Pions and vector mesons in nuclear matter: extra contributions
&
Comparison of dilepton emission model with experimental data

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Progress Report on “Properties of Hadrons in Nuclear Matter

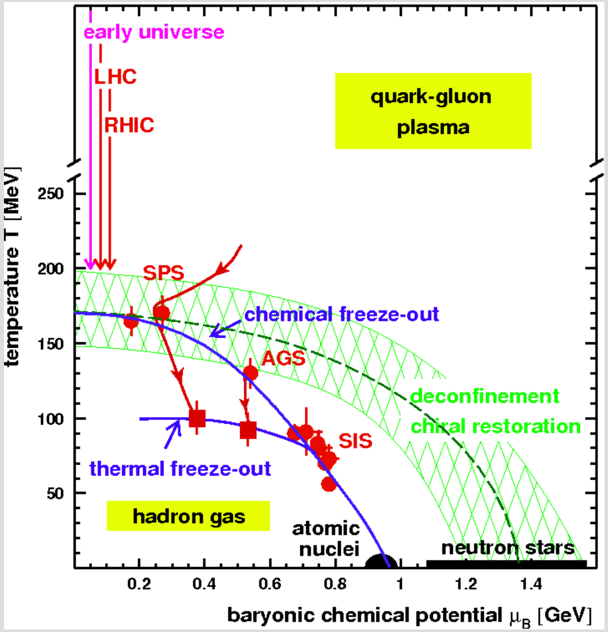
and Dilepton Emission in Relativistic Heavy-Ion Collisions”

Măgurele, July 14th, 2008

OVERVIEW

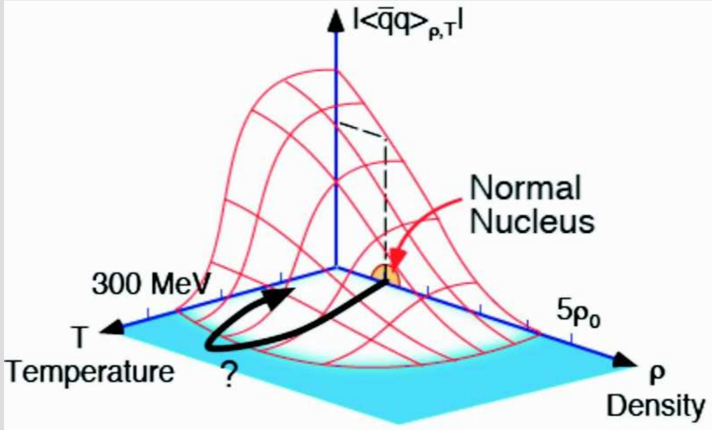
- **Introduction and Motivation**
- **Model for dilepton emission**
  - Elementary sources for dileptons
  - In-medium effects on vector mesons
  - Comparison with HADES and DLS data
- **In-medium description of mesons**
  - Resonance model for in-medium pions
  - Three-level model
  - Rho vector meson
- **Summary and Outlook**

QCD phase diagram and χSR



- SBχS - massless Goldstone bosons, chiral partners ($\pi - \sigma, \rho - a_1$)
- partial restoration of chiral symmetry in nuclei
- medium effects - precursor of χS restoration
- How? dropping masses; melting of resonances

- quark condensate $\langle 0|q\bar{q}|0\rangle$: order parameter
- existence of QGP?
- restoration of chiral symmetry?



The VMD Model

The model provides a **unified description** of:

- meson dilepton decays: $\mathcal{M} \rightarrow X\, e^+\, e^-$
- resonance dilepton decays:

$$R \rightarrow N\, e^+\, e^-\, ,\, R \rightarrow N\, X\, e^+\, e^-$$

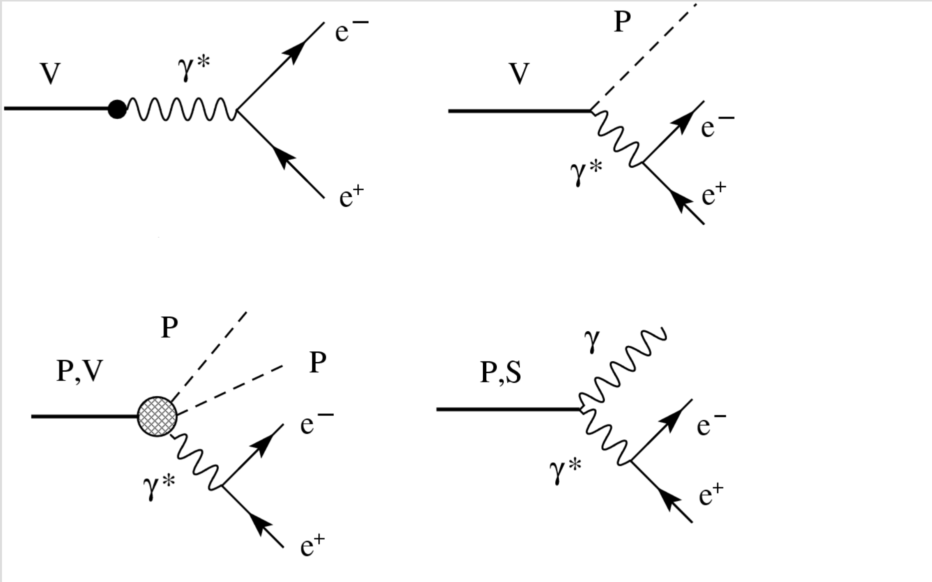
- resonance meson decays: $R \rightarrow N\, \rho(\,\omega)$
- resonance photo-production (decay): $\leftrightarrow N\, \gamma$

