Resonances in hadronic medium

Exploring Hadrons with Electromagnetic Probes: Structures, Excitations, Interactions,

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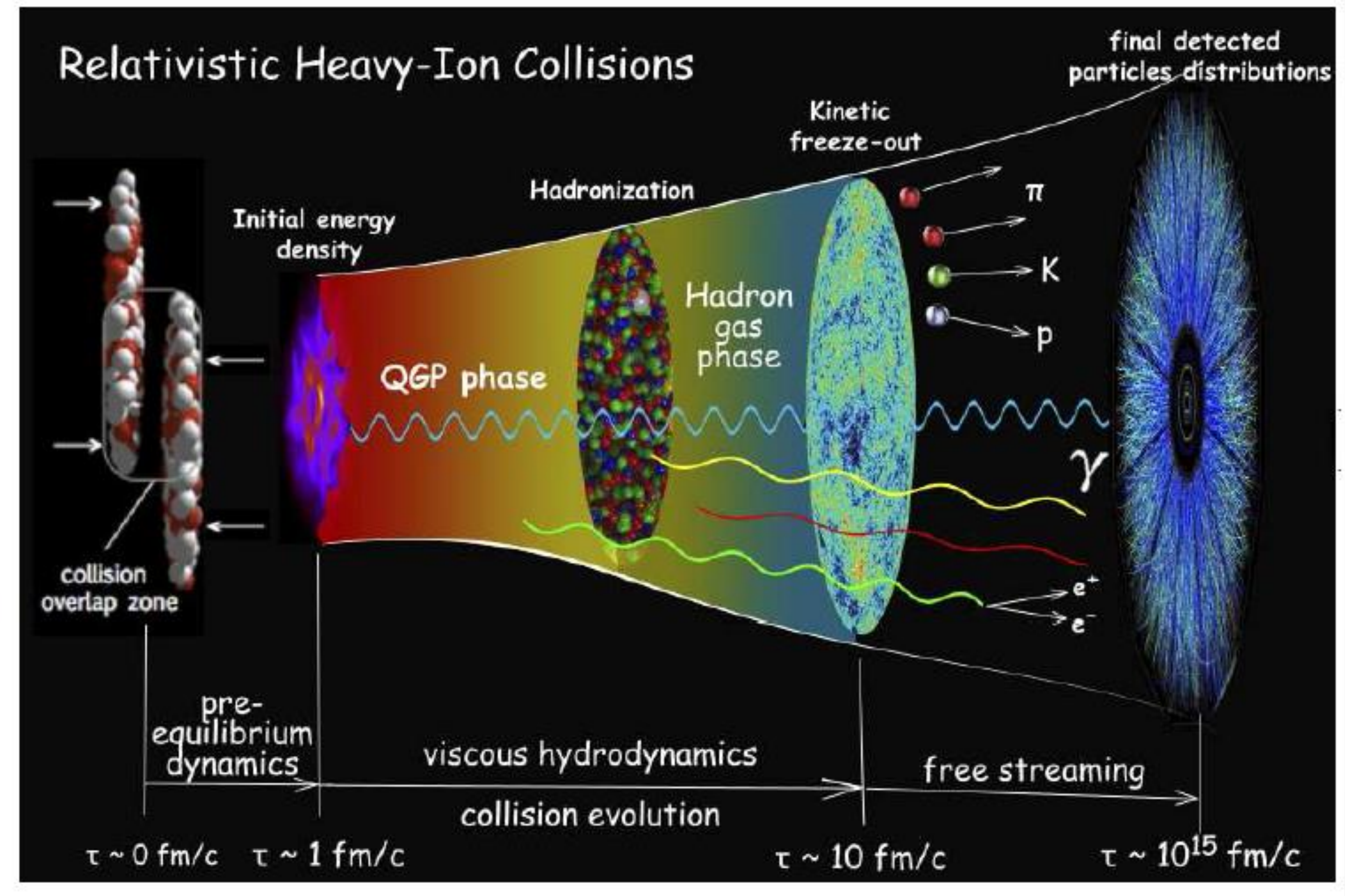
Jefferson Lab.

