h)\}+$$

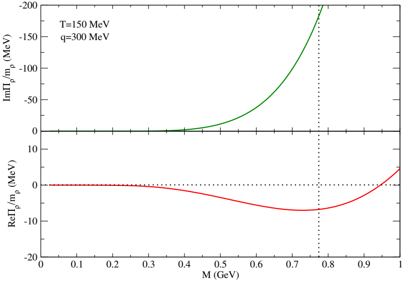
$$N_2\{\boxed{(f^{(0)}(\omega_h)-f^{(0)}(\omega_\pi))\delta(q_0+\omega_\pi-\omega_h)}$$

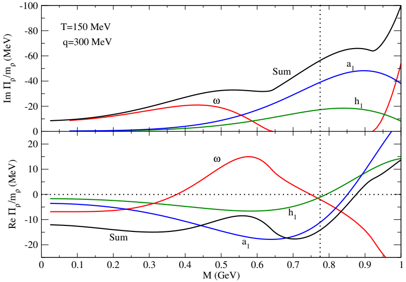
$$-(1-f^{(0)}(\omega_\pi)-f^{(0)}(\omega_h))\delta(q_0+\omega_\pi+\omega_h)\}\Big]$$

- for positive q^2 and q_0 the diagrams (a) and (c) contribute (shown by the boxed terms)



S.Mallik and SS EPJC 61 (2009) 489





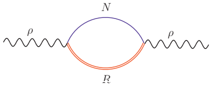
contribution from $\pi - \pi$ loop to real and imaginary parts

additional contributions from the $\pi - \omega$, $\pi - h_1$ and $\pi - a_1$ loops

S. Ghosh, S.S & S. Mallik, EPJC (2010)

ρ self-energy: Baryons

- Baryon contribution is included through RN loops; $R \to$ 4-star baryon resonances



$$\Pi(q) = i \int \frac{d^4p}{(2\pi)^4} Tr[\Gamma_{\mu\alpha} S(p, m_N) \Gamma_{\nu\beta} S^{\beta\alpha}(p-q, m_R)]$$

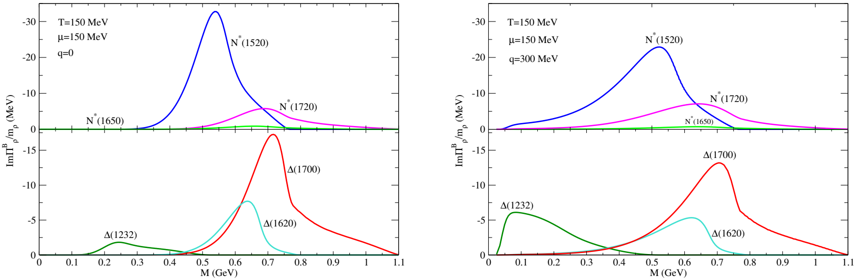
- The ρNR interaction vertices $\Gamma_{\mu\nu}$ are obtained from:

$$\mathcal{L} = g_{RN\rho}[\overline{\psi}_R \sigma^{\mu\nu} \rho_{\mu\nu} \psi_N + h.c.] \qquad J_R^P = \frac{1}{2}^+ [N(940)]$$

$$\mathcal{L} = g_{RN\rho}[\overline{\psi}_R \sigma^{\mu\nu} \gamma^5 \rho_{\mu\nu} \psi_N + h.c.] \qquad J_R^P = \frac{1}{2}^- [N^*(1650), \Delta(1620)]$$

$$\mathcal{L} = g_{RN\rho}[\overline{\psi}_R^{\mu} \gamma^{\nu} \gamma^5 \rho_{\mu\nu} \psi_N + h.c.] \qquad J_R^P = \frac{3}{2}^+ [N^*(1720), \Delta(1232)]$$