Free parameters:

$$f_{RN\rho(\omega)} \leftarrow \text{data}$$

Problem: inconsistency between resonance meson decays and photo-production data

Elementary sources for e^+e^- production



Mesonic decays:

dilepton decays of
pseudoscalar (π,η,$\eta\prime$)
and vector (ρ, ω, ϕ) mesons

$$d\Gamma^{(\mathcal{M}\to X e^+ e^-)} = d\Gamma^{(\mathcal{M}\to X\gamma^\star)} M\Gamma^{(\gamma^\star\to e^+e^-)} \frac{dM^2}{\pi M^4}$$

$$M\Gamma^{(\gamma^\star\to e^+e^-)} = \frac{\alpha}{3}\left(M^2+2m_e^2\right)\sqrt{1-\frac{4m_e^2}{M^2}}$$

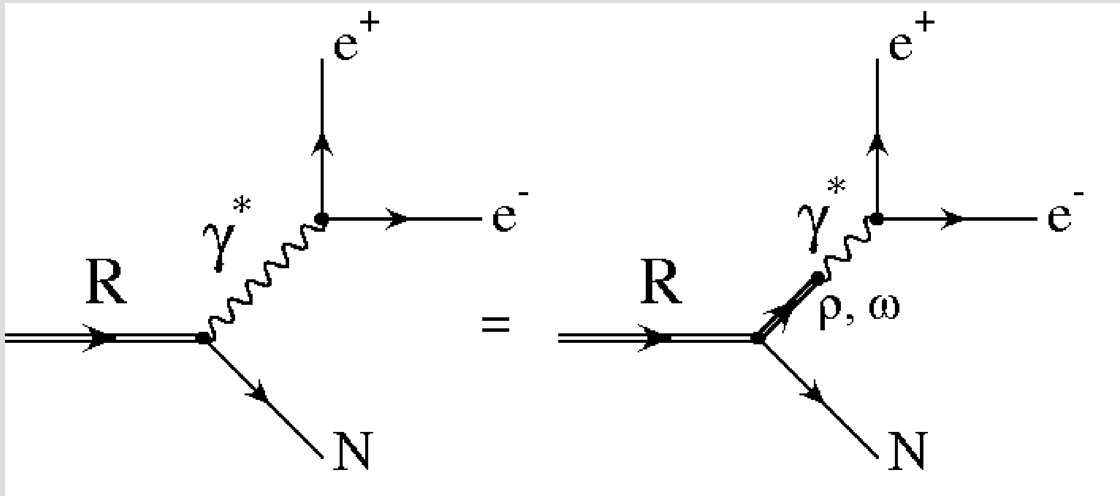
direct decays : $\mathcal{M} \to e^+e^-$ ex: $\rho,\omega \to e^+e^-$

Dalitz decays : $\mathcal{M} \to \pi e^+e^-$ ex: $\pi^0 \to \gamma e^+e^-$, $\eta \to \gamma e^+e^-$

4-body decays : $\mathcal{M} \to \pi\pi e^+e^-$ ex: $\eta \to \pi^+\pi^- e^+e^-$

Resonance Decays

consider nucleon resonances R=Δ^*, N^* with mass below 2 GeV and spin J$\leqslant \frac{7}{2}$



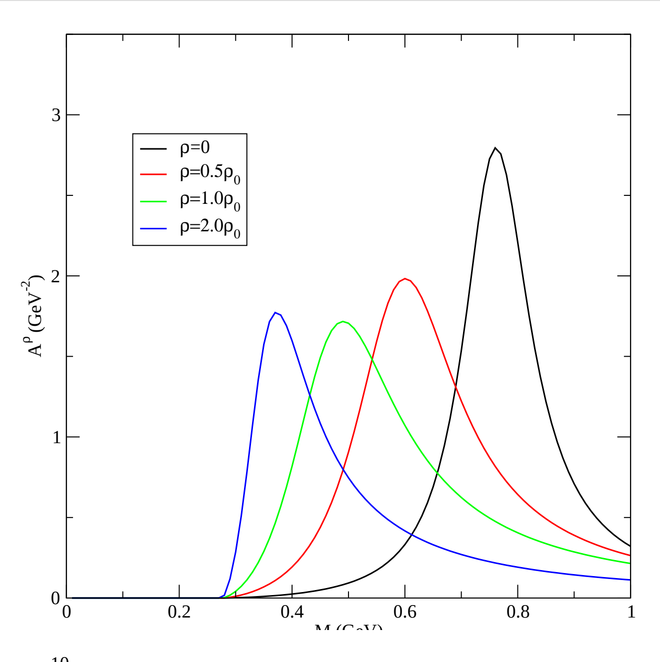
Vector Meson Dominance (VMD):

