In-Medium Properties of Vector Mesons and Dilepton Emission in Heavy-Ion Collisions at SIS energies

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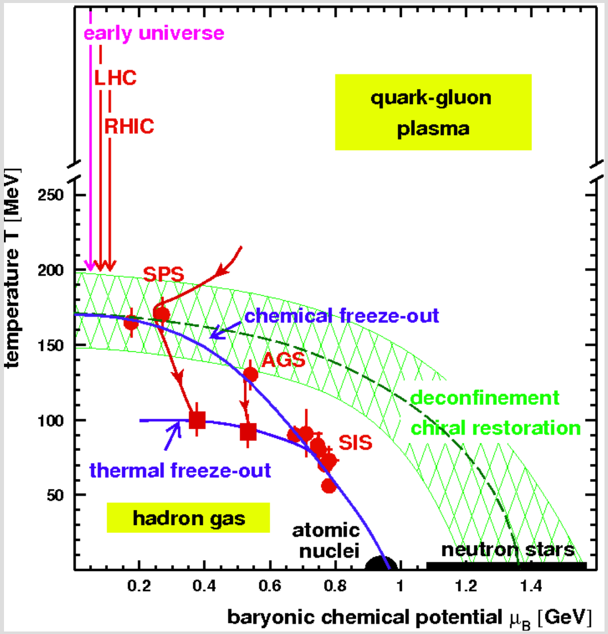
Les Houches, March 28th, 2008

OVERVIEW

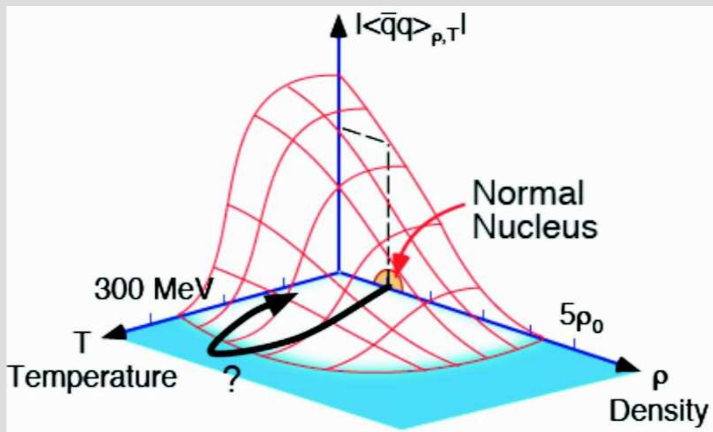
- **Introduction and Motivation**
- **Model for dilepton emission**
  - Elementary sources for dileptons
  - Resonance Model and eVMD
  - QMD Transport model
- **In-medium effects**
  - Brown-Rho scaling and Collisional broadening
  - Many-body model: meson spectral functions
- **Summary and Outlook**

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

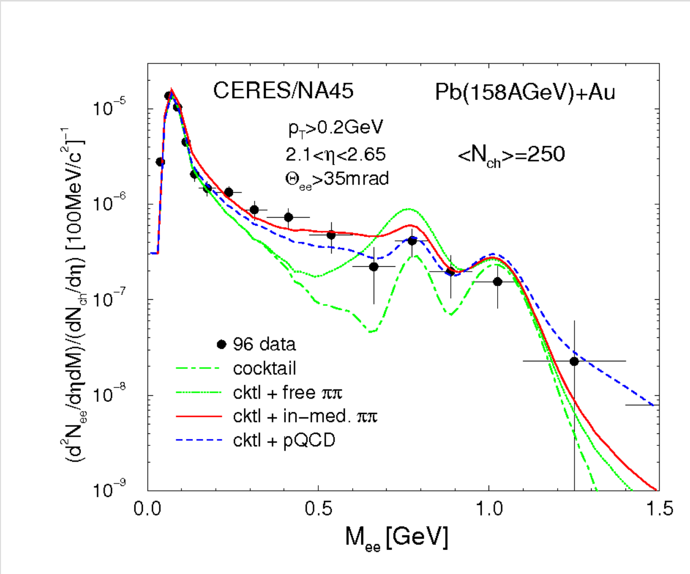
- quark condensate $\langle 0|q\bar{q}|0\rangle$: order parameter
- existence of QGP?
- restoration of chiral symmetry?



