Hadrons in hot and dense matter II

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Outline

Theory of electromagnetic probes

The McLerran-Toimela formula

- derivation of dilepton-production rate [MT85, GK91]

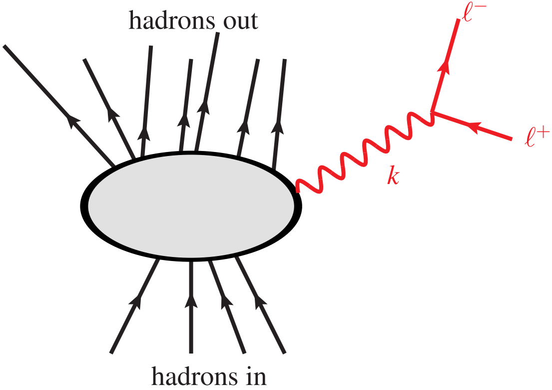
$$\frac{\mathrm{d}R_{\ell^+\ell^-}}{\mathrm{d}^4 k} = \frac{\mathrm{d}N_{\ell^+\ell^-}}{\mathrm{d}^4 x\, \mathrm{d}^4 k}$$

- radiation of dileptons from thermalized strongly interacting particles with total pair four-momentum k
- dileptons escape fireball without any final-state interactions
- calculation exact concerning strong interactions
- leading-order $\mathscr{O}(\alpha^2)$ in QED
- implies assumption that leptons don't suffer final-state interactions

$$\mathbf{H}_{\text{em}}^{(\text{int})} = e \int \mathrm{d}^3 \vec{x}\; \mathbf{J}_\mu(t,\vec{x}) A^\mu(t,\vec{x}), \quad A^\mu(t,\vec{x}) = \frac{\epsilon^\mu}{2\omega V} \exp(i k \cdot x)$$

- $\mathbf{J}_\mu$: exact (wrt. strong interaction!) em. current operator of quarks or hadrons
  in the Heisenberg picture wrt. strong interactions
- $e = \sqrt{4\pi\alpha}$, $\alpha \simeq 1/137$

The McLerran-Toimela formula



- Fermi's golden rule ⇒ transition-matrix element for process $|i\rangle \rightarrow \left|f'\right\rangle = \left|f\right\rangle + |\ell^+\ell^-(k)\rangle$
- QED Feynman rules

$$S_{f'i} = \left\langle f \left| \int \mathrm{d}^4 x \; \mathbf{J}_\mu(x) \right| i \right\rangle D_\gamma^{\mu\nu}(x,x') e \overline{u}_\ell(x') \gamma_\nu v_\ell(x')$$

The McLerran-Toimela formula

- Fourier transformation: energy-momentum conservation $\left|f'\right\rangle = \left|f, \ell^+\ell^-(k)\right\rangle$

$$S_{fi} = T_{fi}(2\pi)^4 \delta^{(4)}(P_f + k - P_i)$$

- Fermi's trick: Rate

$$R_{f'i} = \frac{|S_{f'i}|^2}{\tau V} = (2\pi)^4 \delta^{(4)}(P_f + k - P_i)|T_{f'i}|^2$$

- summing over $\left|f\right\rangle$ and polarizations of dilepton states
- averaging over initial hadron states: heat bath (grand canonical)

$$\boldsymbol{\rho} = \frac{1}{Z} \exp[-\beta(\mathbf{H}_{\text{QCD}} - \mu_B \mathbf{Q}_{\text{baryon}})]$$

The McLerran-Toimela formula

- result (derivation see [GK91], Appendices)

$$\frac{\mathrm{d}R_{\ell^+\ell^-}}{\mathrm{d}^4 k} = -\frac{\alpha^2}{3\pi^3}\frac{k^2+2m_\ell^2}{(k^2)^2}\sqrt{1-\frac{4m_\ell^2}{k^2}}\, g_{\mu\nu} n_{\mathrm{B}}(k^0) \operatorname{Im}\Pi_{\mathrm{ret}}^{\mu\nu}(k)$$

- em. current-current correlator

$$\mathrm{i}\Pi_{\mathrm{ret}}^{\mu\nu}(k) := \int \mathrm{d}^4 x\ \exp(\mathrm{i}k\cdot x)\left\langle [\mathbf{J}^{\mu}(x), \mathbf{J}^{\nu}(0)]\right\rangle_{T,\mu_B} \Theta(x^0)$$

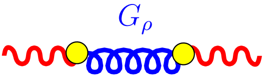
- written in (local) restframe of the medium
- in principle measureable: in linear response approximation Green's function for lepton current running through medium
- $k^2 = M^2 > 0$ invariant mass of dilepton
- probing medium with photons: same correlator for $k^2 = M^2 = 0$
- then correlator $\Leftrightarrow$ dielectric function $\epsilon(\omega)$ in electrodynamics!

