# Rho meson in medium

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# Outline

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– Rho meson in medium
– Rho meson self-energy
– The current issue
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# Introduction

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– Proper tools for the study of the properties of nuclear matter at high temperature and density

: Dileptons and photons

– Vector Meson Dominance (VMD) model

i) In the hadronic electromagnetic interactions, coupling of a photon to a hadron always involves a neutral vector meson

ii) The electromagnetic current operator can be set to be equal to a linear combination of the neutral vector meson field operators.

## – The rho meson and photon Lagrangian

$$L = -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \frac{1}{2}m_\rho^2\rho_\mu\rho^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$-(g\rho_\mu + eA_\mu)J^\mu - \frac{1}{2}\frac{e}{g}F_{\mu\nu}G^{\mu\nu}$$

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu \qquad G^{\mu\nu} = \partial^\mu \rho^\nu - \partial^\nu \rho^\mu$$

i) A direct coupling between photon and rho meson is taken into account

$$-\frac{1}{2}\frac{e}{g}F_{\mu\nu}G^{\mu\nu}$$

ii) It is crucial for gauge invariance that not only the photon, but also the vector meson couples to a conserved current in vector meson dominance model

## – The equations of motion

$$-\partial_\mu G^{\mu\nu} - \frac{e}{g}\partial_\mu F^{\mu\nu} - m_\rho^2 \rho^\nu = -gJ^\nu$$

$$-\partial_\mu F^{\mu\nu} - \frac{e}{g}\partial_\mu G^{\mu\nu} = -eJ^\nu$$

i) The rho meson field is the only source of the electromagnetic field : The rho meson dominance

$$\partial_\mu F^{\mu\nu} = \frac{e}{g} m_\rho^2 \rho^\nu$$

ii) The current is conserved and the rho meson field is transverse : The photon couples to a conserved current

$$\partial_\mu G^{\mu\nu} + m_\rho^2 \rho^\nu = gJ^\nu$$

# Rho meson in vacuum

– Lagrangian

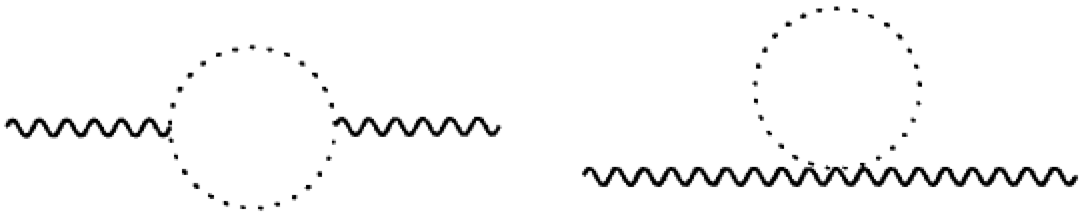
$$L=\frac{1}{2}\partial_\mu\vec{\pi}\cdot\partial^\mu\vec{\pi}-\frac{1}{2}m_\pi^2\vec{\pi}\cdot\vec{\pi}-\frac{1}{4}G_{\mu\nu}G^{\mu\nu}+\frac{1}{2}m_\rho^2\rho_\mu\rho^\mu$$

: The rho meson has a hadronic width about 150 MeV with two pion decay accounting for almost 100% of it

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

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

## – Self-energy of the rho meson



: The results

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

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

# Rho meson in dense matter

- Interaction Lagrangian

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

: The vertex factor

$$\Gamma_a^\mu = g_v \left[ \gamma_\mu \tau^a - \frac{\kappa}{2m} \sigma_{\mu\nu} \tau^a \partial^\nu \right]$$

The tensor coupling

$$\sigma_{\mu\nu} = \frac{1}{2} i \left( \gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu \right)$$

– The nucleon propagator

$$G^H(k) = G_F(k) + G_D(k)$$
$$= \frac{1}{\gamma_\mu k^\mu - m_n^* + i\varepsilon} + (\gamma_\mu k^\mu + m_n^*)\frac{i\pi}{E_k^*}\delta(k_0 - E_k^*)\theta(k_F - |\vec{k}|)$$