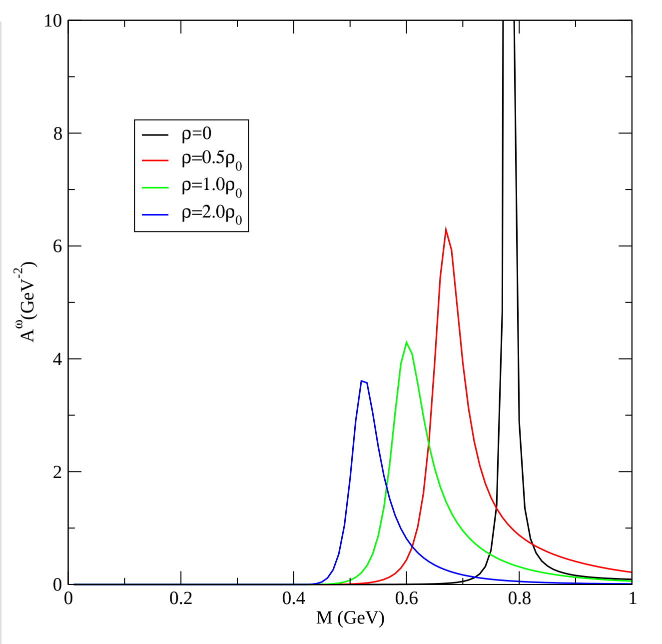
$$d\,\Gamma^{(R\to Ne^+e^-)} = d\,\Gamma^{(R\to N\gamma^*)}\,M\,\Gamma^{(\gamma^*\to e^+e^-)}\,\frac{d\,M^2}{\pi M^4}$$

$$d\,\Gamma^{(R\to NX\gamma^*} = d\,\Gamma^{(R\to NV)}\,\frac{dB^{(V\to X\gamma^*)}}{d\,M}$$

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

Traditional Approach to Medium Effects





Mass scaling (Brown-Rho):

- Scale invariance: Brown, Rho - PRL66, 2720
- QCD sumrules: Hatsuda,Lee - PRC46, R34

$$m_V^* = m_V\,(1 - \alpha\,\rho/\rho_0) \quad \alpha\text{=0.2}$$

Collisional broadening:

$$dB(\mu, M)^{R \to NV} = \frac{d\Gamma^R_{NV}(\mu, M)}{\Gamma_R(\mu)}$$

increases with meson width

$$B(\mu)^{R \to Ne^+e^-} \sim B(\mu)^{R \to NV}\,\frac{\Gamma_{V \to e^+e^-}}{\Gamma_V^{tot}}$$

decreases due to increased meson width

$$\Gamma_V^{tot} = \Gamma_V^{vac} + \rho/\rho_0\,\Gamma_V^{coll}$$

Γ_ρ^{coll} =150 MeV, Γ_ω^{coll} =142 MeV at ρ_0

Many-body approach

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:

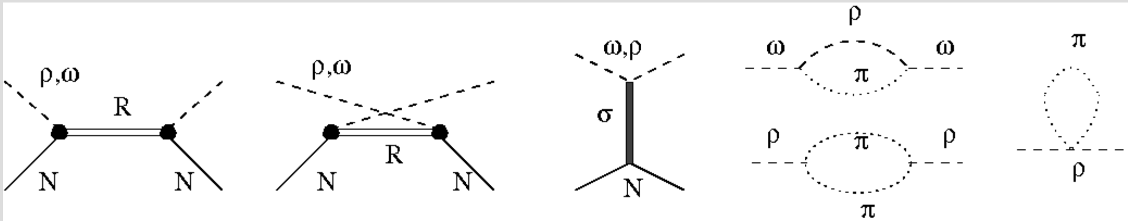
ρNN and ωNN: Bonn nucleon-nucleon potential model

3) Sigma meson exchanges:

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

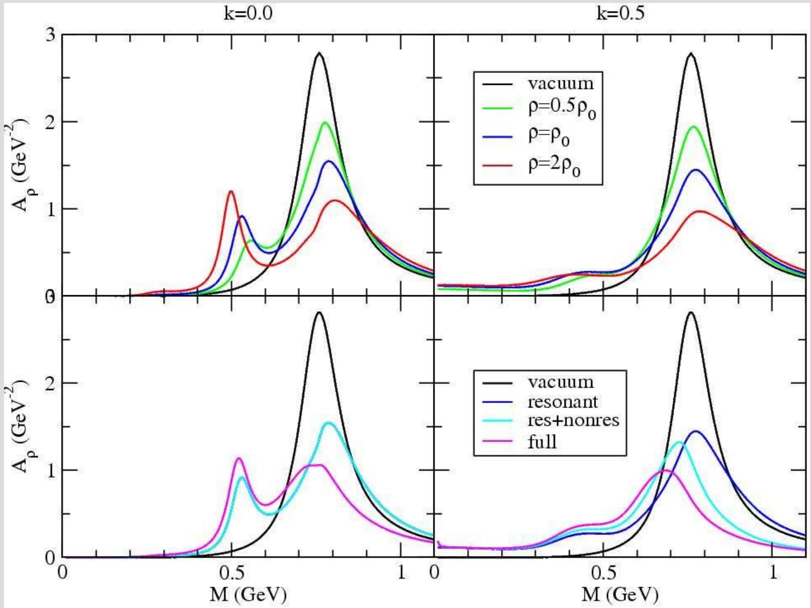
$g_{\omega\omega\sigma}=3g_{\rho\rho\sigma}$