Sungtae Cho
Kangwon National University

Outline

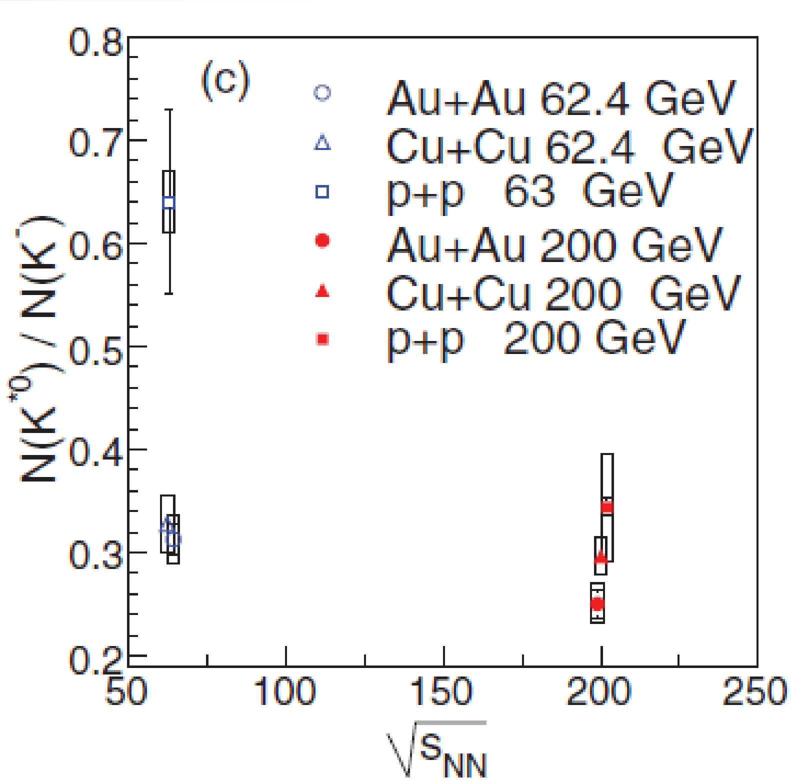
- Introduction
- Rho mesons in hadronic medium
- Pions in neclueon medium
- Results
- Conclusion