Ultrarelativstic vs. medium energy HICs

100s AGeV: CERES, HELIOS (CERN SPS)

hadronic cocktail: $\rho, \omega, \phi, \pi, \eta \rightarrow e^+e^-$



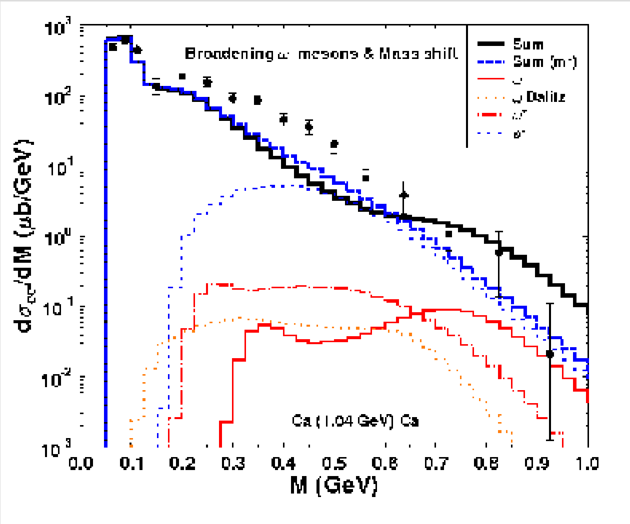
Agakichiev PRL75, 1272

NA45: dropping ρ, in-medium spectral functions $\pi^+\pi^- \rightarrow \rho^* \rightarrow e^+e^-$ or pQCD: $g + g \rightarrow e^+e^-$

NA60: rules out naive dropping mass scenario

few AGeV range DLS/BEVALAC:

1.0 AGeV C+C and Ca+Ca



Ernst PRC58, 447(1998)

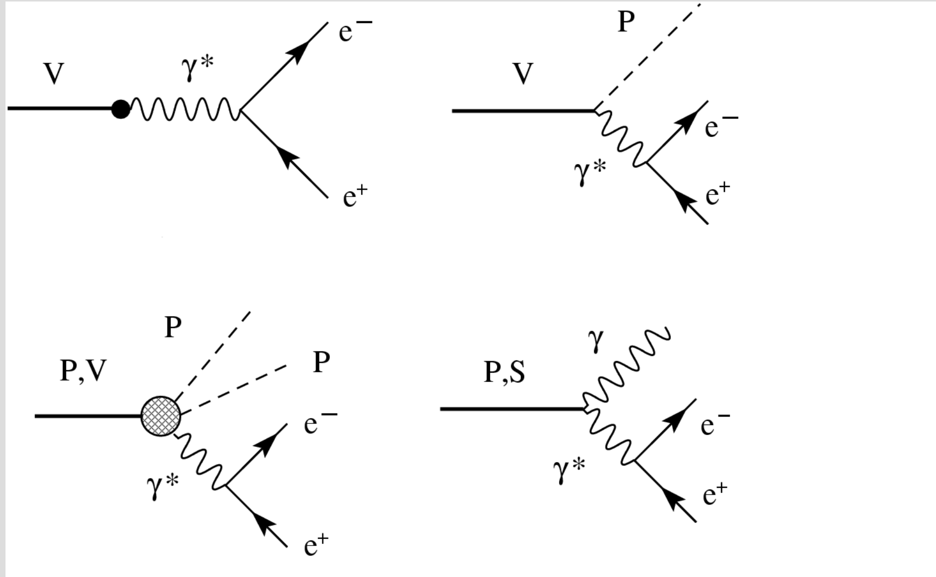
- dropping mass and spectral functions don't help
- pQCD or in-medium effects on η excluded

DLS Puzzle

Elementary sources for e^+e^- production

Mesonic decays:

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



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

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

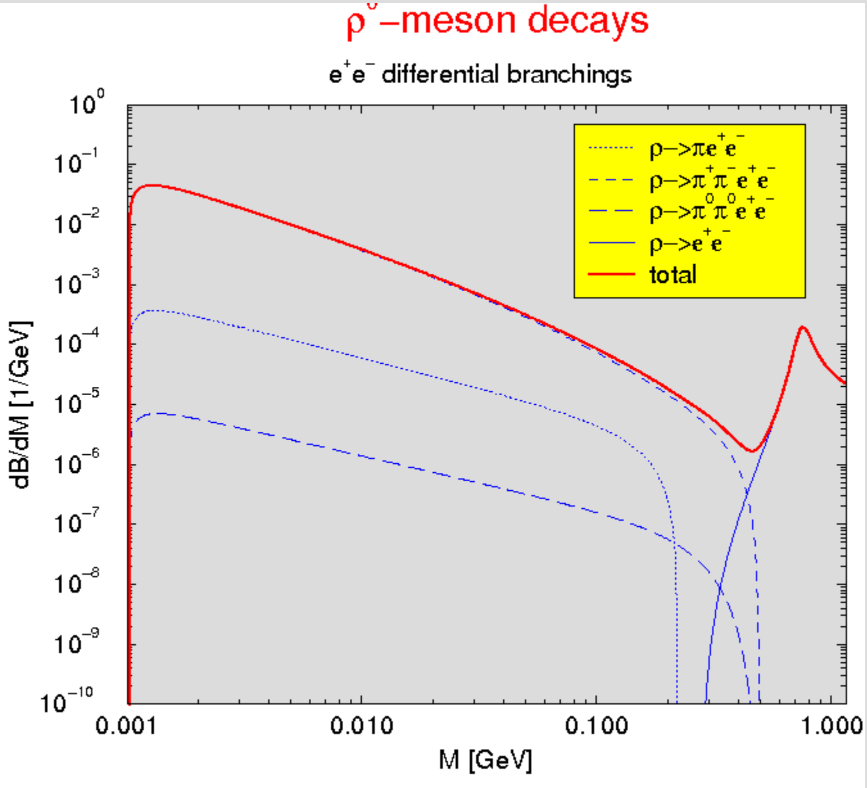
direct decays : $\mathcal{M} \to e^+e^-$ ex: $\rho,\omega \to e^+e^-$

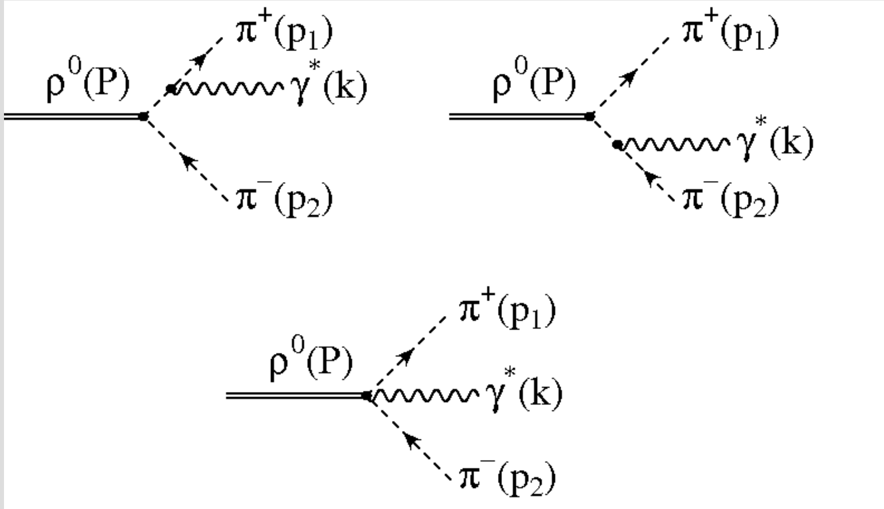
Dalitz decays : $\mathcal{M} \to \pi e^+e^-$ ex: $\pi^0 \to \gamma e^+e^-$, $\eta \to \gamma e^+e^-$

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

Example: ρ_0 decays

$$\frac{dB}{dM} = \frac{1}{\pi} \frac{2 M m_\rho \Gamma^{(\rho \to e^+ e^- X)}(M)}{(M^2 - m_\rho^2)^2 + m_\rho^2 \Gamma_\rho(M)^2}$$