The McLerran-Toimela formula

- for real photons

$$\omega \frac{\mathrm{d}R}{\mathrm{d}^3\vec{k}} = -\frac{\alpha g_{\mu\nu}}{2\pi^2} \operatorname{Im} \Pi^{\mu\nu}_{\mathrm{ret}}(k) n_{\mathrm{B}}(k^0), \quad k^0 \omega = |\vec{k}|$$

- written in (local) restframe of the medium
- Phenomenological effective hadronic model: vector-meson dominance model
- em. current $\propto V^{\mu}$ (with $V \in \{\rho, \omega, \phi\}$)

$\Sigma^{\gamma}_{\mu\nu} =$ 

- Dilepton/photon rates: $\propto A_V = -2 \operatorname{Im} D_V^{(\mathrm{ret})}$ (vector-meson spectral function!)
- measuring in-medium vector-meson spectral function!?!

Em. current-current correlator

Vector Mesons and electromagnetic Probes

- photon and dilepton thermal emission rates given by same electromagnetic-current-correlation function ($J_\mu = \sum_f Q_f \overline{\psi_f} \gamma_\mu \psi_f$)
- McLerran-Toimela formula

$$\Pi^{<}_{\mu\nu}(q) = \int \mathrm{d}^4 x \exp(\mathrm{i} q \cdot x) \left\langle J_\mu(0) J_\nu(x) \right\rangle_T = -2 n_{\mathrm{B}}(q_0) \operatorname{Im} \Pi^{(\mathrm{ret})}_{\mu\nu}(q)$$

$$q_0 \frac{\mathrm{d}N_\gamma}{\mathrm{d}^4 x \, \mathrm{d}^3 \vec{q}} = -\frac{\alpha_{\mathrm{em}}}{2\pi^2} g^{\mu\nu} \operatorname{Im} \Pi^{(\mathrm{ret})}_{\mu\nu}(q,u) \Big|_{q_0 = |\vec{q}|} f_B(p \cdot u)$$

$$\frac{\mathrm{d}N_{e^+e^-}}{\mathrm{d}^4 x \, \mathrm{d}^4 k} = -g^{\mu\nu} \frac{\alpha^2}{3 q^2 \pi^3} \operatorname{Im} \Pi^{(\mathrm{ret})}_{\mu\nu}(q,u) \Big|_{q^2 = M^2_{e^+e^-}} f_B(p \cdot u)$$

- manifestly Lorentz covariant (dependent on four-velocity of fluid cell, u)
- to lowest order in α: $4\pi\alpha \Pi_{\mu\nu} \simeq \Sigma^{(\gamma)}_{\mu\nu}$
- derivable from underlying thermodynamic potential, Ω!

Vector Mesons and chiral symmetry

- vector and axial-vector mesons $\longleftrightarrow$ respective current correlators

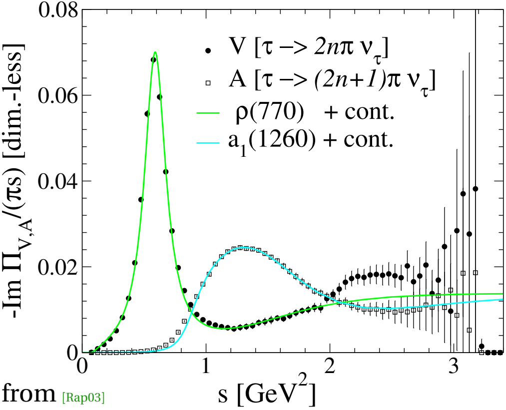
$$\Pi^{\mu\nu}_{V/A}(p) := \int \mathrm{d}^4 x \exp(\mathrm{i} p x) \left\langle J^{\nu}_{V/A}(0) J^{\mu}_{V/A}(x) \right\rangle_{\text{ret}}$$

- Ward-Takahashi Identities of χ symmetry $\Rightarrow$ Weinberg-sum rules

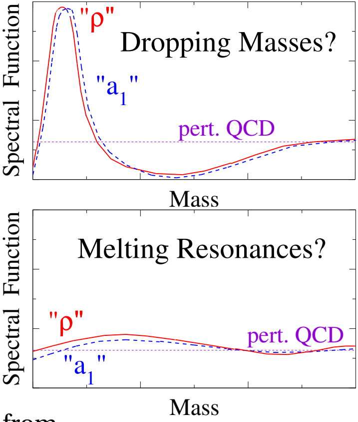
$$f_\pi^2 = -\int_0^\infty \frac{\mathrm{d}p_0^2}{\pi p_0^2} [\operatorname{Im}\Pi_V(p_0,0) - \operatorname{Im}\Pi_A(p_0,0)]$$

- spectral functions of vector (e.g. ρ) and axial vector (e.g. a_1) directly related to order parameter of chiral symmetry!

Vector Mesons and chiral symmetry



from [Rap03]



from [Rap05]

- at high enough temperatures and or densities: melting of $\langle \overline{q} q \rangle$
- $\Rightarrow$ spontaneous breaking of chiral symmetry supended
- $\Rightarrow$ chiral phase transition; chiral-symmetry restoration (χSR)
- which scenario is right? microscopic mechanisms behind χSR?

