Effective model for the description of pions, eta and vector mesons in nuclear matter

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Progress Report on “Properties of Hadrons in Nuclear Matter

and Dilepton Emission in Relativistic Heavy-Ion Collisions”

Măgurele, December 11th, 2008

OVERVIEW

- **Introduction and Motivation**
- **Model for pion-nucleon-resonance interaction**
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  - Three-level model
  - In-medium pion spectral functions
- **Model for vector mesons in vacuum**
  - Rho meson
  - Omega meson
  - Corrections to vacuum spectral functions
- **Model for eta-nucleon-resonance interaction**
- **Summary and Outlook**

Introduction: the model so far

determine self energies of vector mesons in-medium

1) Nucleonic Resonances Contributions: forward Compton scattering

resonances: $N^*(1440)$, $N^*(1520)$, $N^*(1535)$, $N^*(1650)$, $N^*(1680)$
$\Delta^*(1232)$, $\Delta^*(1620)$, $\Delta^*(1700)$, $\Delta^*(1905)$

2) Nonresonant scattering of vector mesons off nucleons:

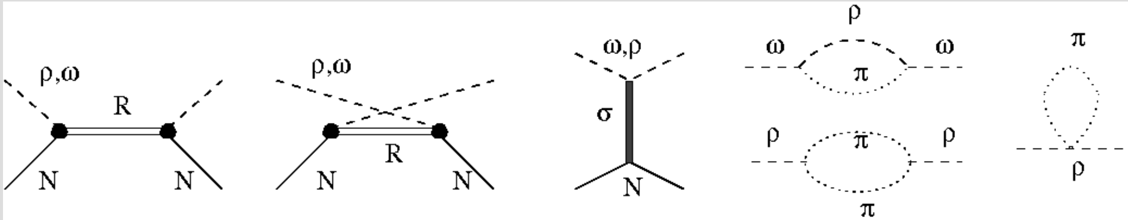
ρNN and ωNN: Bonn nucleon-nucleon potential model

3) Sigma meson exchanges:

$g_{\rho\rho\sigma}$: from the decay $\rho^0 \to \rho^0\sigma \to \pi^+\pi^-\pi^+\pi^-$

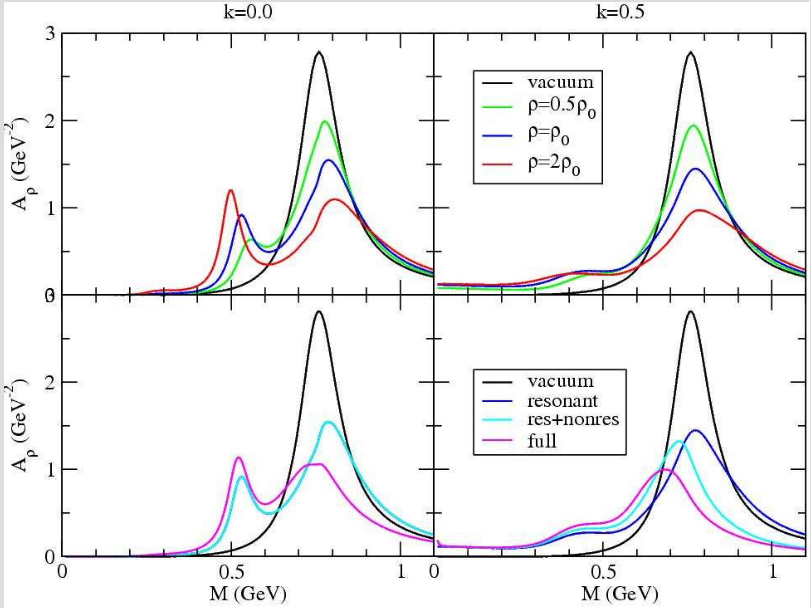
$g_{\omega\omega\sigma}=3g_{\rho\rho\sigma}$

4) Vacuum self-energies parametrize results of $\rho\pi\pi$ interaction for ρ and of the effective Gell-Mann-Sharp-Wagener for the ω