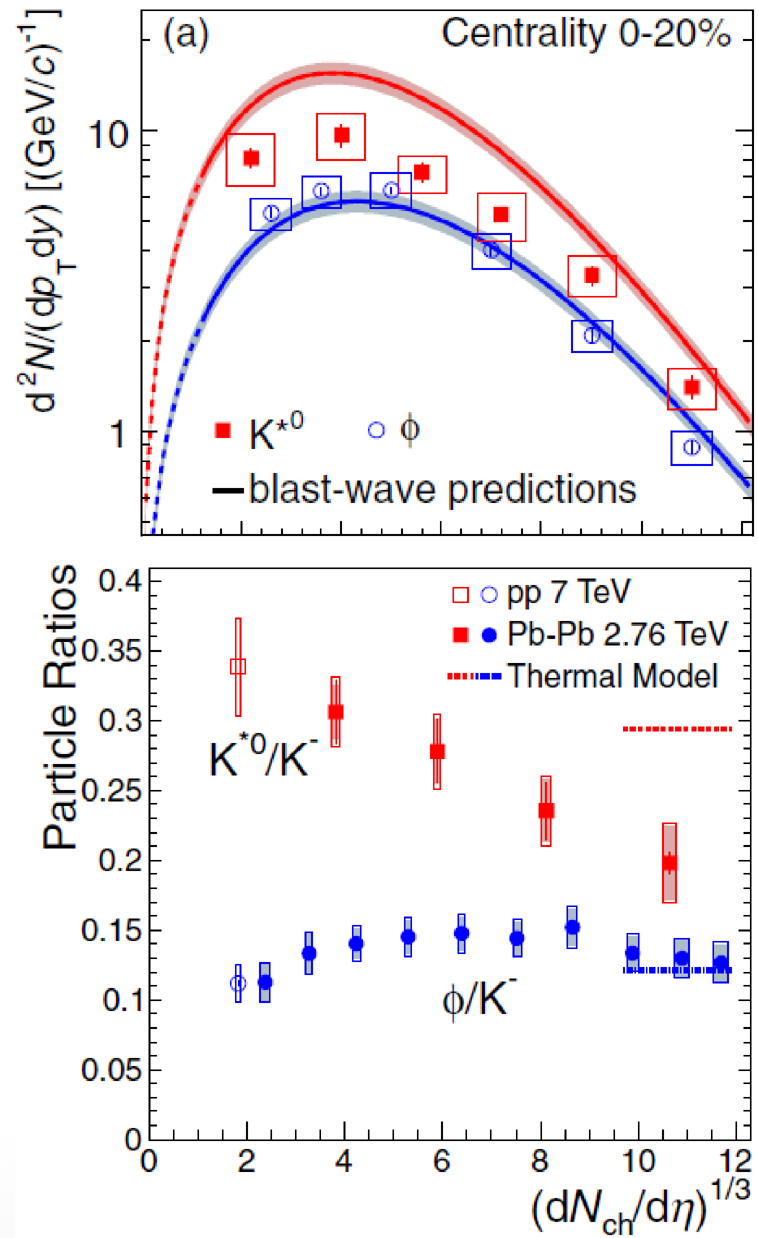
Introduction



U. W. Heinz, J. Phys. Conf. Ser. **455**, 012044 (2013)

– K* mesons in heavy ion collisions



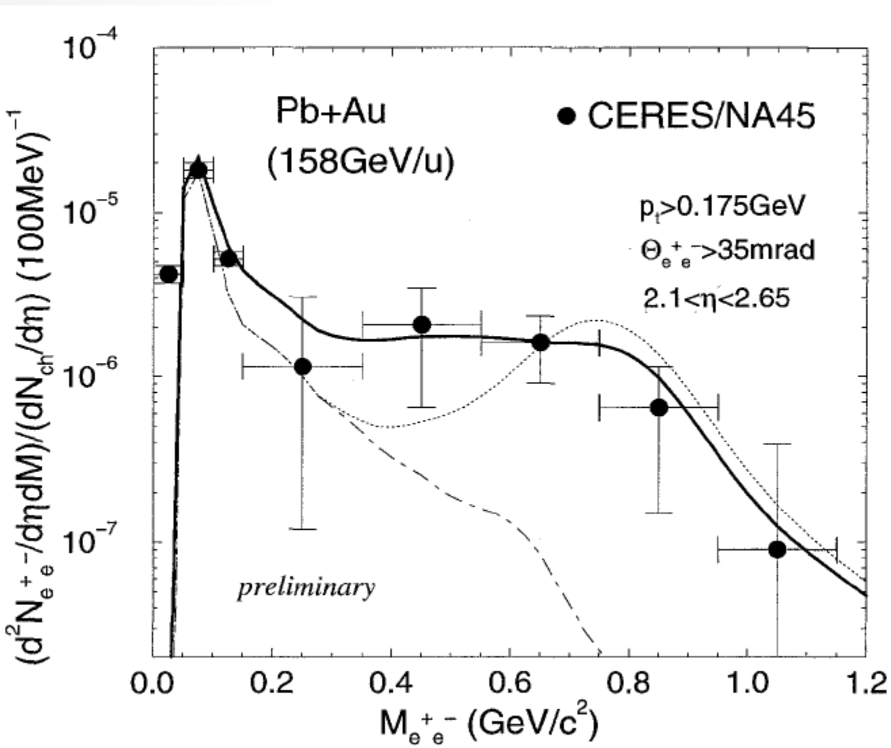


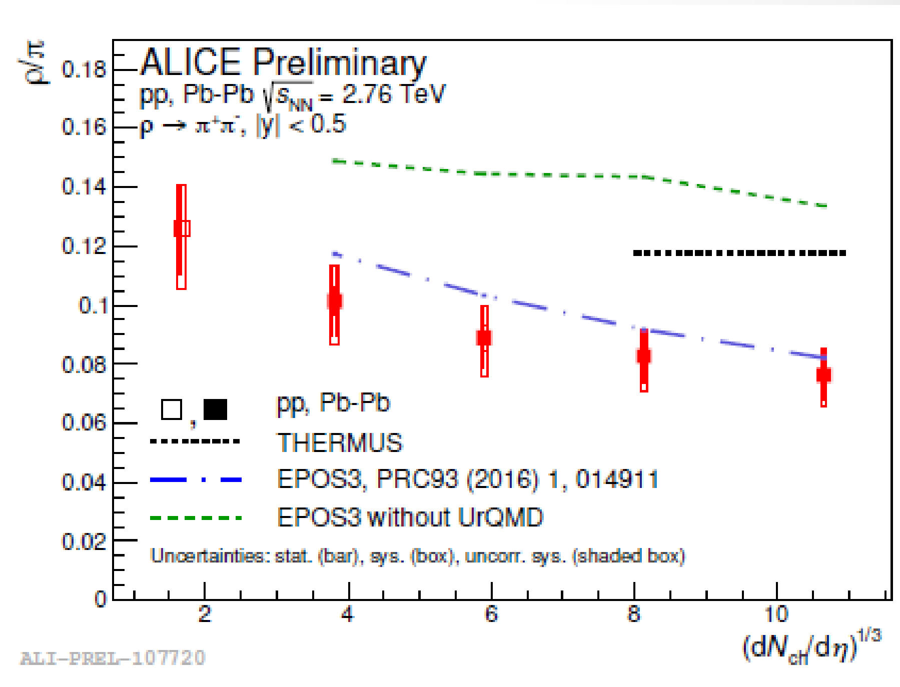
M. M. Aggarwal et al, [STAR Collaboration], Phys. Rev. C **84**, 034909 (2011)
B. Abelev et al. [ALICE Collaboration], Phys. Rev. C **91**, 024609 (2015)

– Rho mesons in heavy ion collisions

1) Good probes to a quark matter in heavy ion collisions

: the enhancement of the rho meson spectral function and the yield ratio between pions and rho mesons





R. Rapp, G. Chanfray, J. Wanbach, Nucl. Phys. A **617**, 472 (1997)

– Rho meson properties in hadronic matter at finite temperatures and densities

1) The relativistic resonance model using a phenomenological Lagrangians suitable to study high momentum effects

2) Rho mesons in a hadronic medium composed of pions, nucleons, and p-wave resonances