QCD Sum Rules

- based on [LPM98]
- calculate current correlator, e.g., the vector part of the em. current

$$j_\mu = \frac{1}{2}(\overline{u}\gamma_\mu u - \overline{d}\gamma_\mu d)$$

- corresponds to the ρ meson!
- use pQCD to determine correlator

$$\Pi_{\mu\nu}(k) = \left(g_{\mu\nu} - \frac{k_\mu k_\nu}{k^2}\right)\Pi(k^2)$$

  in deep spacelike region, $Q^2 = -k^2 \gg \Lambda_{\text{QCD}}$
- related to time-like region ⇒ sum rule

$$\Pi(k^2) = \Pi(0) + cQ^2 + \frac{Q^4}{\pi}\int_0^\infty \mathrm{d}s \, \frac{\operatorname{Im}\Pi(s)}{s^2(s+Q^2-\mathrm{i}\epsilon)}$$

- dispersion relation: spectral function $\operatorname{Im}\Pi$!

QCD Sum Rules

- left-hand side of sum rule
- pQCD + chiral models for baryon-pion interactions [see, e.g., [DGH92]]

$$R(Q^2) := \frac{\Pi(k^2 = -Q^2)}{Q^2} = -\frac{1}{8\pi^2}\left(1 + \frac{\alpha_s}{\pi}\right)\ln\left(\frac{Q^2}{\mu^2}\right)$$
$$+ \frac{1}{Q^4} m_q \langle \overline{q} q \rangle + \frac{1}{24 Q^4}\left\langle \frac{\alpha_s}{\pi} F^a_{\mu\nu} F^{a\mu\nu}\right\rangle - \frac{112}{81 Q^6} \kappa \langle \overline{q} q \rangle^2$$

- additional cold-nuclear matter contributions

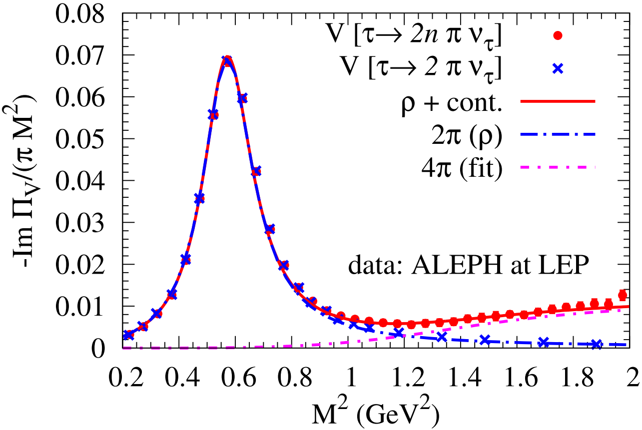
$$\Delta R(Q^2) = \frac{m_N}{4Q^4} A_2 \rho_N - \frac{5 m_N^3}{12 Q^6} A_4 \rho_N$$

- $A_{2,4}$ from parton-distribution functions
- also condensates medium-modified (in low-density approximation)

$$\langle \overline{q} q \rangle = \langle \overline{q} q \rangle_{\text{vac}} + \frac{\sigma_N}{2 m_q} \rho_N,$$
$$\left\langle \frac{\alpha_s}{\pi} F^a_{\mu\nu} F^{a\mu\nu}\right\rangle = \left\langle \frac{\alpha_s}{\pi} F^a_{\mu\nu} F^{a\mu\nu}\right\rangle_{\text{vac}} - \frac{8}{9} m_N^{(0)} \rho_N$$

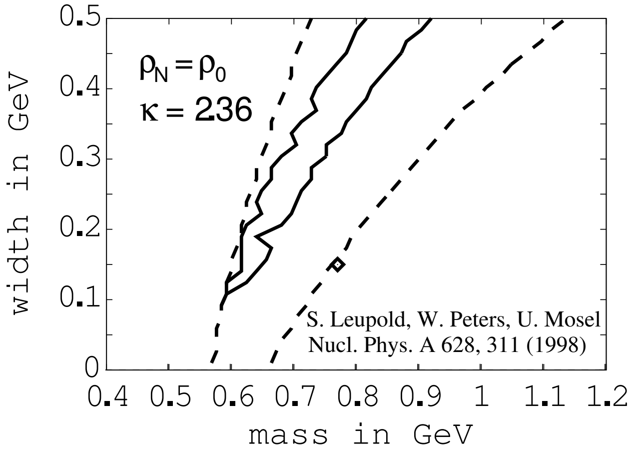
QCD Sum Rules

- right-hand side of sum rule
- use hadronic models to fit measured vector-current correlator
- e.g., ALEPH/OPAL data of $\tau \rightarrow \nu + 2n\pi$



QCD Sum Rules

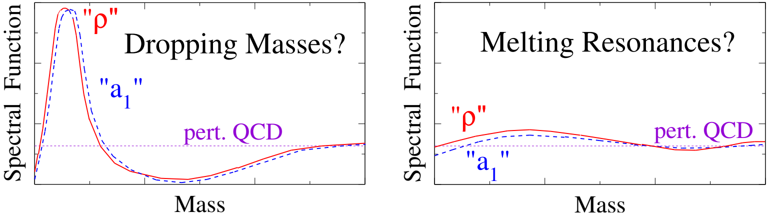
- typical result from [LPM98]



- possible medium effects on ρ meson
  - dropping mass, unchanged/small width
  - unchanged mass, broadened spectrum (large width)