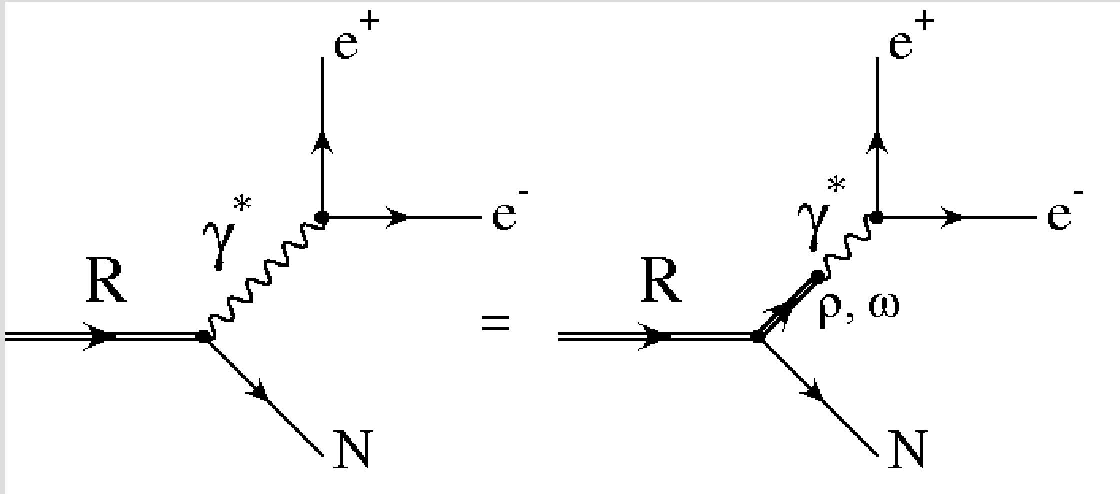




A. Faessler *et al.* PRC 61, 035206 (2000)

Resonance Decays

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



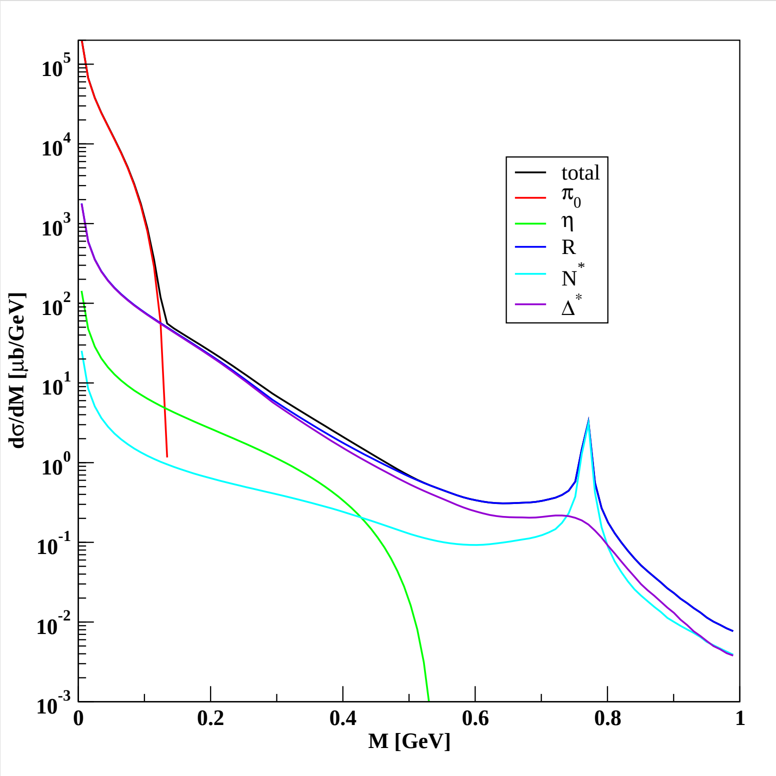
Vector Meson Dominance (VMD):