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

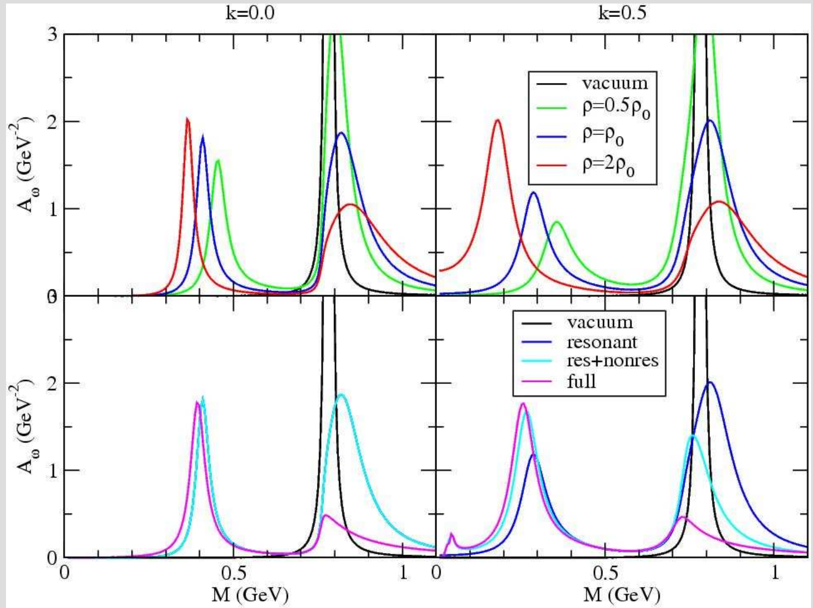


In-medium spectral functions

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

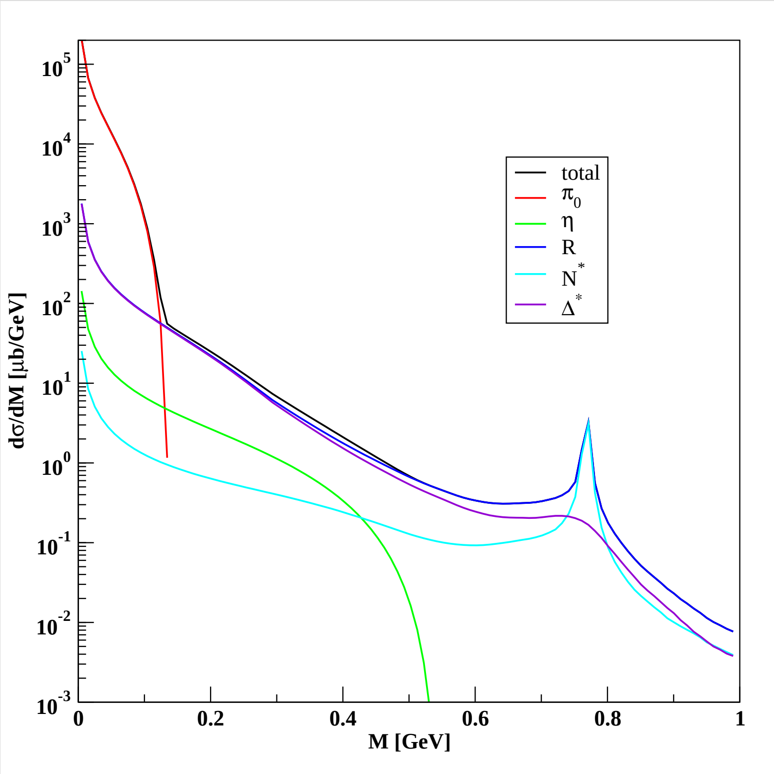


N*(1520), N*(1535), Δ(1620)

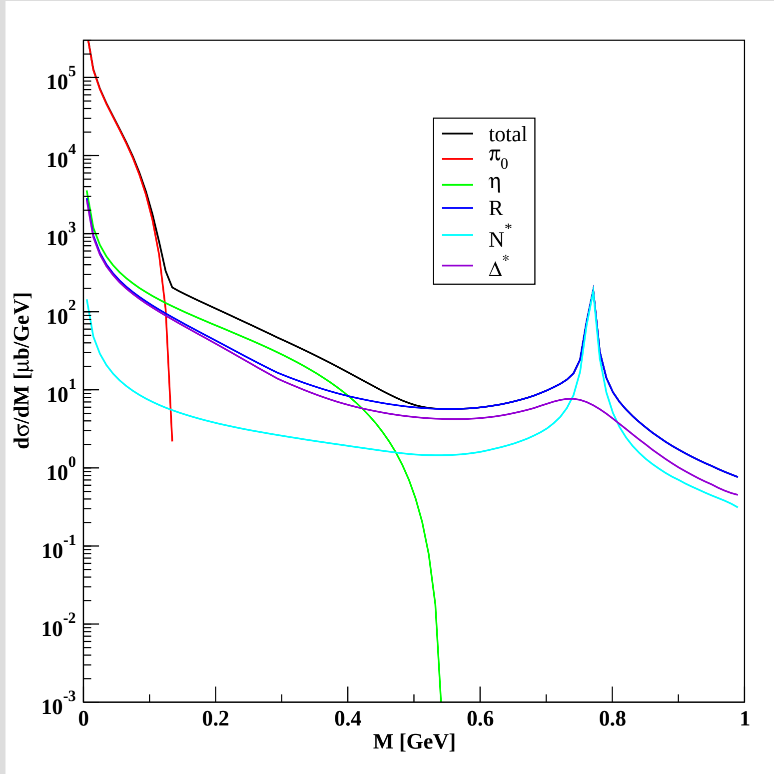


N*(1535), N*(1520)