Scenarios for chiral symmetry restoration

- hadron spectrum must become degenerate between chiral partners



- models alone of little help (realization of χS not unique!)
  - "vector manifestation" $\rho_{\text{long}} = \chi$ partner of $\pi \Rightarrow$ dropping mass
  - "standard realization" $\rho = \chi$ partner of a_1,
    extreme broadening + little mass shifts
- theory "shopping list"
  - effective hadronic models (well constrained in vacuum!)
  - and concise evaluation in the medium!
  - models for fireball evolution
    (blast-wave parametrizations, hydro, transport, and transport-hydro hybrids)
  - must include partonic → phase transition → hadronic evolution
- precise $\ell^+\ell^-$ (γ) data from HICs mandatory!

Hadronic models

Effective hadronic models: chiral-symmetry constraints

- different realizations of chiral symmetry
- equivalent only on shell ("low-energy theorems")
- model-independent conclusions only in low-temperature/density limit (chiral perturbation theory) or from lattice-QCD calculations
- QCD sum rules: allow dropping-mass or melting-resonance scenario
- use phenomenological hadronic many-body theory (HMBT) to assess medium modifications of vector mesons
  - build models with hadrons as effective degrees of freedom
  - based on (chiral) symmetries
  - constrained by data on cross sections, branching ratios,... in the vacuum
  - in-medium properties assessed by many-body (thermal) field theory

Example: vector meson dominance model

- early model for electromagnetic interaction of charged pions
  [Sak60, KLZ67, GS68, Her92, Hee00]
- QED like U(1)-gauge model with massive vector meson for ρ_0 and $\pi^{\pm}$
- Stückelberg: introduce auxiliary scalar field for free vector mesons:

$$\mathscr{L}_\rho = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m^2 V_\mu V^\mu + \frac{1}{2} (\partial_\mu \varphi)(\partial^\mu \varphi) + m \varphi \partial_\mu V^\mu$$

- gauge invariant under local transformation

$$\delta V_\mu(x) = \partial_\mu \chi(x), \quad \delta \varphi = m \chi(x)$$

- Coupling to pions: obey gauge invariance! (like scalar QED)

$$\mathscr{L}_\pi = (\mathrm{D}_\mu \pi)^* (D^\mu \pi) - m_\pi^2 |\pi|^2 - \frac{\lambda}{8} |\pi|^4$$

- $\mathrm{D}_\mu = \partial_\mu + \mathrm{i} g V_\mu$; g: $\rho\pi\pi$ coupling

VMD model (photon part)

- add photons: $\mathrm{D}_\mu = \partial_\mu + \mathrm{i} g V_\mu + \mathrm{i} e A_\mu$
- Lagrangian for photons: usual (gauge fixed) QED
- additional direct $\rho\gamma$ mixing [KLZ67]

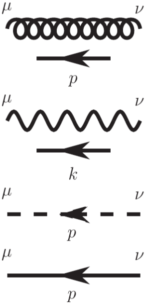
$$\mathscr{L}_{\rho\gamma} = -\frac{e}{2 g_{\rho\gamma}} V_{\mu\nu} A^{\mu\nu}$$

- classical field equations: ⇒ electromagnetic current

$$j_{\text{em}}^{\nu} = \partial_\mu A^{\mu\nu} = \mathrm{i} e \left(1 - \frac{g}{g_{\rho\gamma}}\right) \pi \overleftrightarrow{\mathrm{D}}^{\nu} \pi^* + \frac{e}{g_{\rho\gamma}} m^2 V^{\mu} + \frac{e^2}{g_{\rho\gamma}^2} \partial_\mu A^{\mu\nu}$$

- for $g_{\rho\gamma} = g$: $j_{\text{em}}^{\nu} = \frac{e}{g} m^2 V^{\nu} + \mathscr{O}(e^2)$: ⇒ “vector-meson dominance”

VMD model (Feynman rules in Feynman gauge)



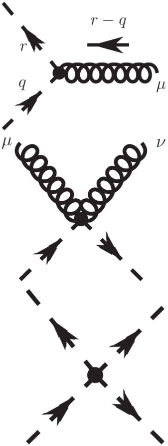
$$= -\mathrm{i}\frac{\eta^{\mu\nu}}{p^2 - M^2 + \mathrm{i}0^+}$$

$$= -\mathrm{i}\frac{\eta^{\mu\nu}}{k^2 + \mathrm{i}0^+},$$

$$= \frac{\mathrm{i}}{p^2 - m_\pi^2 + \mathrm{i}0^+},$$

$$= \mathrm{i}\frac{\not{p} + m_\mathrm{e}}{p^2 - m_\mathrm{e}^2 + \mathrm{i}0^+},$$