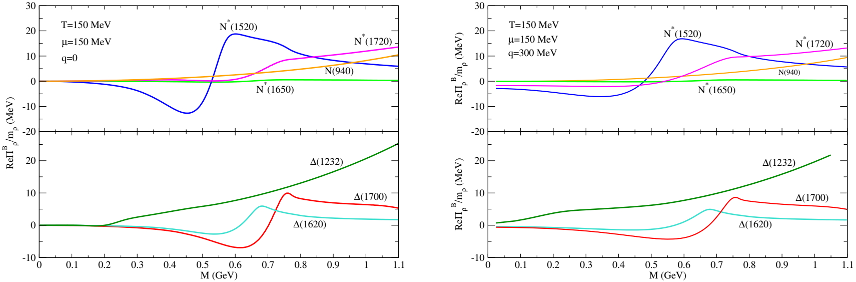
$$\mathcal{L} = g_{RN\rho}[\overline{\psi}_R^{\mu} \gamma^{\nu} \rho_{\mu\nu} \psi_N + h.c.] \qquad J_R^P = \frac{3}{2}^- [N^*(1520), \Delta(1700)]$$



- baryonic loops significantly contribute to the spectral strength in the low mass region

S. Ghosh & S.S. NPA (2011)

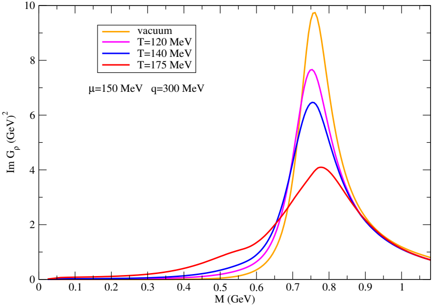
Real parts

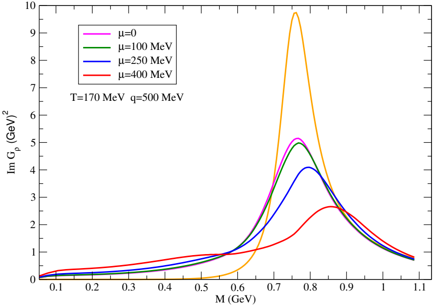


- The real parts from baryonic loops make a small positive contribution

S. Ghosh & S.S. NPA (2011)

The ρ spectral function

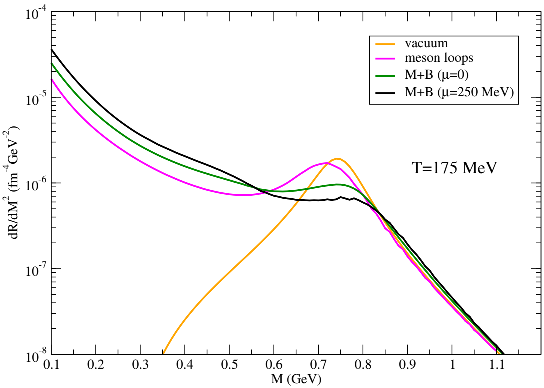




- ρ spectral function from meson and baryon loops:

$$A_\rho = \frac{\mathrm{Im}\Pi_\rho}{(p^2-m^2+\mathrm{Re}\Pi_\rho)^2+(\mathrm{Im}\Pi_\rho)^2}; \quad \Pi_\rho = \sum_{h=\pi,\omega,h_1,a_1} \Pi_{\pi h} + \sum_{R=N,N^*,\Delta} \Pi_{NR}$$

S. Ghosh & S.S. NPA (2011)

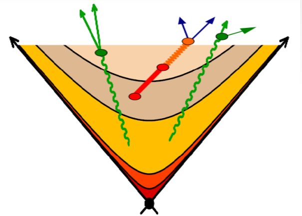


$$\frac{dN_{l\bar{l}}}{d^4x\ dM^2 q_T dq_T dy} = -\frac{\alpha^2}{3\pi^3\ q^2}\,\frac{1}{e^{\beta q_0}+1}\,F_\rho^2 m_\rho^2 A_\rho(q_0,\vec{q},T,\mu_B)$$

S.S. & S.Ghosh (2013)

Space-time evolution

- QGP → Hadron gas → chem. freeze-out → thermal freeze-out
- The total yield is obtained as