3) The finite three-momentum effects on the change of the rho mesons spectral density:

the dispersion relation in a hadronic medium

$$q_0^2 - (1+a)\vec{q}^{\,2} - m_\rho^2 = 0 \quad (a \neq 0)$$

4) The self-energy of rho mesons in various medium,

: pions, nucleons, nucleon-resonances

– The rho meson self-energy

1) The self-energy is transverse : $q^{\mu}\Pi_{\mu\nu}(q)=0$

the current conservation condition

2) The self-energy in medium : broken Lorentz invariance

transverse and longitudinal components with projection operators

$$P^L_{\mu\nu}=\frac{q_\mu q_\nu}{q^2}-g_{\mu\nu}-P^T_{\mu\nu}\quad P^T_{ij}=\delta_{ij}-\frac{q_i q_j}{\vec{q}^{\,2}}\qquad P^T_{0i}=P^T_{i0}=P^T_{00}=0$$

$$\Pi^{\rho}_{\mu\nu}(q)=P^L_{\mu\nu}\Pi^L(q)+P^T_{\mu\nu}\Pi^T(q)$$

3) The rho meson propagator in medium

$$D_{\mu\nu}(q)=-\frac{1}{q^2-m_\rho^2}\left(g^{\mu\nu}-\frac{q_\mu q_\nu}{m_\rho^2}\right)=-\frac{1}{q^2-m_\rho^2}\left(g^{\mu\nu}-\frac{q_\mu q_\nu}{q^2}\right)+\frac{1}{m_\rho^2}\frac{q_\mu q_\nu}{q^2}$$

$$\rightarrow D_{\mu\nu}=\frac{P^L_{\mu\nu}}{q^2-m_\rho^2-\Pi^L(q^2)}-\frac{P^T_{\mu\nu}}{q^2-m_\rho^2-\Pi^T(q^2)}+\frac{1}{m_\rho^2}\frac{q_\mu q_\nu}{q^2}$$

Rho mesons in hadronic medium

– Rho mesons in pion medium

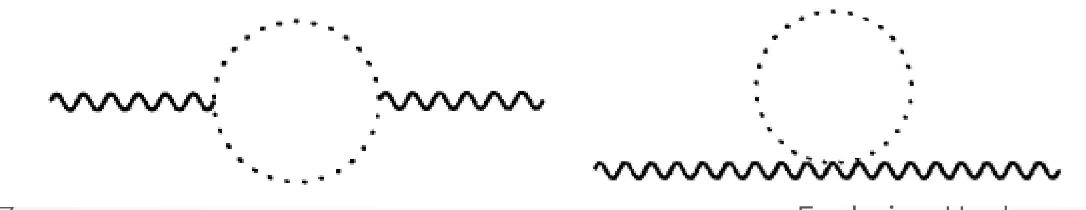
1) Interaction Lagrangians from free Lagrangians with minimal substitution

$$L = \frac{1}{2}\partial_\mu \vec{\pi}\cdot\partial^\mu \vec{\pi} - \frac{1}{2}m_\pi^2 \vec{\pi}\cdot\vec{\pi} - \frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \frac{1}{2}m_\rho^2 \rho_\mu \rho^\mu \qquad G_{\mu\nu} = \partial_\mu \rho_\nu - \partial_\nu \rho_\mu$$

$$\partial_\mu \vec{\pi} \rightarrow (\partial_\mu + ig\rho_\mu \tau_3)\vec{\pi}$$

$$L_{\pi\rho} = \frac{1}{2} ig\rho_\mu \tau_3 (\vec{\pi}\cdot\partial^\mu \vec{\pi} + \partial^\mu \vec{\pi}\cdot\vec{\pi}) - \frac{1}{2} g^2 \rho_\mu \tau_3 \rho^\mu \tau_3 \vec{\pi}\cdot\vec{\pi}$$

2) Diagrams for rho meson self-energies



3) Rho meson self-energy in pion medium

$$-i\Pi_{\mu\nu} = g_{\rho\pi\pi}^2 \int \frac{d^4k}{(2\pi)^4} \frac{(2k+q)_\mu (2k+q)_\nu}{((k+q)^2 - m_\pi^2 + i\varepsilon)(k^2 - m_\pi^2 + i\varepsilon)}$$
$$- 2g_{\rho\pi\pi}^2 g_{\mu\nu} \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m_\pi^2 + i\varepsilon}$$

The same result for a scalar electromagnetism with a photon of rho meson mass

: Real parts of the longitudinal μ and transverse components with a renomalization condition $\mathrm{Re}\,\Pi_{\mu\nu}^{L,T}(q)|_{q^2=m_\rho^2} =,0$

$$\Pi_{\mu\nu}^{L,T}(q) = \frac{g_{\rho\pi\pi}^2}{48\pi^2} q^2 \left[\left(1 - \frac{4m_\pi^2}{q^2}\right)^{2/3} Ln\left(\frac{1 + \sqrt{1 - 4m_\pi^2/q^2}}{1 - \sqrt{1 - 4m_\pi^2/q^2}} \right) \right.$$
$$\left. + 8m_\pi^2 \left(\frac{1}{q^2} - \frac{1}{m_\rho^2} \right) - 16 \left(\frac{m_\rho^2}{4} - m_\pi^2 \right)^{3/2} \frac{1}{m_\rho^3} Ln\left(\frac{1}{m_\pi} \left(\frac{m_\rho}{2} + \sqrt{\frac{m_\rho^2}{4} - m_\pi^2} \right) \right) \right]$$