Dilepton spectrum: example



CC @ 1.0AGeV



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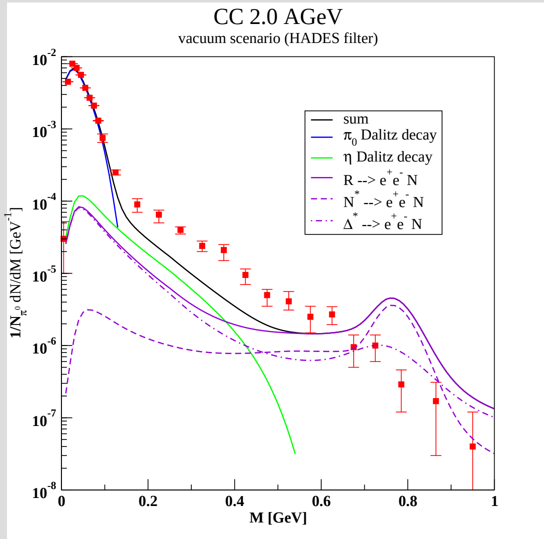
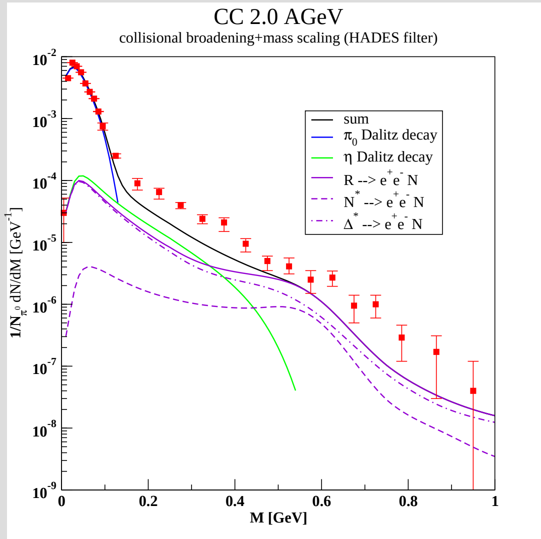
Resonance list:

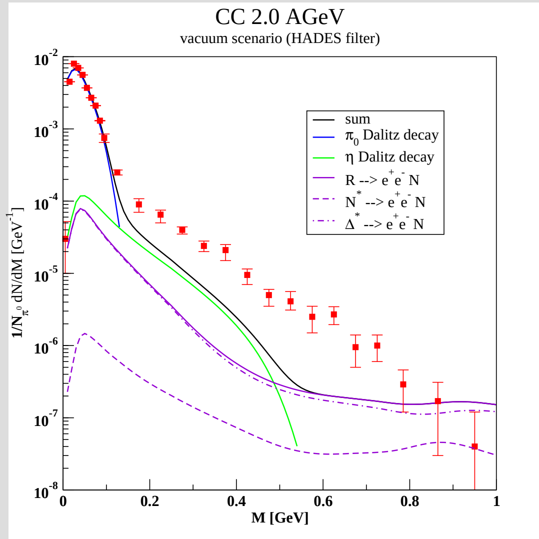
N^*: N(1440), N(1520), N(1535), N(1650), N(1680), N(1720)

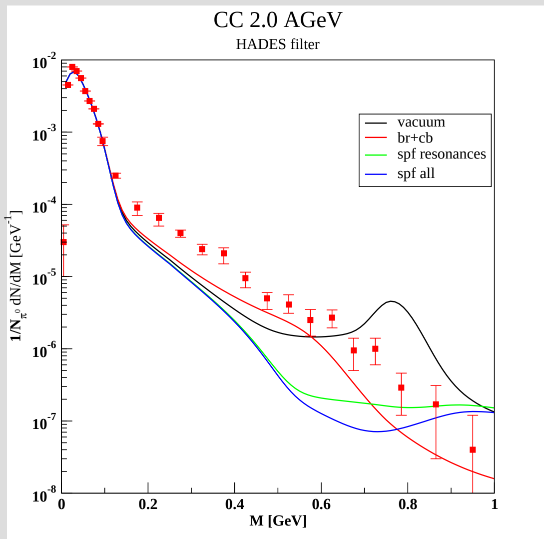
Δ^*: Δ(1232), Δ(1620), Δ(1700), Δ(1905)

Dilepton Spectra @ HADES









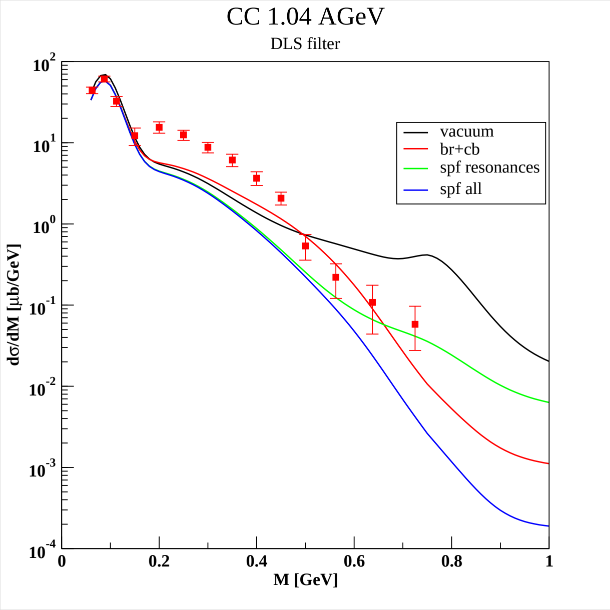
-iteration of meson and resonance spfs important