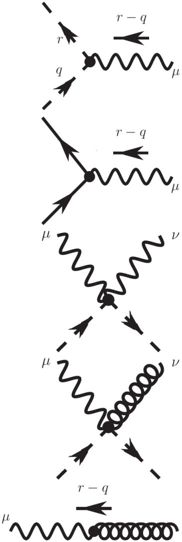
- $\eta^{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$
- $\Theta^{\mu\nu}(p) = \eta^{\mu\nu} - p^\mu p^\nu / p \cdot p$



$$= -\mathrm{i}g(q^\mu + r^\mu),$$

$$= \mathrm{i}g^2,$$

$$= -\mathrm{i}\frac{\lambda}{8}$$



$$= -\mathrm{i}e(q^\mu + r^\mu),$$

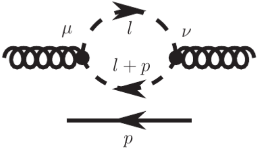
$$= \mathrm{i}e\gamma^\mu,$$

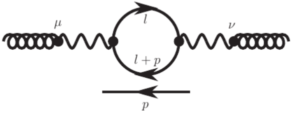
$$= \mathrm{i}e^2\eta^{\mu\nu},$$

$$= 2\mathrm{i}eg\eta^{\mu\nu},$$

$$= -\mathrm{i}\frac{e}{g'}p^2\Theta^{\mu\nu}(p).$$

- calculate ρ-self-energy (transversality from gauge invariance)

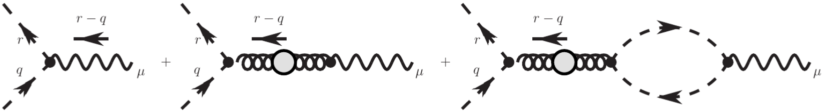
$\mathrm{i}\Pi^{\mu\nu}_{\rho\pi\pi}(p) =$  $= \mathrm{i} s \Pi_{\rho\pi\pi}(s)\Theta^{\mu\nu}(p), \quad s = p^2$

$\mathrm{i}\Pi^{\mu\nu}_{\rho ee}(p) =$  $= \mathrm{i} s \Pi_{\rho ee}(s)\Theta^{\mu\nu}(p), \quad s = p^2$

- Dressed Green's function

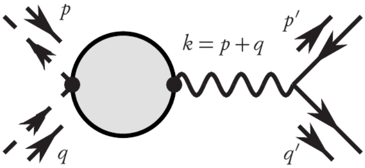
$$G^{\mu\nu}_{\rho}(p) = -\frac{\Theta^{\mu\nu}(p)}{p^2 - M^2 - p^2\Pi_{\rho\pi\pi}(p^2)} - \frac{\Lambda^{\mu\nu}(p)}{p^2 - M^2 + \mathrm{i}0^+}$$

- dressed $\gamma\pi\pi$ vertex to $\mathscr{O}(e)$

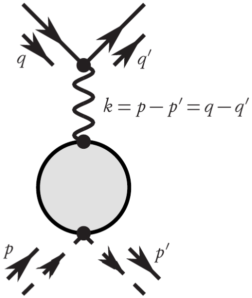
$\mathrm{i}\Gamma^{\mu}_{\gamma\pi\pi} =$ 

VMD model (em. form factor of the π)

- $\pi^+ + \pi^- \rightarrow e^+ + e^-$ ("time-like form factor")

$i\mathcal{M}_{fi} =$ 

- $\Rightarrow |F(s)|^2$ with Mandelstam $s = (p+q)^2$
- physical region $s > 4m_\pi^2$
- $\pi^+ + e^- \rightarrow \pi^+ + e^-$ ("space-like form factor")

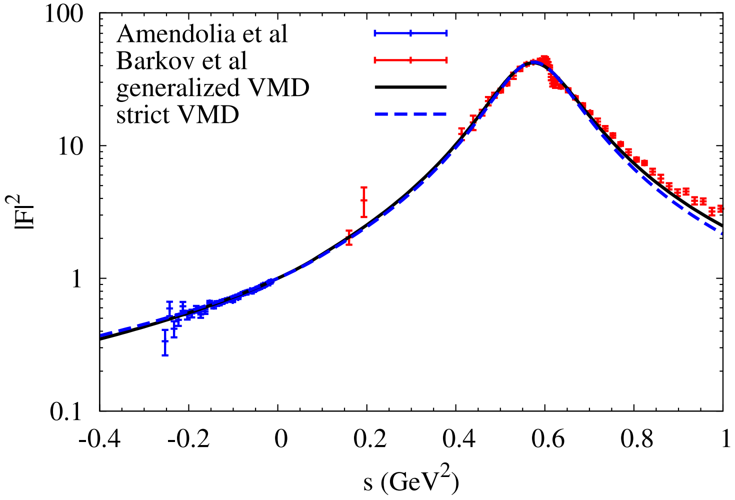
$i\mathcal{M}_{fi} =$ 

- $\Rightarrow |F(t)|^2$ with Mandelstam $t = (p-p')^2$
- physical region $t < 0$

VMD model: (fit of parameters)

- best fit to form-factor data: $g = 5.461$, $g' = 5.233$, $m_\rho = 763.1\ \text{MeV}/c^2$

  strict VMD: $g \overset{!}{=} g' = 5.328$, $m_\rho = 763.1\ \text{MeV}/c^2$



data from [A+86, BCE+85]

VMD model: (fit of parameters)