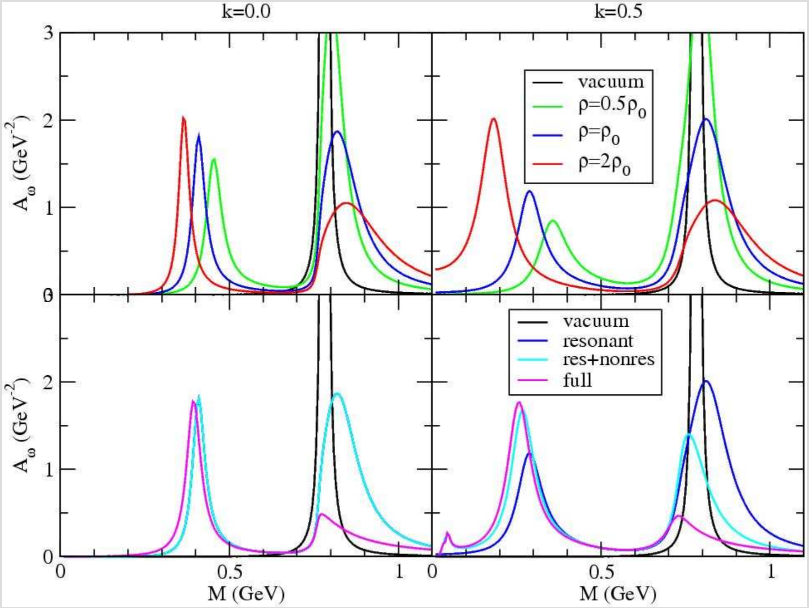


In-medium spectral functions

$$A^{L,T}(p^2) = -\frac{1}{\pi}\,\frac{-Im\,\Sigma^{L,T}(p)\,+\sqrt{p^2}\,\Gamma^{vac}(p)}{[p^2 - m_0^2 - Re\,\Sigma^{L,T}(p]^2 + [-Im\,\Sigma^{L,T}(p)\,+\sqrt{p^2}\,\Gamma^{vac}(p)]^2}$$



N*(1520), N*(1535), Δ(1620)



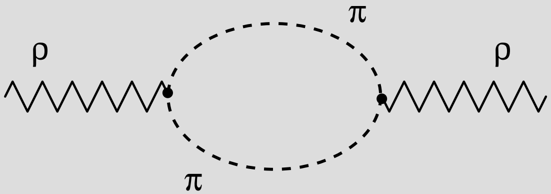
N*(1535), N*(1520)

What does PDG tell us about ρ/ω ?

Rho (770)

Mass: 769.3±0.8 MeV
Width: 150.2±0.8 MeV
Decay modes:

$\pi\pi \quad \rightarrow \quad$ 100%



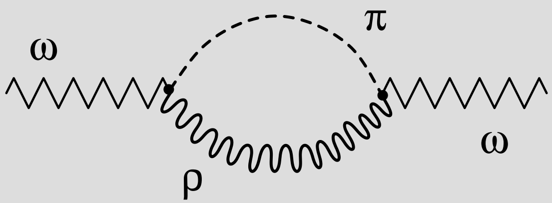
Omega (782)

Mass: 782.57±0.12 MeV
Width: 8.44±0.09 MeV
Decay modes:

$\pi^+\pi^-\pi^0 \quad \rightarrow \quad$ 88.8%

$\pi^0\gamma \quad \rightarrow \quad$ 8.5%

$\pi^+\pi^- \quad \rightarrow \quad$ 2.2%



Mesons In Nuclear Matter

Objective: extend the present model to properly (and consistently) consider all contributions at first order in an expansion in density

At present: - eVMD: $RN\rho$ and $RN\omega$

- nonresonant contributions: $NN\rho$, $NN\omega$
- t channel ρ-N and ω-N scattering with σ exchange

Missing:

- proper treatment of the pion cloud (vacuum self-energies) in-medium
- at present only a parametrisation of the vacuum widths is considered

Why should they be considered?

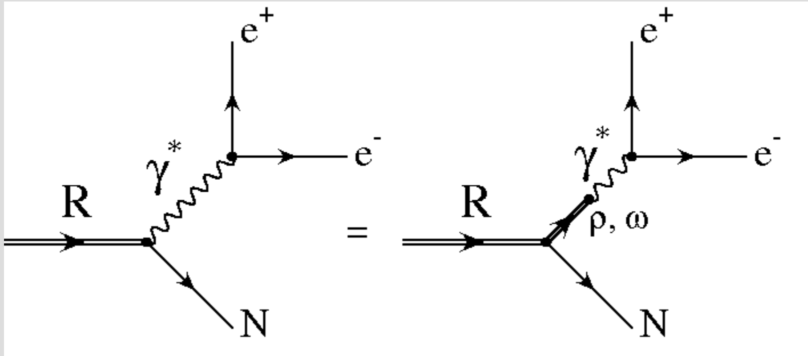
-1) consistency and 2) strong RNπ interaction
- hints that they are important: Urban *et al.*, NPA 641, 433 (1998)

Strategy:

- model for pions in nuclear matter
- model for pion-rho meson interaction
- model for omega-rho-pion-photon interaction

Extended VMD model

consider nucleon resonances R=Δ^*, N^* with mass below 2 GeV and spin J$\leqslant \frac{7}{2}$ unified description of resonance dilepton decays, resonance meson decays,resonance photo-production and meson dilepton decays