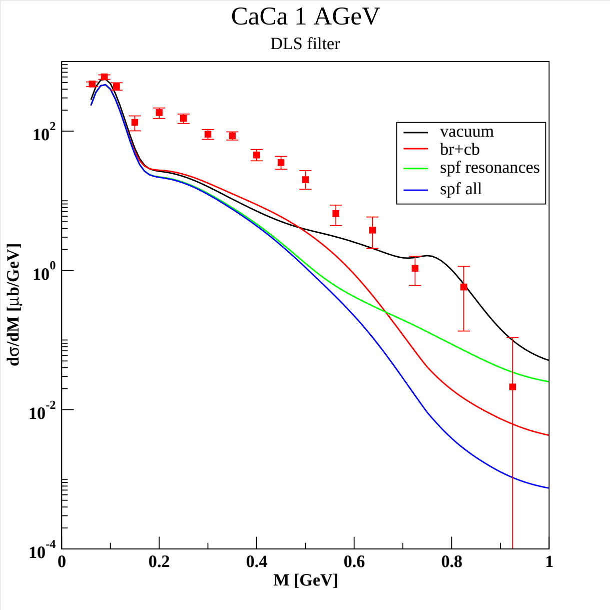
-omitted contribution: nucleon-nucleon bremsstrahlung could be important (Kaptari, NPA 764, 338 (2005))

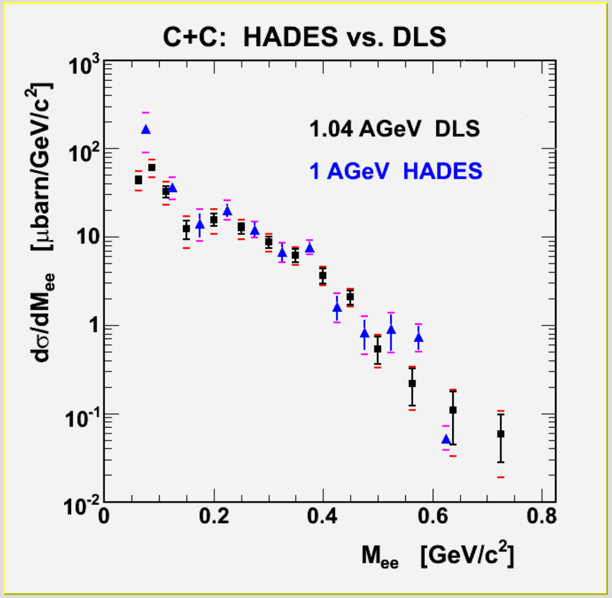
-issues: poorly known $RN\omega$ couplings

experimental data points Agakichiev *et al.*, PRL98, 052302(2007)

Dilepton Spectra @ DLS







Pachmayer, Workshop on Dileptons, Trento, 2007

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 (accomplished, mostly)
- model for pion-rho meson interaction (in progress, some preliminary results)
- model for omega-rho-pion-photon interaction (yet to be done)

$RN\pi$ 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

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

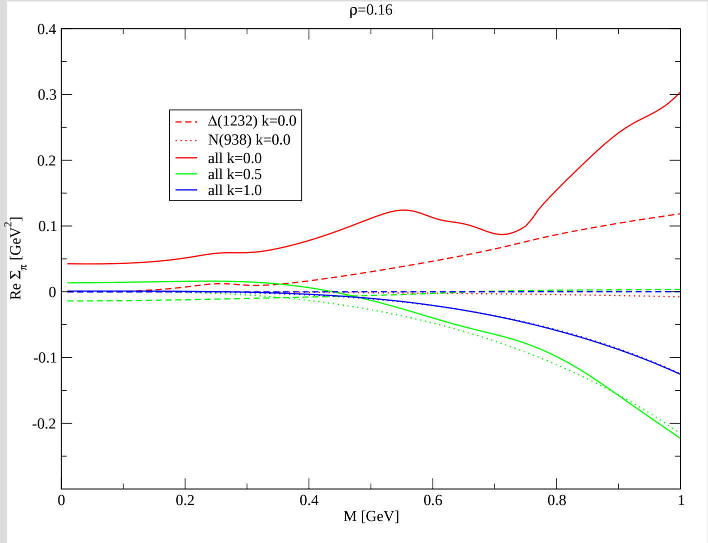
$NN\pi$: customary pseudo-vector coupling