– Rho meson propagator

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

: a longitudinal and a transverse part

# Rho meson self-energy

– The self-energy is transverse

: The current is conserved

$$q^{\mu}\Pi^{ab}_{\mu\nu}(q)=0$$

– Self-energy in a medium

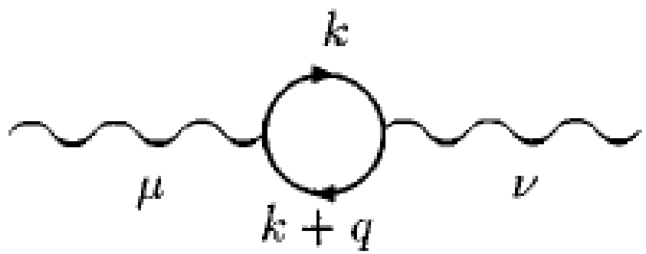
$$\Pi^{\rho}_{\mu\nu}(q)=P^{L}_{\mu\nu}\Pi^{L}(q)+P^{T}_{\mu\nu}\Pi^{T}(q)$$

$$P^{L}_{\mu\nu}=\frac{q_{\mu}q_{\nu}}{q^{2}}-g_{\mu\nu}-P^{T}_{\mu\nu}\qquad P^{T}_{ij}=\delta_{ij}-\frac{q_{i}q_{j}}{\vec{q}^{\,2}}$$

: The propagator of the rho meson

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

## – Rho meson self-energy




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

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

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

## – The density dependent self-energy

$$\Pi^{vv}_{\mu\nu} = \frac{g_v^2}{\pi^3}\int_{k_F}\frac{d^3k}{E^*(k)}\frac{1}{q^2-4(k\cdot q)^2}$$
$$\times\left[q^2\left(k_\mu-\frac{k\cdot q}{q^2}q_\mu\right)\left(k_\nu-\frac{k\cdot q}{q^2}q_\nu\right)+(k\cdot q)^2\left(g_\mu-\frac{q_\mu q_\nu}{q^2}\right)\right]$$

$$\Pi^{vt+tv}_{\mu\nu} = \frac{g_v^2}{\pi^3}\left(\frac{\kappa m^*}{4m}\right)\left(g_\mu-\frac{q_\mu q_\nu}{q^2}\right)2q^4\int_{k_F}\frac{d^3k}{E^*(k)}\frac{1}{q^2-4(k\cdot q)^2}$$

$$\Pi^{tt}_{\mu\nu} = -\frac{g_v^2}{\pi^3}\left(\frac{\kappa}{4m}\right)^2 4q^4\int_{k_F}\frac{d^3k}{E^*(k)}\frac{1}{q^2-4(k\cdot q)^2}$$
$$\times\left[\left(k_\mu-\frac{k\cdot q}{q^2}q_\mu\right)\left(k_\nu-\frac{k\cdot q}{q^2}q_\nu\right)-m^{*2}\left(g_\mu-\frac{q_\mu q_\nu}{q^2}\right)\right]$$

– The longitudinal self-energy

$$\Pi^L = \frac{g_v^2}{\pi^3}\int_{k_F}\frac{d^3k}{E_k^*}\frac{1}{q^2-4(k\cdot q)^2}\Bigg[-q^2(|\vec{k}|^2\cos^2\theta - E_k^{*2}) + 2q^4\frac{\kappa m^*}{4m} + 4q^2\left(\frac{\kappa}{4m}\right)^2\left((|\vec{q}\,|E_k^* - q_0|\vec{k}|\cos\theta)^2 + m^{*2}\right)\Bigg]$$

– The transverse self-energy

$$\Pi^T = \frac{g_v^2}{\pi^3}\int_{k_F}\frac{d^3k}{E_k^*}\frac{1}{q^2-4(k\cdot q)^2}\Bigg[\frac{q^2}{2}|\vec{k}|^2(1-\cos^2\theta) - (E_k^* q_0 - |\vec{k}||\vec{q}\,|\cos\theta)^2 - 2q^4\frac{\kappa m^*}{4m} - 4q^4\left(\frac{\kappa}{4m}\right)^2\left(|\vec{k}|^2(1-\cos^2\theta) + 4m^{*2}\right)\Bigg]$$

# – Finite three-momentum effect

i) The dispersion relation in a medium

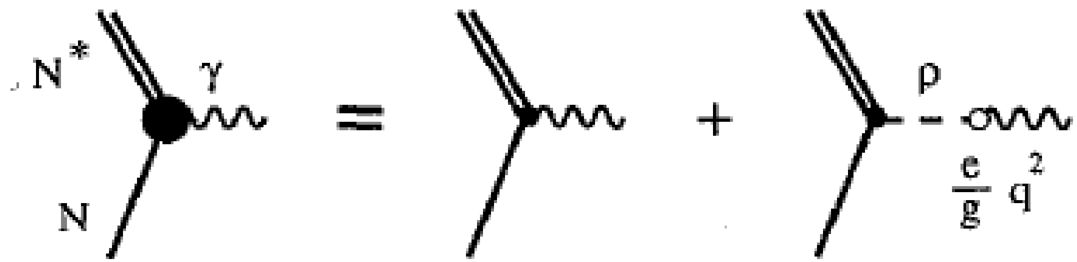
$$\omega^2 - (1+a)\vec{q}^{\,2} - m_\rho^2 = 0 \qquad (a \neq 0)$$