– Rho mesons in nucleon medium

1) Phenomenological interaction Lagrangians
: vertex factors in momentum space

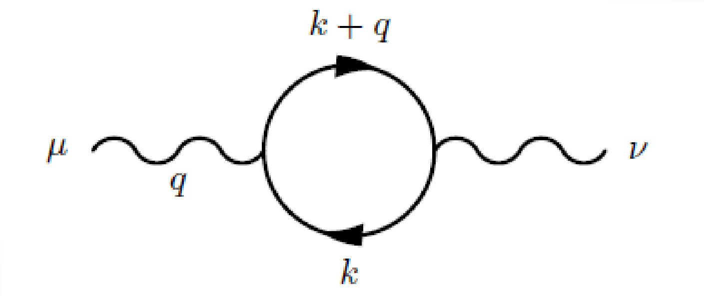
$$L_{\rho NN} = g_{\rho NN}\left[\bar{N}\gamma_\mu \tau^a N - \frac{\kappa}{2m}\bar{N}\sigma_{\mu\nu}\tau^a N\partial^\nu\right]\rho_a^\mu$$

$$\Gamma_\mu^a(q) = ig_{\rho NN}\left[\gamma_\mu\tau^a + i\frac{\kappa}{2m}\sigma_{\mu\nu}\tau^a q^\nu\right], \quad \sigma_{\mu\nu} = \frac{1}{2}i\left(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu\right)$$

2) The in-medium nucleon propagator

$$G_N(k) = G_F(k) + G_D(k)$$
$$= \frac{i}{\gamma_\mu k^\mu - m_n^* + i\varepsilon} + i(\gamma_\mu k^\mu + m_n^*)\frac{i\pi}{E_k^*}\delta(k_0 - E_k^*)\theta(k_F - |\vec{k}|)$$

3) A diagram for
rho meson self-energy



4) Rho meson self-energy in nuclear matter

$$i\Pi^{ab}_{\mu\nu}(q) = N_I \int \frac{d^4k}{(2\pi)^4} Tr\left[\Gamma^a_\mu(q) G_N(k+q) \Gamma^b_\nu(-q) G_N(k)\right]$$

$$= i\Pi^F_{\mu\nu} + i\Pi^D_{\mu\nu}$$

$$\Pi^D_{\mu\nu}(q) = \Pi^{vv}_{\mu\nu}(q) + \Pi^{vt+tv}_{\mu\nu}(q) + \Pi^{tt}_{\mu\nu}(q)$$

: density dependent parts of the self-energy

$$\Pi^{vv}_{\mu\nu}(q) = N_I \frac{g^2_{\rho NN}}{\pi^3} \int \frac{d^4k}{E^*_{\vec{k}}} \frac{\Theta(k_F - |\vec{k}|)\delta(k_0 - E^*_{\vec{k}})}{q^2 - 4(k\cdot q)^2}$$
$$\times\left[q^2\left(k_\mu - \frac{k\cdot q}{q^2} q_\mu\right)\left(k_\nu - \frac{k\cdot q}{q^2} q_\nu\right) + (k\cdot q)^2\left(g_\mu - \frac{q_\mu q_\nu}{q^2}\right)\right]$$

$$\Pi^{vt+tv}_{\mu\nu}(q) = N_I \frac{g^2_{\rho NN}}{\pi^3}\left(\frac{\kappa m^*_n}{4m_n}\right)\left(g_\mu - \frac{q_\mu q_\nu}{q^2}\right) 2q^4 \int \frac{d^4k}{E^*_{\vec{k}}} \frac{\Theta(k_F - |\vec{k}|)\delta(k_0 - E^*_{\vec{k}})}{q^2 - 4(k\cdot q)^2}$$

$$\Pi^{tt}_{\mu\nu}(q) = -N_I \frac{g^2_{\rho NN}}{\pi^3}\left(\frac{\kappa}{4m_n}\right)^2 4q^4 \int \frac{d^3k}{E^*_{\vec{k}}} \frac{\Theta(k_F - |\vec{k}|)\delta(k_0 - E^*_{\vec{k}})}{q^2 - 4(k\cdot q)^2}$$
$$\times\left[\left(k_\mu - \frac{k\cdot q}{q^2} q_\mu\right)\left(k_\nu - \frac{k\cdot q}{q^2} q_\nu\right) - m^{*2}\left(g_\mu - \frac{q_\mu q_\nu}{q^2}\right)\right]$$

– Rho mesons in nucleon-resonance medium

1) Phenomenological interaction Lagrangian containing $J^P=3/2^+$ P-wave N*(1720) resonances