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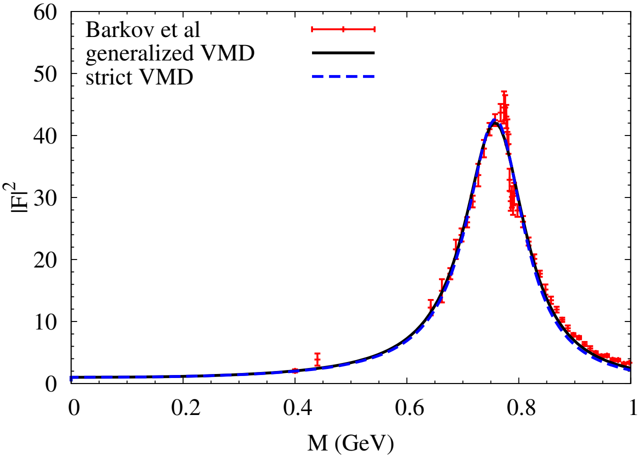
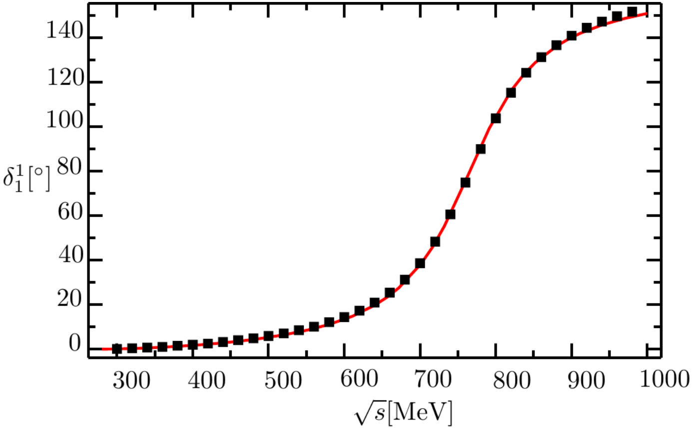


data from [BCE+85]

- small discrepancies around ρ peak: contribution from $\omega(782)$ meson!

- $\pi\pi \to \pi\pi$ phase shift in $I = 1$ channel

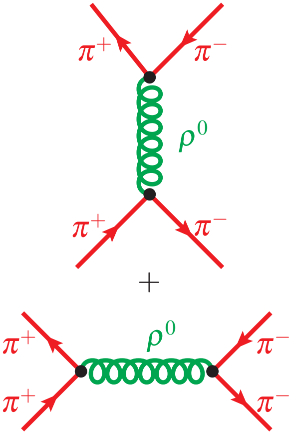
$$\delta_1^1 = \arccos \frac{\mathrm{Re}\, G_\rho}{|G_\rho|}$$

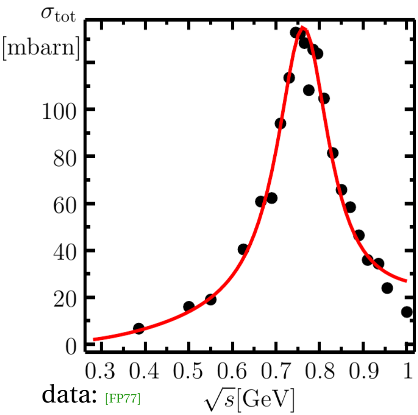


data: [FP77]

VMD: (total $\pi\pi$ elastic scattering cross section

- $\pi\pi \to \pi\pi$ total cross section



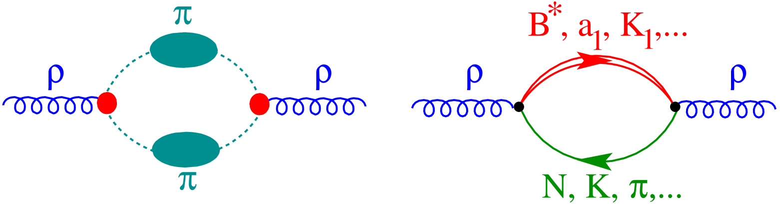


Realistic hadronic models for light vector mesons

- CERES data: pion-ρ model too simplistic
- many approaches to more realistic models
  - gauged linear σ-model + vector-meson dominance [Pis95, UBW02]
    gauge-symmetry breaking $\Rightarrow$ pions still in physical spectrum!
  - massive Yang-Mills model; gauged non-linear chiral model with explicitly broken gauge symmetry [Mei88, LSY95]
  - hidden local symmetry: Higgs-like chiral model [BKU$^+$85, HY03]
    allows for vector manifestation or usual manifestation (with a_1)
- here we concentrate on the phenomenological model by Rapp, Wambach, et al [RW99]

Hadronic many-body theory

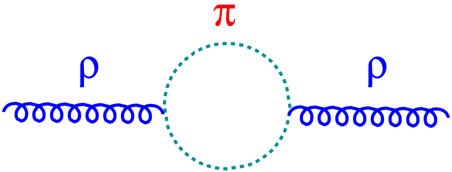
- Phenomenological HMBT [RW99] for vector mesons
- $\pi\pi$ interactions and baryonic excitations