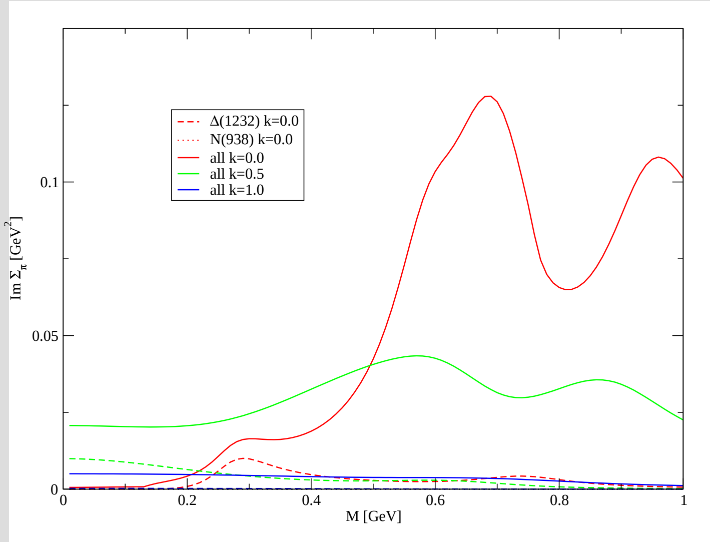
Table of included resonances

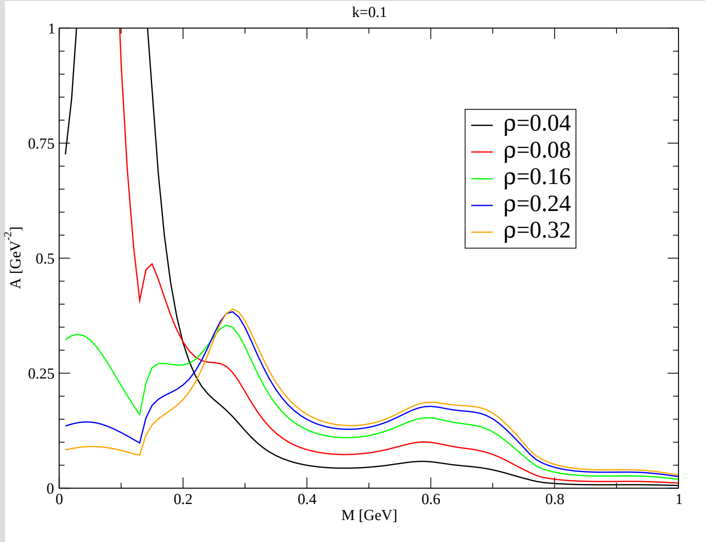
Resonance	Spectroscopic Notation	Parity	Total width	Partial width (pi)	Coupling
N(1535)	S11	-	0.150	0.135	1.81
N(1650)	S11	-	0.150	0.120	1.90
N(1520)	D13	-	0.120	0.066	18.63
N(1700)	D13	-	0.100	0.010	7.46
N(1440)	P11	+	0.350	0.227	7.32
N(1710)	P11	+	0.100	0.015	2.23
N(1720)	P13	+	0.150	0.022	3.18
N(1900)	P13	+	0.500	0.130	8.36
Δ(1620)	S31	-	0.150	0.037	1.79
Δ(1900)	S31	-	0.200	0.040	2.41
Δ(1700)	D33	-	0.300	0.045	27.41
Δ(1940)	D33	-	0.500	0.100	48.40
Δ(1750)	P31	+	0.300	0.030	5.67
Δ(1910)	P31	+	0.250	0.062	9.62
Δ(1232)	P33	+	0.120	0.120	17.91
Δ(1600)	P33	+	0.350	0.070	9.35
Δ(1920)	P33	+	0.200	0.030	7.03

In-medium pion properties

$$i\,\Delta_F(p^2) = \frac{i}{p^2 - m_0^2 + \Sigma(p^2)} \quad \rightarrow \quad A(p^2) = -\frac{1}{\pi}\frac{+Im(\,\Sigma(p^2)\,)}{[p^2 - m_0^2 + Re\,\Sigma(p^2)\,]^2 + [\,Im\,\Sigma(p^2)\,]^2}$$







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

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

$$\Omega_N(\vec{k}) = \omega_N(\vec{k}) - m_N \qquad \alpha_N(\vec{k}) = 4\frac{p_F^3}{3\pi^2}\, g_{NN\pi}^2\, \Omega_N(\vec{k})$$

$$\Omega_\Delta(\vec{k}) = \omega_\Delta(\vec{k}) - m_N - \frac{i}{2}\Gamma_\Delta \qquad \alpha_\Delta(\vec{k}) = \frac{16}{9}\frac{p_F^3}{3\pi^2}\, g_{N\Delta\pi}^2\, \Omega_\Delta(\vec{k})$$

Pion propagator:

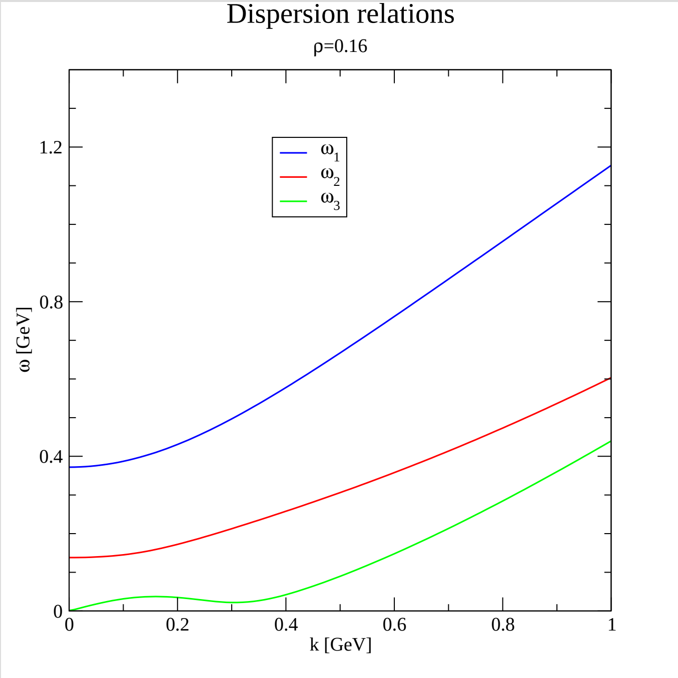
$$\begin{aligned}\Delta_\pi(k) &= \frac{1}{k^2 - m_\pi^2 + \Sigma\pi N + \Sigma\pi\Delta} \\ &= \frac{S_1(\vec{k})}{k_0^2 - \omega_1^2(\vec{k})} + \frac{S_2(\vec{k})}{k_0^2 - \omega_2^2(\vec{k})} + \frac{S_3(\vec{k})}{k_0^2 - \omega_3^2(\vec{k})}\end{aligned}$$