Vector Meson Dominance (VMD):

$$
\begin{aligned}
J_\mu(p_R,\lambda_R,p,\lambda) &= e\,\bar{u}_{\beta_1\ldots\beta_2}(p_R,\lambda_R)\,\Gamma^{(\pm)}_{\beta_1\ldots\beta_2\,\mu}u(p,\lambda),\\
\Gamma^{(\pm)}_{\beta_1\ldots\beta_l\,\mu} &= q_{\beta_1}\cdots q_{\beta_{l-1}}\sum_k \Gamma^{(\pm)\,k}_{\beta_l\;\mu}\,F^{(\pm)}_k\\
F^{(\pm)}_k(q^2) &= \sum_V \frac{f^{(\pm)}_{VNR,k}}{g_V}\,\frac{1}{1-q^2/m_V^2}.
\end{aligned}
$$

Decay modes: $\Delta^* \to N\rho \qquad N^* \to N\rho/\omega$

M.Krivoruchenko, B. Martemmyanov Ann.Phys 296, 299 (2002)

$RN\pi$ interactions

consider all resonances of spin 1/2 and spin 3/2

S_{11} and S_{31} resonances

$$\mathcal{L} = -g\overline{\psi}_R \, \vec{\tau} \, \psi \, \vec{\pi} + h.c.$$

P_{11} and P_{31} resonances

$$\mathcal{L} = -g\overline{\psi}_R \, \gamma_5 \, \gamma_\mu \, \vec{\tau} \, \psi \, \partial^\mu \, \vec{\pi} + h.c.$$

spin 3/2: gauge invariant couplings (Pascalutsa nucl-th/9905065)

P_{13} and P_{33} resonances

$$\begin{aligned} \mathcal{L} &= -g\overline{\psi} \, \gamma_5 \, \gamma_\mu \, \vec{\tau} \, \widetilde{G}^{\mu\nu} \, \partial_\nu \, \vec{\pi} + h.c. \\ \widetilde{G}^{\mu\nu} &= \frac{1}{2}\varepsilon^{\mu\nu\rho\sigma} \, G_{\rho\sigma}; \qquad G^{\mu\nu} = \partial^\mu \, \psi^\nu - \partial^\nu \, \psi^\mu \end{aligned}$$

D_{13} and D_{33} resonances

$$\mathcal{L} = -g\overline{\psi} \, \gamma_5 \, \gamma_\mu \, \gamma_n u \, \vec{\tau} \, G^{\mu\rho} \, \partial_\rho \partial^\nu \, \vec{\pi} + h.c.$$

$NN\pi$: customary pseudo-vector coupling

Three-level model

simplification of the model allowing analytical calculations (Urban, NPA 643, 433)

Approximations:

- allow only for $\Delta(1232)$ and non-resonant scattering
- perform a non-relativistic reduction
- assume momentum of the hole ($\vec{p}$) small compared with pion momentum ($\vec{k}$)

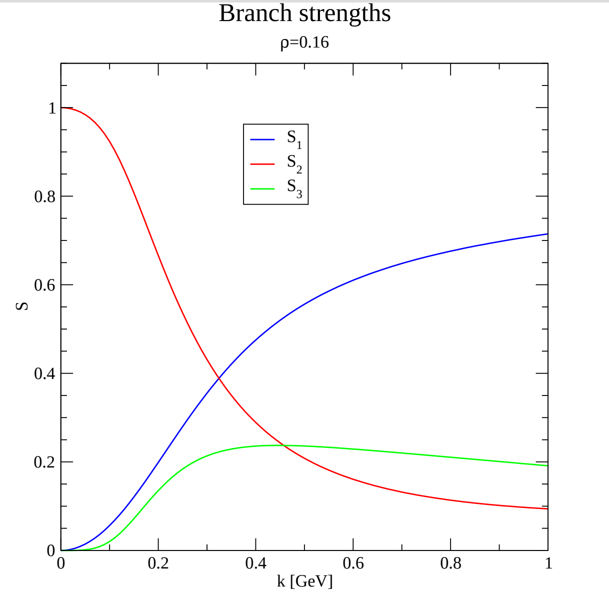
Simplifications: - self-energies expressions

$$\Sigma_{\pi N}(k) = \frac{\alpha_N(\vec{k})}{k_0^2 - \Omega_N^2(\vec{k}) + i\varepsilon} \qquad \Sigma_{\pi\Delta}(k) = \frac{\alpha_\Delta(\vec{k})}{k_0^2 - \Omega_\Delta^2(\vec{k}) + i\varepsilon}$$

Pion propagator:

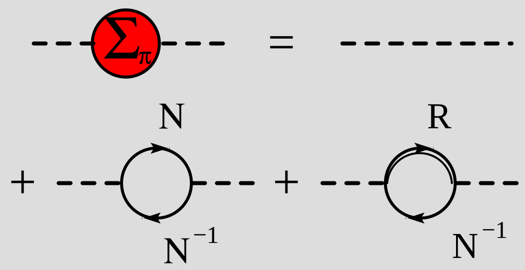
$$\Delta_\pi(k) = \frac{1}{k^2 - m_\pi^2 + \Sigma\pi N + \Sigma\pi\Delta}$$

$$= \frac{S_1(\vec{k})}{k_0^2 - \omega_1^2(\vec{k})} + \frac{S_2(\vec{k})}{k_0^2 - \omega_2^2(\vec{k})} + \frac{S_3(\vec{k})}{k_0^2 - \omega_3^2(\vec{k})}$$

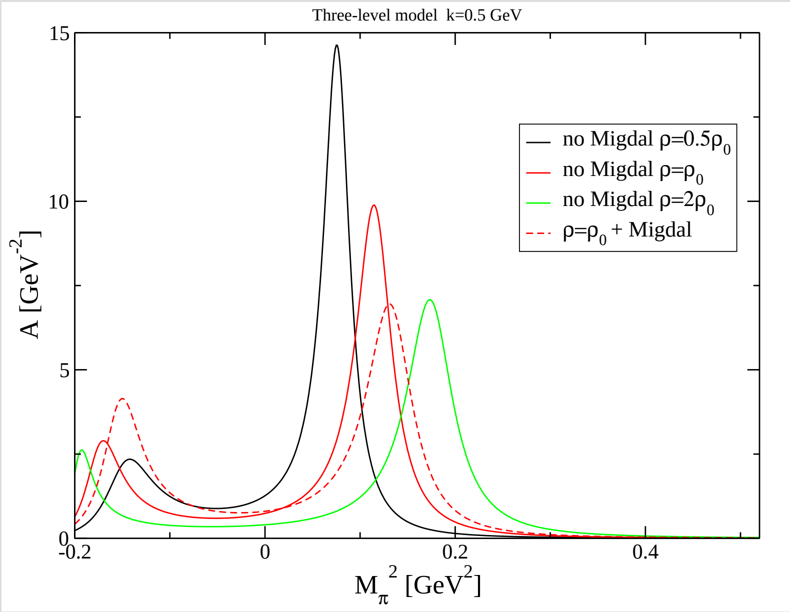


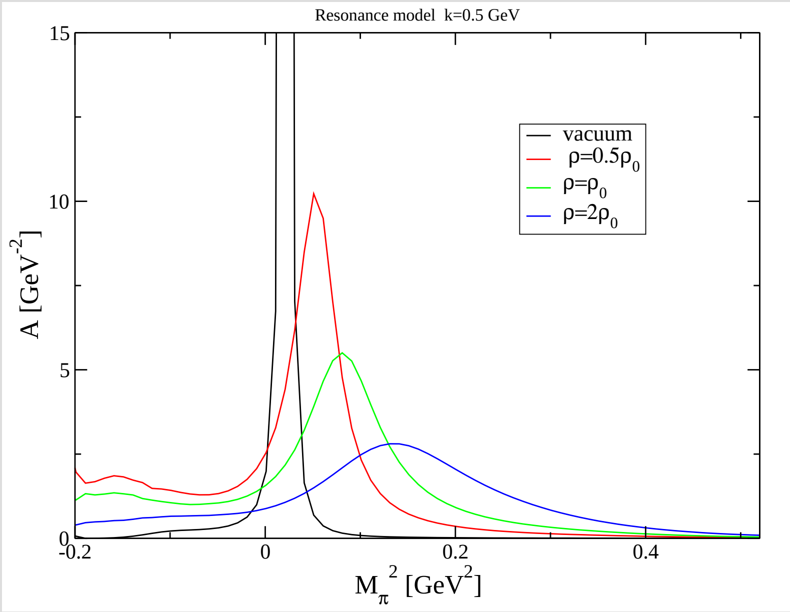
In-medium pion spectral functions

Density expansion of the pion propagator



Three-level model vs. Resonance model pion spf





Rho meson - pion interaction

Vacuum ρ meson - pion interaction

$$\mathcal{L}_0 = \frac{1}{2}\partial_\mu \vec{\pi}\cdot\partial^\mu \vec{\pi} - \frac{1}{2}\, m_\pi^2\, \vec{\pi}\cdot\vec{\pi} - \frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2}\, m_V^2\, V_\mu\, V^\mu$$