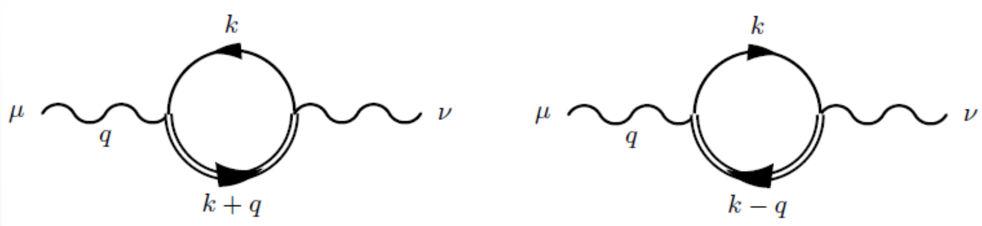
$$L_{\rho NN*} = \frac{g_{\rho NN*}}{m_\rho} \overline{N}^{*\mu} \gamma^5 \gamma^\nu N G_{\mu\nu}$$

: vertex factor in momentum space $\Gamma_{\mu\rho}(q) = \frac{g_{\rho NN*}}{m_\rho} \gamma^5 (\gamma_\mu q_\rho - \gamma_\alpha q^\alpha g_{\mu\rho})$

2) $J^P=3/2^+$ Rarita-Schwinger propagator

$$G^{\mu\nu}_{N*}(k) = i \frac{\gamma_\mu k^\mu + M}{k^2 - M^2 + iM\Gamma_{tot}} \left[-g^{\mu\nu} + \frac{1}{3}\gamma^\mu \gamma^\nu + \frac{2}{3M^2} p^\mu p^\nu + \frac{1}{3M}\left(\gamma^\mu p^\nu - p^\mu \gamma^\nu\right) \right]$$

3) Diagrams for rho meson self-energy in nucleon-resonance medium



(a) The direct term

(b) The exchange term

4) Rho meson self-energy in nucleon-resonance matter
: direct and exchange terms

$$i\Pi_{\mu\nu}^{N*}(q) = N_I \int \frac{d^4k}{(2\pi)^4} Tr\big[\Gamma_{\mu\rho}(q) G_N(k) \Gamma_{\nu\sigma}(q) G_{N*}^{\rho\sigma}(k+q) + \Gamma_{\mu\rho}(-q) G_N(k) \Gamma_{\nu\sigma}(-q) G_{N*}^{\rho\sigma}(k-q)\big]$$

$$= i\Pi_{\mu\nu}^{N*,F}(q) + i\Pi_{\mu\nu}^{N*,D}(q) \qquad \Pi_{\mu\nu}^{N*,D}(q) = \Pi_{\mu\nu}^{dir}(q) + \Pi_{\mu\nu}^{ex}(q)$$

Density dependent parts of the self-energy

$$\Pi_{\mu\nu}^{\pm}(q) = N_I \left(\frac{g_{\rho NN*}}{m_\rho}\right)^2 \int \frac{d^4k}{(2\pi)^4} \frac{8\pi}{E_{\vec{k}}^*} \Theta(k_F - |\vec{k}|) \delta(k_0 - E_{\vec{k}}^*) \frac{(k \pm q)^2 - M^2}{[(k \pm q)^2 - M^2]^2 + M^2 \Gamma_{tot}^2}$$

$$\times \Bigg[q^2 \left(1 + \frac{2}{3}\frac{m_n^*}{M} + \frac{1}{3}\frac{k^2}{M^2} \pm \frac{1}{3}\frac{k \cdot q}{M^2}\right)\left(k_\mu - \frac{k \cdot q}{q^2} q_\mu\right)\left(k_\nu - \frac{k \cdot q}{q^2} q_\nu\right)$$

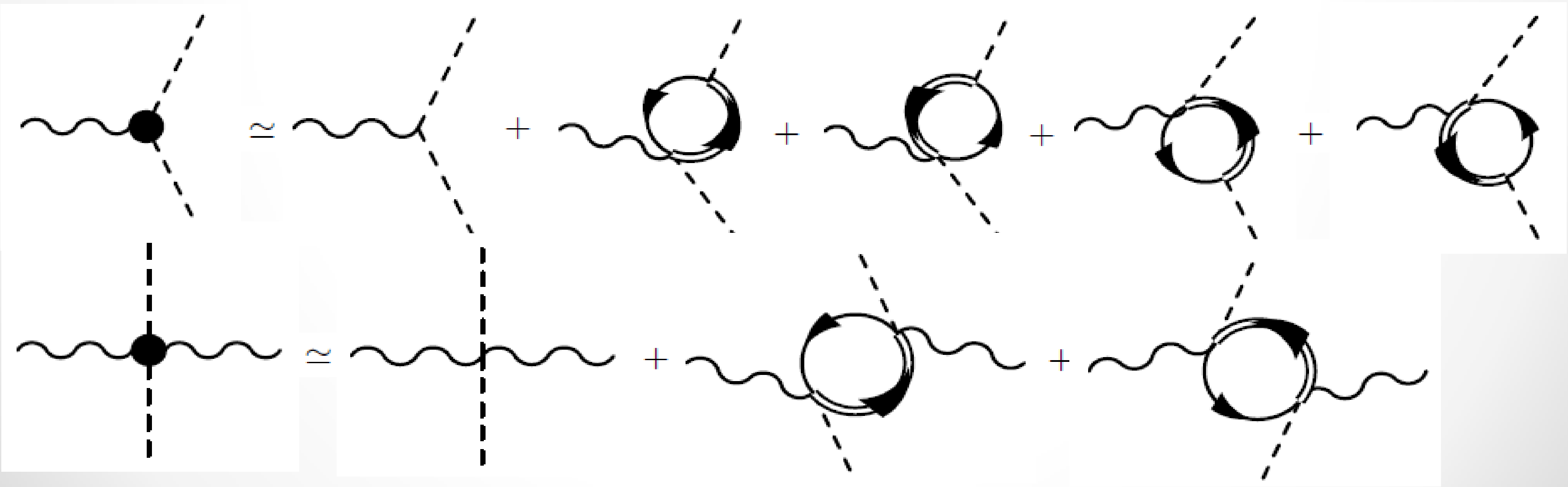
$$- \left(q^2 \left(-k^2 - m_n^* M + \frac{2}{3}\frac{m_n^*}{M} q^2 + \frac{1}{3}\frac{k^2 q^2}{M^2} \right) \pm k \cdot q q^2 \left(\frac{4}{3}\frac{m_n^*}{M} + \frac{1}{3}\frac{q^2}{M^2} + \frac{2}{3}\frac{k^2}{M^2} \right) + (k \cdot q)^2 \left(1 + \frac{2}{3}\frac{m_n^*}{M} + \frac{1}{3}\frac{k^2}{M^2} + \frac{2}{3}\frac{q^2}{M^2}\right) \pm \frac{1}{3}\frac{(k \cdot q)^3}{M^2} \right)\left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) \Bigg]$$