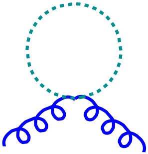


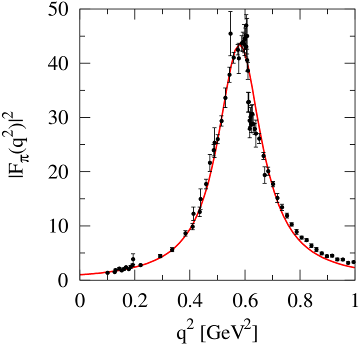
- Baryon (resonances) important, even at RHIC with low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

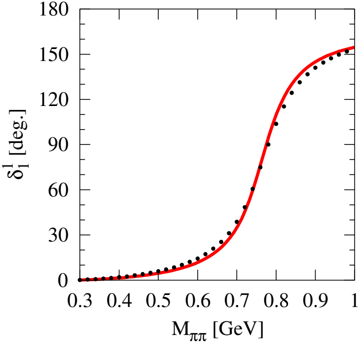
The meson sector (vacuum)

- most important for ρ-meson: pions



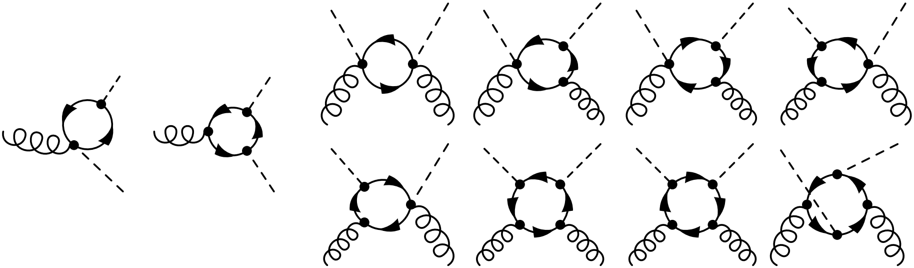




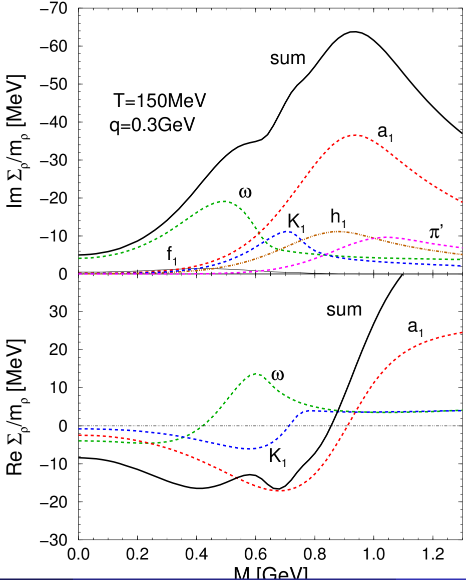


The meson sector (matter)

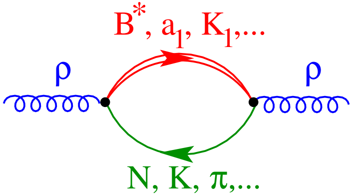
- Pions dressed with N-hole-, Δ-hole bubbles
- Ward-Takahashi $\Rightarrow$ vertex corrections mandatory!



The meson sector (contributions from higher resonances)

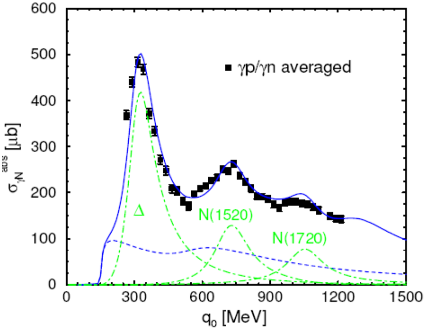


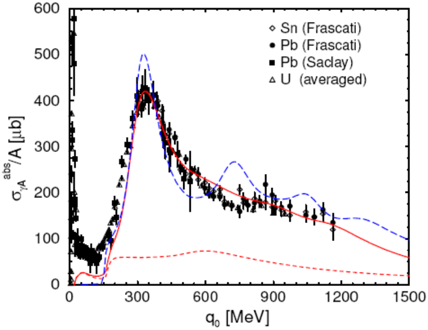
The baryon sector (vacuum)



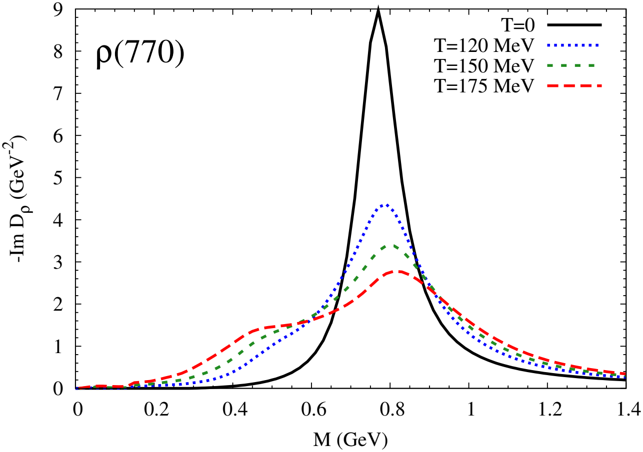
- $P = 1$-baryons: p-wave coupling to ρ:
  N(939), Δ(1232), N(1720), Δ(1905)
- $P = -1$-baryons: s-wave coupling to ρ:
  N(1520), Δ(1620), Δ(1700)