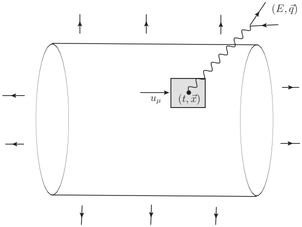


$$\frac{dN}{d^4Q} = \int d^4x \frac{dN}{d^4x\, d^4Q}(E^*(x), T(x))$$
$$E^* = u^\mu Q_\mu$$
$$= \gamma_T[M_T \cosh(y-\eta) + q_T\ v_T \cos\varphi]$$

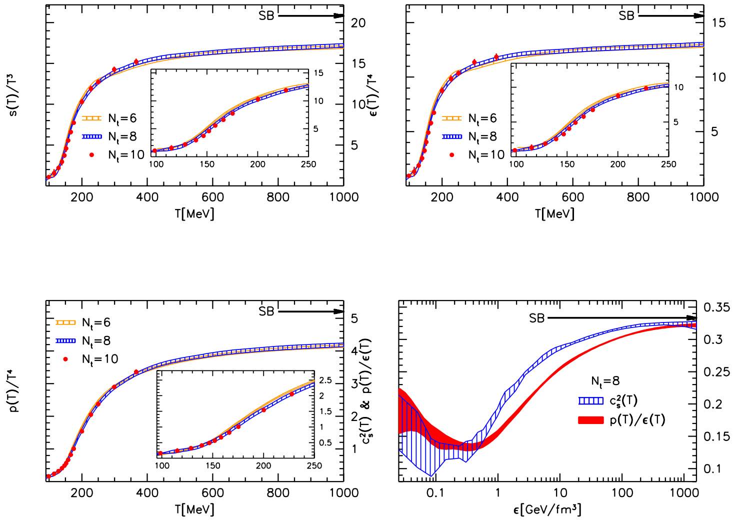
- $v_T = v_T(x, y, \tau, \eta)$ and $T = T(x, y, \tau, \eta)$ are obtained from

$$\partial_\mu T^{\mu\nu} = 0; \quad T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - g^{\mu\nu} p$$

using the Equation of State : $p = p(\epsilon)$ e.g from lattice

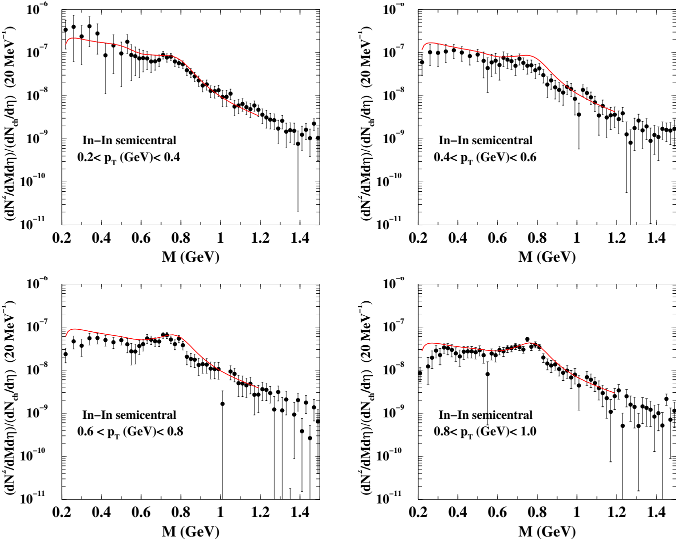


Lattice Equation of State



S. Borsanyi et al JHEP (2010)

Dimuon mass spectra from In-In collisions @ SPS



S.S. & S. Ghosh (2013)