Pions in nucleon medium

– Corrections for pion-rho meson interactions

M. Asakawa, C. M. Ko, P. Levai, and X. J. Qiu, Phys. Rev. C **46**, R1159 (1992)

1) Diagrams for pion-rho meson interaction vertices



2) Lagrangians for three- and for-point interactions

$$\mathcal{L}_{\pi NN} = \frac{f_N}{m_\pi}\bar{N}\gamma^5\gamma^\mu\tau^a N\partial_\mu\pi^a \qquad \mathcal{L}_{\rho\pi NN} = ig_{\rho\pi\pi}\frac{f_N}{m_\pi}\bar{N}\gamma^5\gamma^\mu\rho_\mu\tau^a NT_3\partial_\mu\pi^a$$

$$\mathcal{L}_{\pi N\Delta} = -\frac{f_\Delta}{m_\pi}\bar{N}T^{a\dagger}\Delta_\mu\partial^\mu\pi^a + H.C \qquad \mathcal{L}_{\rho\pi N\Delta} = -ig_{\rho\pi\pi}\frac{f_\Delta}{m_\pi}\bar{N}T^{a\dagger}\Delta_\mu\rho^\mu T_3\pi^a + H.C$$

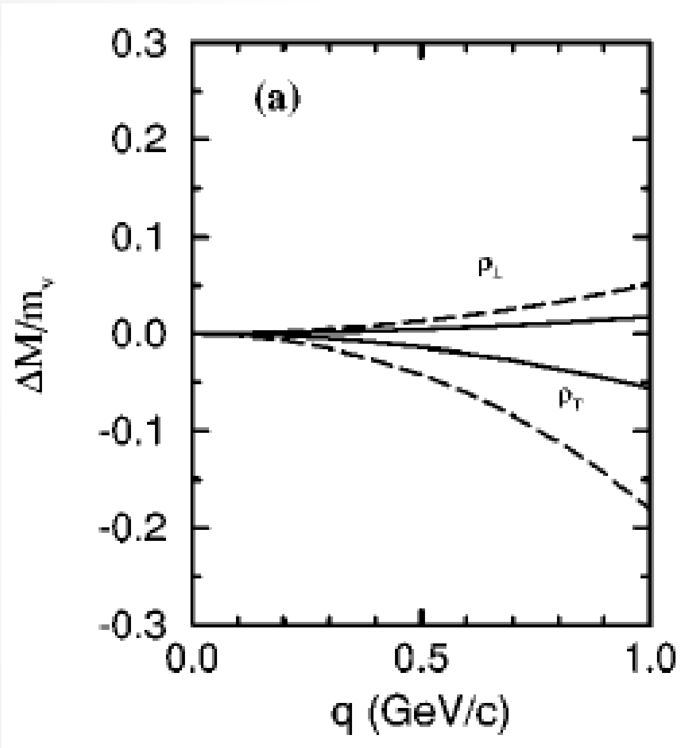
3) Density dependent parts of the pion self-energies for nucleon-hole, and delta-hole excitations

$$\Pi^{\mu\nu}_{\pi,N}(q) = -2\Big(\frac{f_N}{m_\pi}\Big)^2\int\frac{d^4l}{(2\pi)^4}\Big[\frac{\pi}{E^*_l}\frac{\Theta(k_F-|\vec{l}|)\delta(l_0-E^*_l)}{(l-q)^2-m^{*2}_n} + \frac{\pi}{E^*_{l-q}}\frac{\Theta(k_F-|\vec{l}-\vec{q}|)\delta(l_0-E^*_{l-q})}{l^2-m^{*2}_n}\Big]$$
$$\times 4\Big((l-q)^\mu l^\nu + l^\nu(l-q)^\mu - \Big(l\cdot(l-q)+m^{*2}_n\Big)g^{\mu\nu}\Big)$$