Photoabsorption on nucleons and nuclei





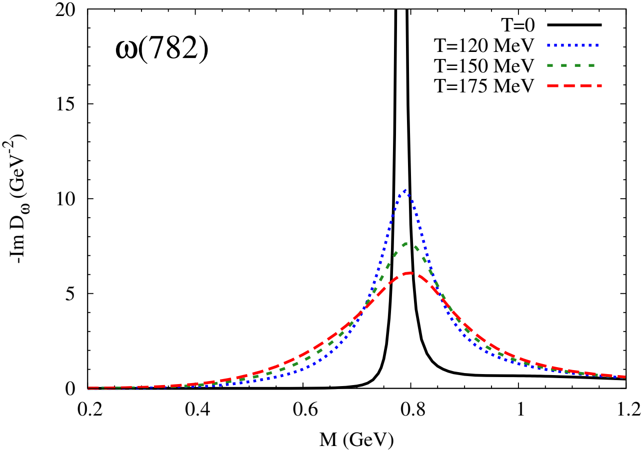
In-medium spectral functions and baryon effects



[R. Rapp, J. Wambach 99]

- baryon effects important
  - large contribution to broadening of the peak
  - responsible for most of the strength at small M

In-medium spectral functions and baryon effects



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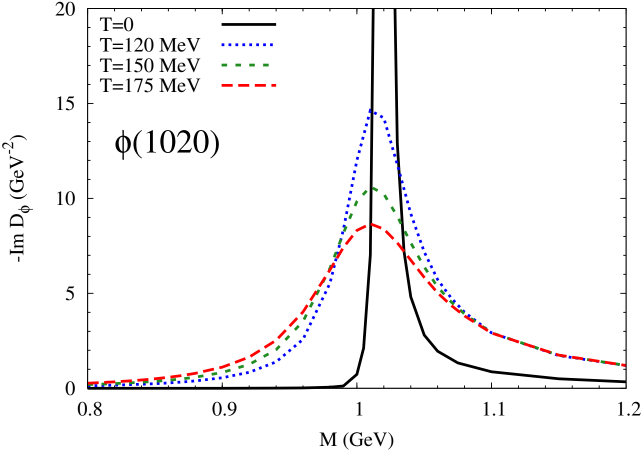

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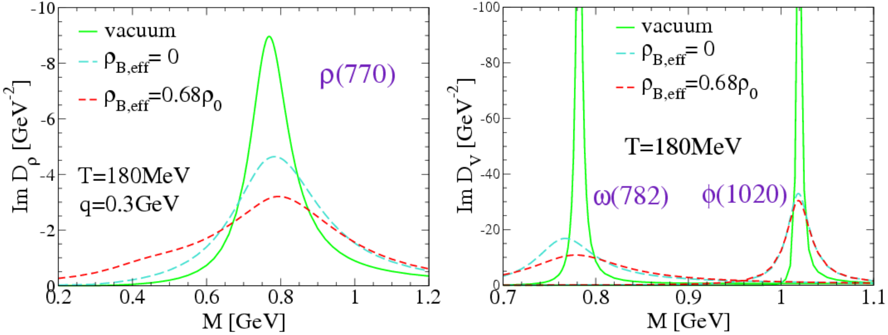

[R. Rapp, J. Wambach 99]

- baryon effects important
  - large contribution to broadening of the peak
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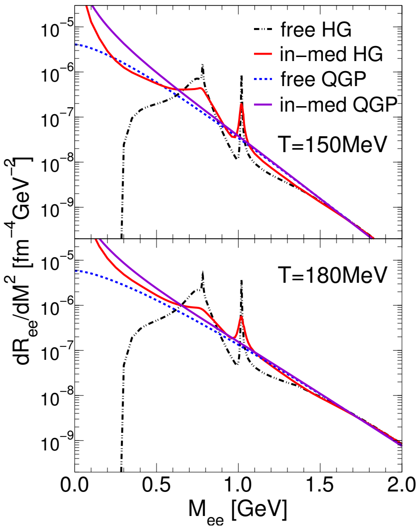
Dilepton rates: Hadron gas $\longleftrightarrow$ QGP



- in-medium hadron gas matches with QGP
- similar results also for γ rates
- "quark-hadron duality"?
- hidden local symm.+baryons?

[BKU+85, HY03, HS06, HSW08]

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Quiz

Quiz

1. which important "theoretical quantity" can be measured by observing electromagnetic probes in HICs (and elementary reactions)?
2. what is chiral-symmetry restoration and in which ways could it be realized in nature?
3. what can we learn from QCD sum rules about χSR?
4. what tell effective hadronic models about the medium modification of light vector mesons and the related χSR? dilepton data in HICs?
5. why are baryon-vector-meson interactions important even at high collision energies, where $\mu_{\text{B}} \simeq 0$ (nearly 0 net-baryon density)?