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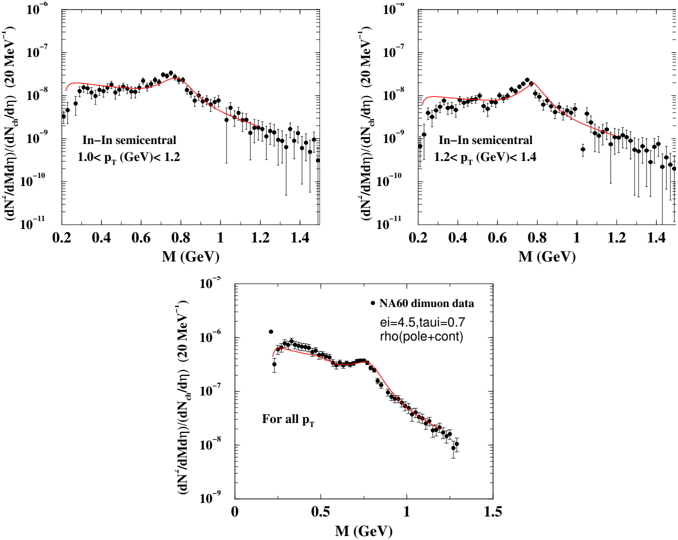


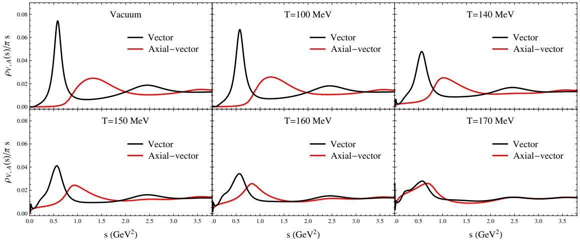
S.S. & S. Ghosh (2013)

Conclusions and Outlook : observing χSR using dileptons

- comprehensive agreement with data at several p_T and M provides confidence about the vector spectral function
- consistent with a scenario where the ρ spectral function is significantly broadened
- to check for χSR we need to obtain the axial-vector (a_1) spectral function :-
  - Start from a microscopic theory (chiral effective theory)
  - should reproduce the vacuum axial-vector spectral function
  - obtain the in-medium spectral function
  - no experimental verification forthcoming $\Longrightarrow$ check consistency with in-medium Weinberg Sum Rules
  - test if the vector and axial-vector spectral functions conform to any of the scenarios of χSR

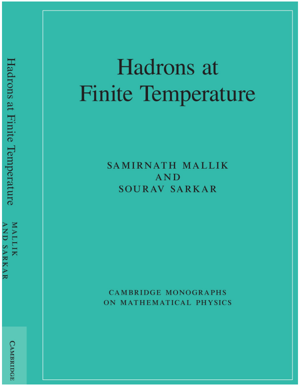
Conclusions and Outlook : schematic study

- Connecting dileptons and χSR using ansatz a_1 sp-fn (Rapp 2014)
  - the a_1 resonance is parametrised with Breit-Wigner functions
  - in-medium modification of a_1 implemented through 4-parameter ansatz compatible with Weinberg Sum Rules



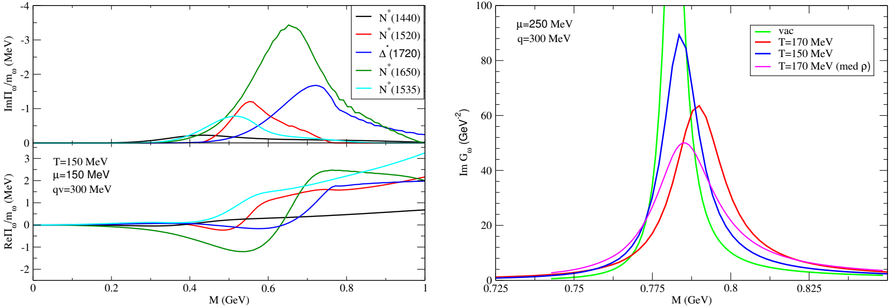
- scheme to be scrutinized by microscopic calculations
- Status: calculation of the a_1 spectral function is challenging even in vacuum (existing schemes do not lead to measured sp-fn)

Theoretical details are discussed in the upcoming book



Thanks

The ω spectral function



- meson loop: $\rho - \pi$
  baryon loop: $N - R$,
  $[R = N^*(1440), N^*(1520), N^*(1535), N^*(1650), \Delta(1720)]$

S. Ghosh & S.S. EPJC (2013)