ii) The comparison with the previous work

| | Transverse | Longitudinal |
|---|---|---|
| Current work | -0.366 | -0.078 |
| QCD sum rule | -0.108 | +0.023 |

# The current issue

– Consideration of P-wave resonance $N^*(3/2)$




– Rarita-Schwinger propagator

$$S^{\mu\nu}(k) = \frac{1}{\gamma_\mu k^\mu - m + i\varepsilon}\left[-g^{\mu\nu} + \frac{1}{3}\gamma^\mu\gamma^\nu + \frac{2}{3m^2}p^\mu p^\nu - \frac{1}{3m}\left(p^\mu\gamma^\nu - \gamma^\mu p^\nu\right)\right]$$

## – Interaction Lagrangians

i) Non-relativistic limit

$$L_{\text{int}}^{N^*} = \frac{f_{N^* N\rho}}{m_\rho}\left[N^{*+}(S_{3/2}\times\vec{q})\cdot\rho^a\tau^a N + h.c\right]$$

: Spin transition operator (tensor)

$$S_{2/3}^{Mm_s} = \sum_r \left\langle \frac{3}{2}M \,|\, 1r\frac{1}{2}m_s \right\rangle \varepsilon^{r*}$$

$$\varepsilon^1 = -\frac{1}{\sqrt{2}}(1,i,0),\ \ \varepsilon^0 = (0,0,1),\ \ \varepsilon^{-1} = \frac{1}{\sqrt{2}}(1,-i,0)$$

ii) General relativistic consideration

$$L_{\text{int}}^{N^*} = i\frac{g_{N^* N\rho}}{2m_N}\overline{N}^{*\mu}T_{3/2}^a\gamma^5\gamma^\nu N G_{\mu\nu}^a + h.c$$

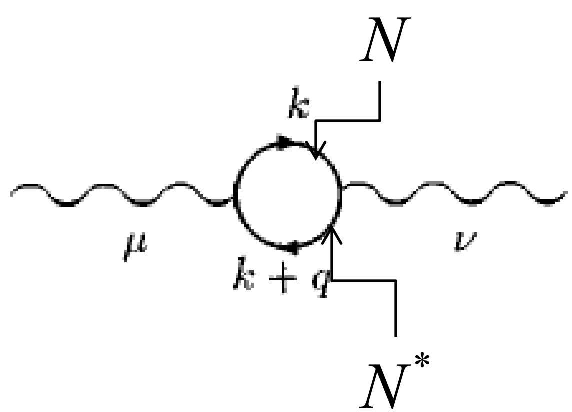
## : iii) Covariant gauge interaction

$$L^{N^*}_{gauge} = i\frac{g_{N^*N\rho}}{Mm_N}\overline{N}T^a_{3/2}\widetilde{N}^{*\lambda\rho}\gamma_\rho\gamma^\sigma G^a_{\lambda\sigma} + h.c$$
$$= \frac{g_{N^*N\rho}}{2Mm_N}\overline{N}T^a_{3/2}\gamma^{\mu\nu\lambda}N^*_{\mu\nu}\gamma^5\gamma^\sigma G^a_{\lambda\sigma} + h.c$$

where $\widetilde{N}^{*\lambda\rho} = \frac{1}{2}\varepsilon^{\mu\nu\lambda\rho}N^*_{\mu\nu},\ N^*_{\mu\nu} = \partial_\mu N^*_\nu - \partial_\nu N^*_\mu,$

$$\gamma^{\mu\nu\lambda} = \gamma^\mu\gamma^\nu\gamma^\lambda - \gamma^\lambda\gamma^\nu\gamma^\mu$$

– The self-energy



# Conclusion

– Rho meson in dense matter

i) Proper tools for the study of the matter created at HIC
ii) Vector dominance model (VDM)
iii) Rho meson self-energy in dense matter
iv) Finite three-momentum effect

– Current and future work

i) P-wave resonance of the rho meson in a medium
ii) Dilepton yields from the imaginary part of the rho meson self energy