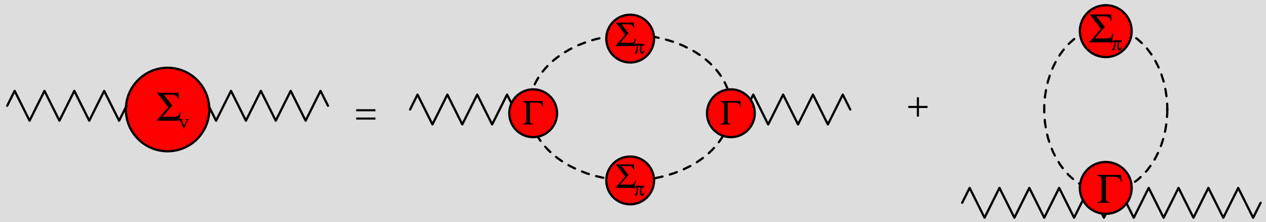
$$\mathcal{L}_{\pi\rho} = \frac{i}{2} g\, V_\mu^a\, (\partial^\mu\, \pi_i\, T_{ij}^a\, \pi_j + \pi_i\, T_{ij}^a\, \partial^\mu\, \pi_j) - \frac{1}{2} g^2\, V_\mu^a\, V^{\mu,b}\, T_{ij}^a\, \pi_j\, T_{ik}^b\, \pi_k$$

General expression for self-energy:

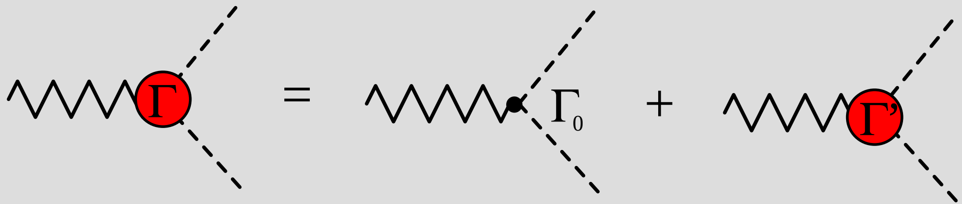
$$\begin{aligned} i\Sigma_{\mu\nu(p)} &= \frac{1}{2}\int \frac{d^4k}{(2\pi)^4}\, iD_\pi(k)\,\Gamma_{\mu ab}(k,p)\, iD_\pi(k+p)\,\Gamma_{\nu ba}(k+p,-p) \\ &\quad + \frac{1}{2}\int \frac{d^4k}{(2\pi)^4}\, iD_\pi(k)\,\Gamma_{\mu\nu aa}(k,k,q) \\ \Gamma_{\mu ab}(k,q) &= g\varepsilon_{3ab}\,(2k+p)_\mu + \Gamma'_{\mu ab}(k,q) \\ \Gamma_{\mu\nu ab}(k_1,k_2,p) &= 2ig^2\,(\delta_{ab} - \delta_{3a}\delta_{3b})\, g_{\mu\nu} + \Gamma'_{\mu\nu ab}(k_1,k_2,p) \end{aligned}$$

Rho meson diagrammatics

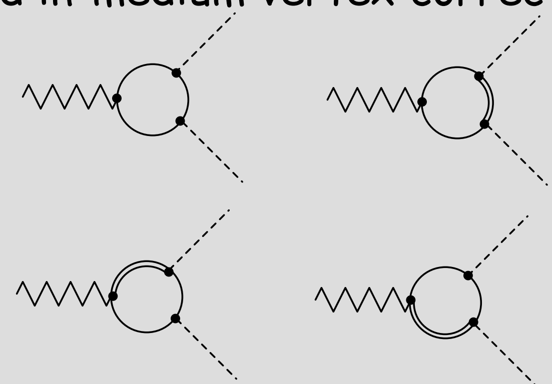
Diagrammatic representation of in-medium rho meson self-energy:

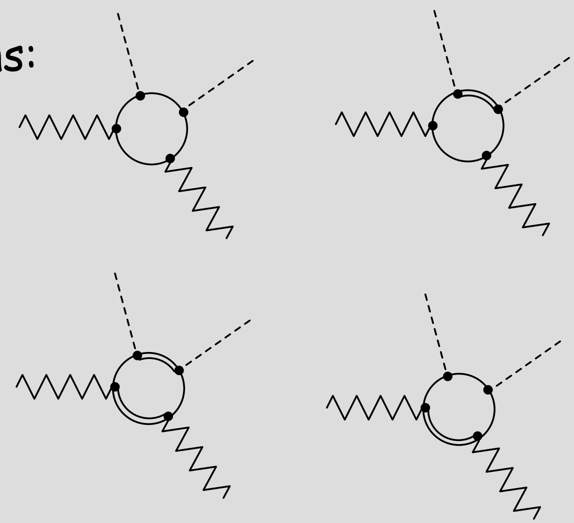


In-medium corrections to the $\rho\pi\pi$ and $\rho\rho\pi\pi$ vertices



Selected in-medium vertex correction contributions:



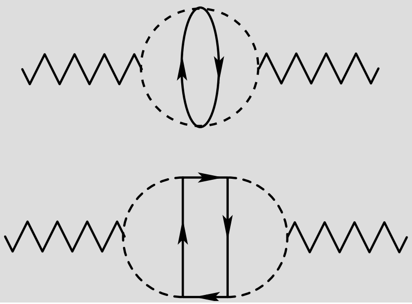


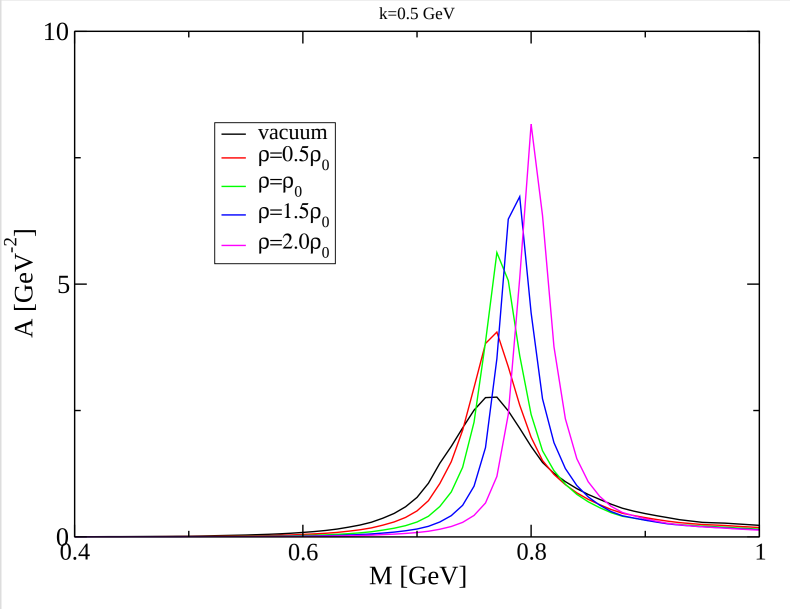
Rho meson spectral functions

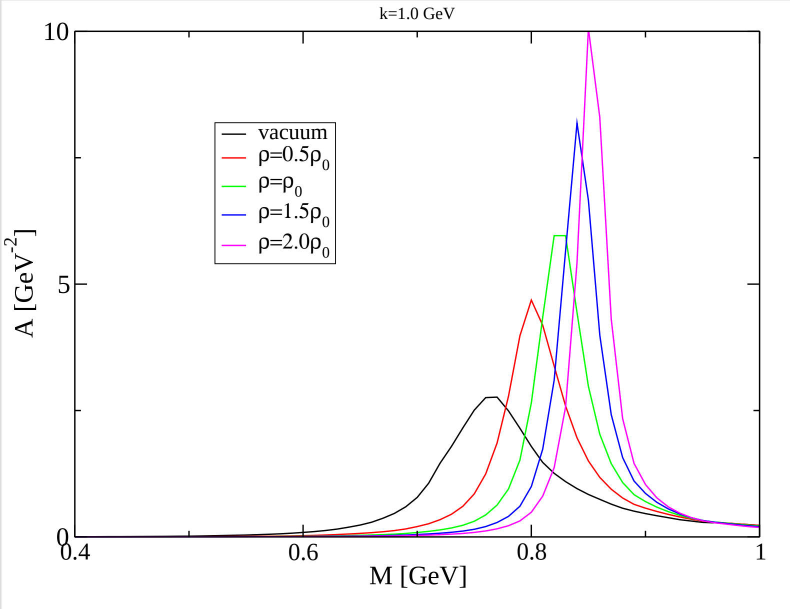
Only contributions from the in-medium decay channer $\rho \rightarrow \pi\pi$

No resonance contributions !