$$\Pi^{\mu\nu}_{\pi,\Delta}(q) = -\frac{4}{3}\Big(\frac{f_\Delta}{m_\pi}\Big)^2\int\frac{d^4l}{(2\pi)^4}\Big[\frac{\pi}{E^*_l}\frac{\Theta(k_F-|\vec{l}|)\delta(l_0-E^*_l)}{(l-q)^2-M^{*2}}$$
$$\times 4\frac{2}{3}l\cdot(l-q)\Big(-g^{\mu\nu}+\frac{1}{M^2}(l-q)^\mu(l-q)^\mu\Big) + (q\to -q)\Big]$$

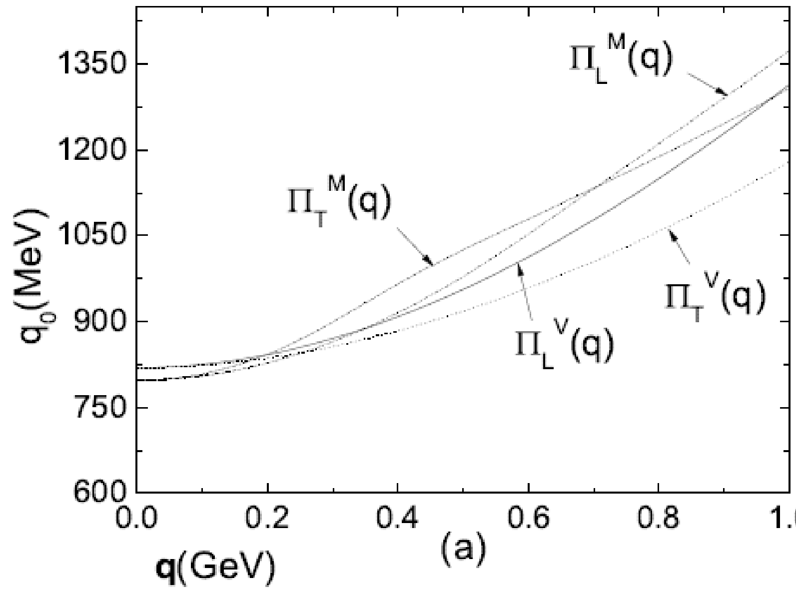
Results

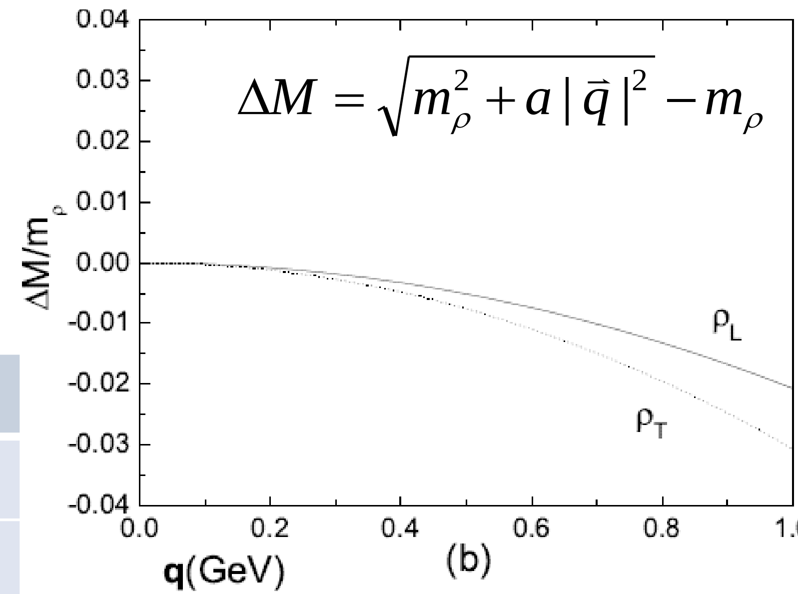
– Dispersion relations



S. H. Lee, Phys. Rev. C **57**, 927 (1998)

	Transverse	Longitudinal
This work	-0.036	-0.024
QCD sum rule	-0.108	+0.023





Conclusion

– Resonances in hadronic medium

1) Study of resonance production or its evolution during the hadronic stage in heavy ion collisions can provides us information on the possible change of resonance properties in hadronic medium at high temperatures and densities
2) The final yield ratio between K* mesons and kaons, and also that between rho mesons and pions in heavy ion collisions may reflect the condition at the last stage of the hadronic effects, the self-energies of resonances in the hadronic medium
3) The investigation on the self-energy of resonances, or the rho meson in hadron medium provides us information on three-momentum dependence of the change in the resonance spectral density
4) The more quantitative analysis considering interactions between pions and medium, and also the relative short-range correlations in the medium must be necessary