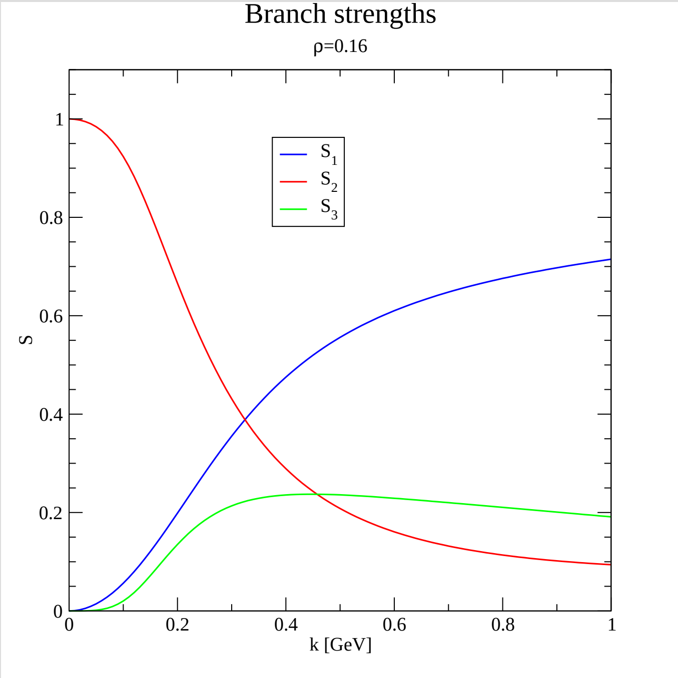
Three-level model

Implications:

-pion is a mixture of three quasiparticles

-1 nucleon-hole branch; 2 pion branch; 3 delta-hole branch





Rho meson - pion interaction

Vacuum ρ meson - pion interaction

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

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

Expression of the in-medium self-energy:

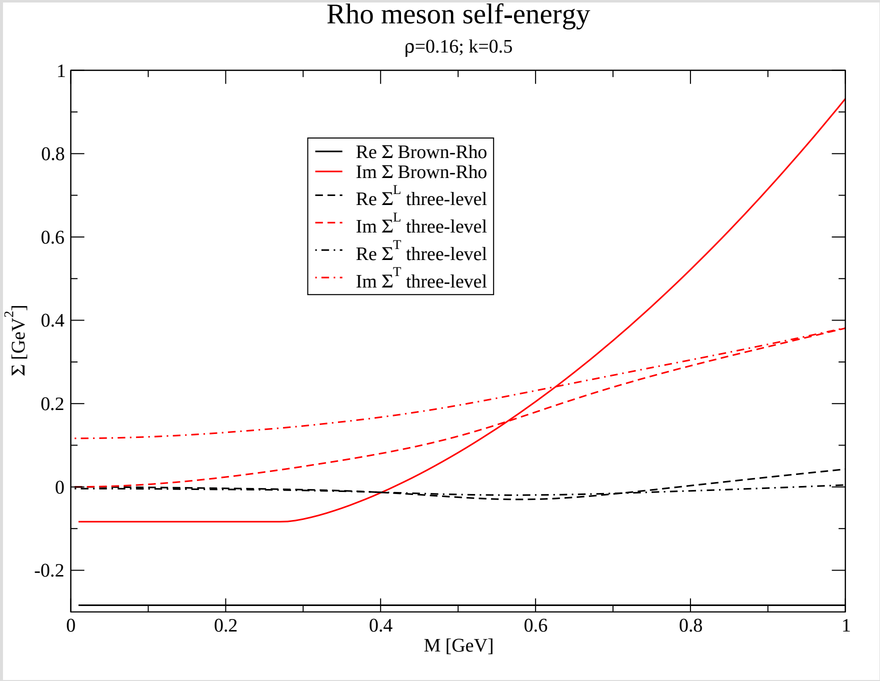
$$\begin{aligned} i\Sigma_{\mu\nu(p)} &= \frac{1}{2}\int \frac{d^4k}{(2\pi)^4}\, iD_\pi(k)\,\Gamma_{\mu ab}(k,p)\, iD_\pi(k+p)\,\Gamma_{\nu ba}(k+p,-p) \\ &\quad + \frac{1}{2}\int \frac{d^4k}{(2\pi)^4}\, iD_\pi(k)\,\Gamma_{\mu\nu aa}(k,k,q) \\ \Gamma_{\mu ab}(k,q) &= g\varepsilon_{3ab}\,(2k+p)_\mu +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

Rho-meson self-energy

Approximations:

pion-propagator: three-level model

vertex-corrections: excitations of nucleon-hole and delta-hole corrections



Summary and Outlook

- Used eVMD to describe in-medium properties of vector mesons
- Comparison of theoretical dilepton spectra with experiment reveals important differences
- Region where discrepancy largest is dominated by Dalitz decay of $\Delta(1232)$
- Resonance model for pion propagation in-medium: important differences with the three level model
- Medium effects on pion cloud around rho-meson; first hints indicate that so far used parametrization is crude at densities comparable with ρ_0
- Include spin 5/2 resonances for the in-medium pion description
- Consider the full in-medium pion propagator when extraction rho-meson self-energy
- Extend to model for the omega meson