Intentionally omitted graphs (would lead to double-counting):







Omega meson effective model

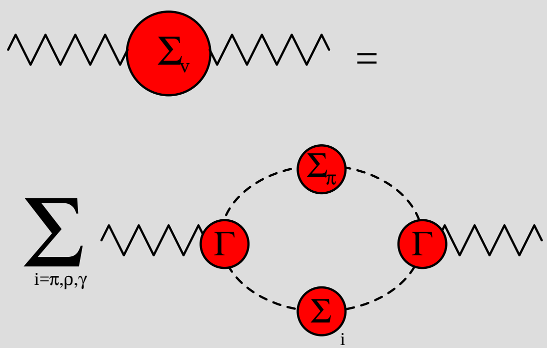
Model to explain the main decay channels in vacuum:

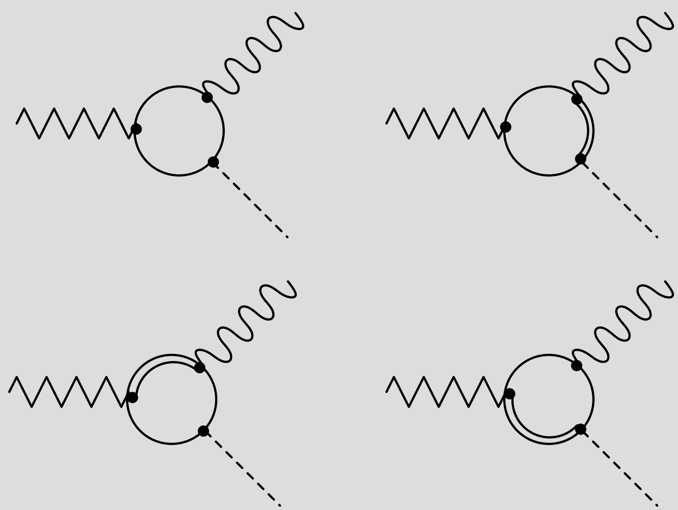
$$\mathcal{L}_{\omega\rho\pi} = -\frac{g_{\omega\rho\pi}}{4m_\pi}\vec{\pi}\epsilon_{\mu\nu\alpha\beta}\vec{\rho}^{\mu\nu}\omega^{\alpha\beta}$$

$$\mathcal{L}_{\omega\pi\gamma} = -e\frac{g_{\omega\pi\gamma}}{4m_\pi}\pi_0\,\epsilon_{\mu\nu\alpha\beta}\,\omega^{\mu\nu}F^{\alpha\beta}$$

$$\mathcal{L}_{\omega\pi\pi} = -\frac{g_{\omega\pi\pi}}{2m_\pi}\omega_\mu\left(\partial^\mu\vec{\pi}\cdot\vec{\pi}+\vec{\pi}\cdot\partial^\mu\vec{\pi}\right)$$

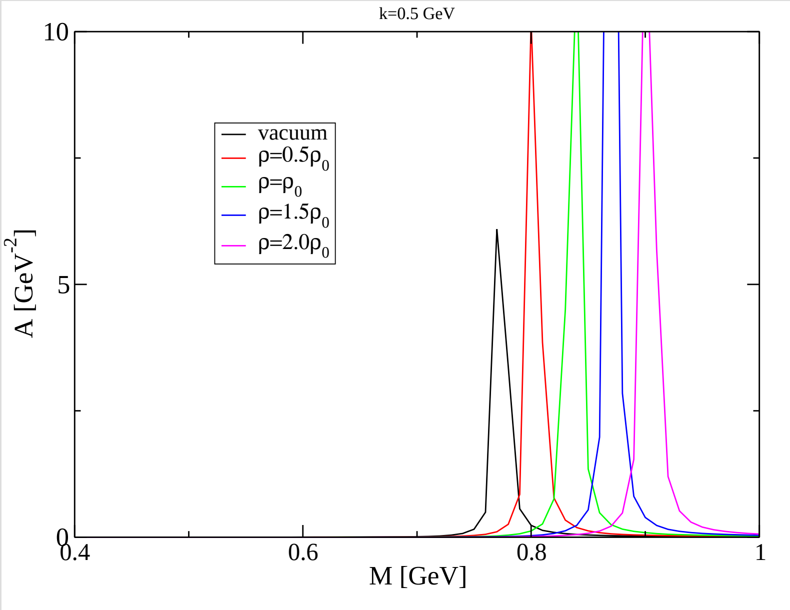
In-medium self-energy vs. Medium corrections to the vertex function:

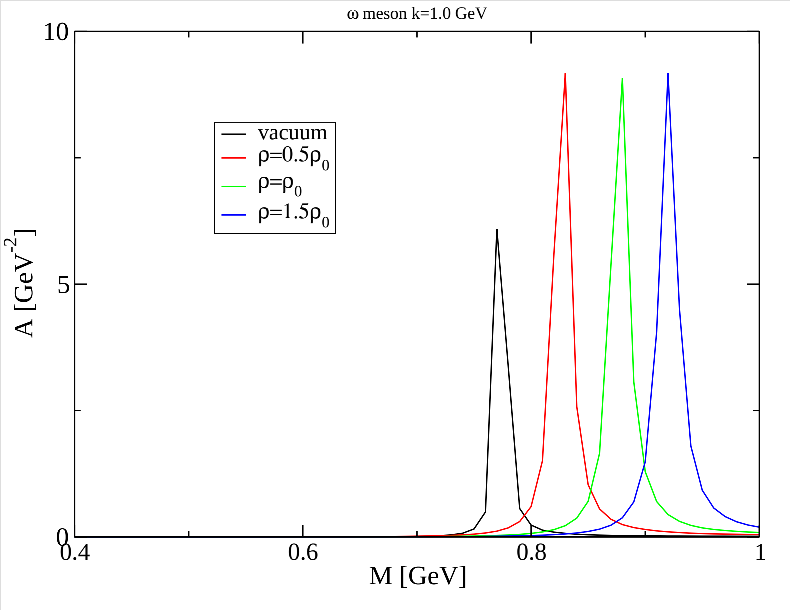




Omega meson spectral functions

No resonance contributions to self-energy (same as for ρ)

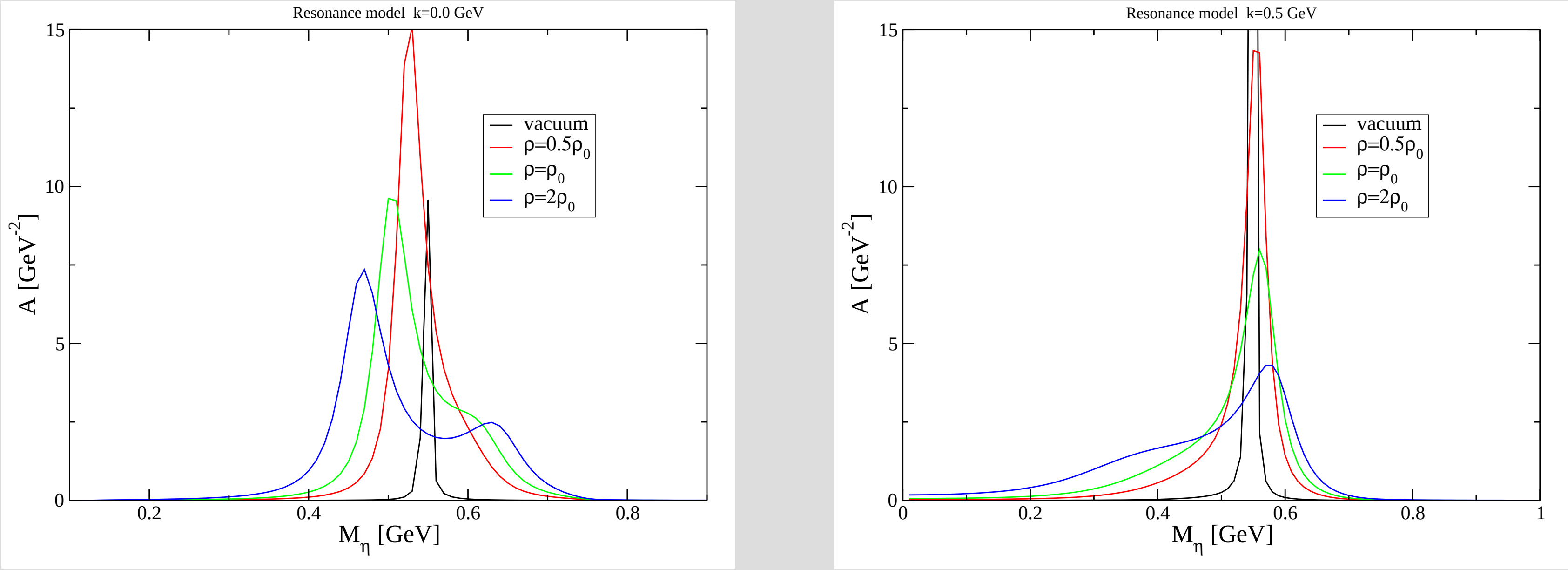




In-medium eta (547) meson spf

the only quantum number different from pion is isospin
use relevant πNR couplings as ηNR
non zero $\Gamma_{R\to N\eta}$ decay widths: N(1535), N(1650), N(1700), N(1710)
background contribution: $NN\eta$ - from an OBE model (not Bonn CD!)

Spectral function results:



Summary and Outlook

- It is neccesarry to include medium corrections to the vm vacuum self energy diagrams
- Extended the eVMD resoanance model by including explicit πNR and ηNR couplings
- Important medium-modification of the pion propagator, inline with findings by other authors
- Computed medium-corrections to the ρ and ω vacuum self-energies by considering medium contributions to the virtual meson propagators and vertices
- Preliminary results indicate important contributions leading to a upward shift of vacuum masses
- Result for the ρ meson conter-intuitive
- To be done: Take into account all the vertex corrections contributing to the leading order in a expansion over density