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

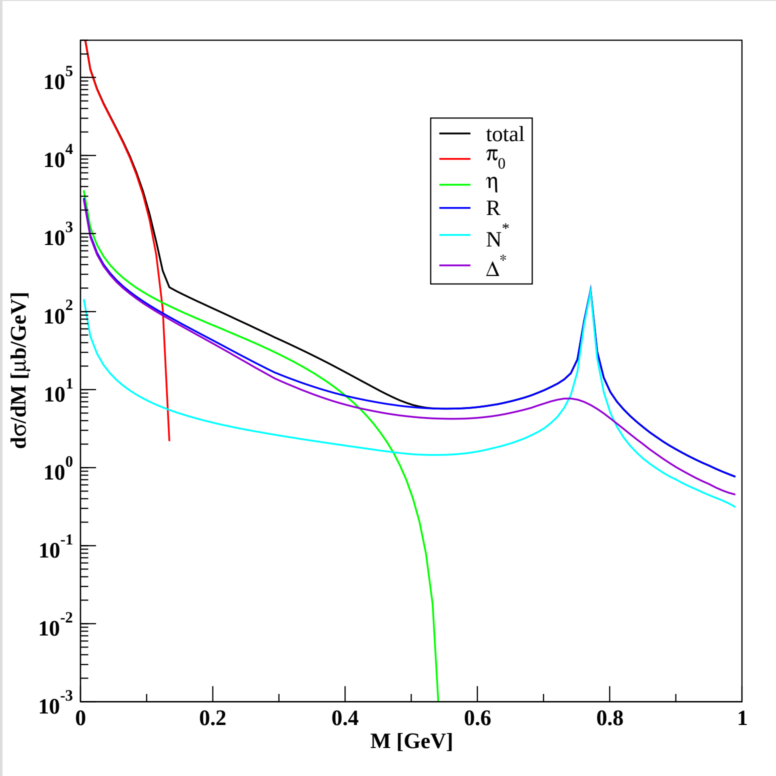
$$d\,\Gamma^{(R\to NX\gamma^*} = d\,\Gamma^{(R\to NV)}\,\frac{dB^{(V\to X\gamma^*)}}{d\,M}$$

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

Dilepton spectrum: example



CC @ 1.0AGeV



CC @ 2.0AGeV

Resonance list:

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

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

$R \to N\gamma$ transition amplitudes

Covariant description for nuclear resonances

$R = \Delta^*, N^*$ with arbitrary spin and parity

Helicity amplitudes:

$$\langle\, R \,|\, T \,|\, N\gamma \,\rangle = \sum_{k=1}^{3} F_k(M^2)\, \bar{u}_{\beta_1 \ldots \beta_l}\, q_{\beta_1} \cdots q_{\beta_{l-1}}\, \Gamma^k_{\beta_l \mu}\, u\, \varepsilon^\mu$$

$$F_k(M^2) = \sum_V \frac{f_{RNV,k}}{g_V} \frac{1}{1 - M^2/m_V^2}\,, \; V = \rho, \omega$$

Spin J=1/2: 2 independent form-factors (electric/mag.+Coulomb)

Spin J=3/2: 3 independent form-factors (electric+magnetic+Coulomb)

Decay modes: $\Delta^* \to N\rho \quad N^* \to N\rho, \omega$

Krivoruchenko Ann.Phys. 206, 299 (2002)

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

Naive VMD vs. eVMD

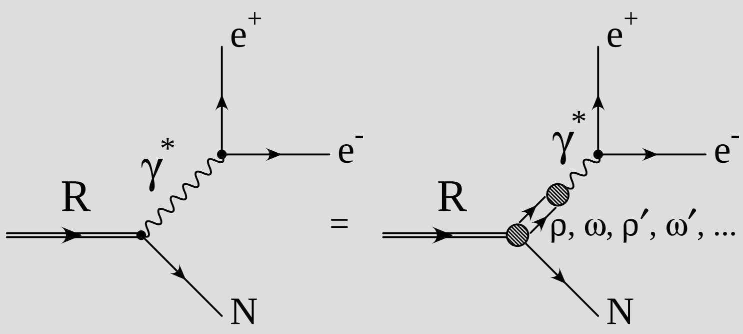
Problems naive VMD:

-form factors have wrong asymptotics

-contradiction meson $\leftrightarrow$ radiative decays

$$R \to N\gamma \leftrightarrow R \to N\rho$$

R	N_{1440}	N_{1520}	N_{1720}	Δ_{1232}	Δ_{1620}
J^P	$\frac{1}{2}^+$	$\frac{3}{2}^-$	$\frac{3}{2}^+$	$\frac{3}{2}^+$	$\frac{1}{2}^-$
$f_{RN\rho}$	< 26.0	7.0	7.8	15.3	2.5
$f^{\gamma}_{RN\rho}$	1.3	3.8	2.2	10.8	0.7



Possible solutions:

1) modify $f_{\rho\gamma}$ vertex ($M \to 0\ f_{\rho\gamma} \to 0$) and add direct $RN\gamma$ coupling (Friman,Pirner)

2) **eVMD** - include excited ρ-states (ρ', ρ'')

- correct asymptotics ($M \to \infty$)
- constraint from quark counting rules

Transport Model: QMD

Transport model: **Quantum Molecular Dynamics**

Monte Carlo cascade + Mean field + Pauli-blocking + in medium cross section

all 4* resonances below 2 GeV - 10 Δ^* and 11 N^*

- included baryon-baryon collisions:

  all elastic channels

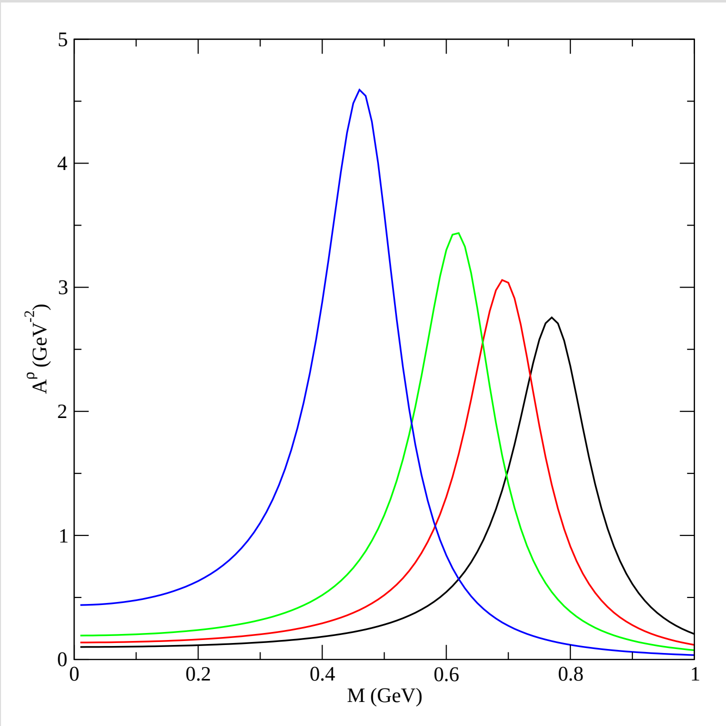
  inelastic channels $NN \to NN^\star$, $NN \to N\Delta^\star$, $NN \to \Delta N^\star$, $NN \to \Delta\Delta^\star$, $NR \to NR'$

- included pion-absorption $\rightleftharpoons$ resonance-decay channels:

  $\Delta \rightleftharpoons N\pi$, $\Delta^\star \rightleftharpoons \Delta\pi$, $\Delta^\star \rightleftharpoons N_{1440}\pi$, $N^\star \rightleftharpoons N\pi$, $N^\star \rightleftharpoons N\pi\pi$, $(N^\star \rightleftharpoons \Delta\pi$, $N^\star \rightleftharpoons N_{1440})$

- meson production/absorption: ρ,ω,η

Medium Effects



Approaches: 1) Traditional

- QCD sumrules: Hatsuda,Lee - PRC46, R34

$$\frac{m_V(\rho)}{m_V(\rho_0)} = 1 - \alpha \frac{\rho}{\rho_0}$$

- Scale invariance: Brown, Rho - PRL66, 2720

$$\frac{m_V^*}{m_V} = \frac{m_N^*}{m_N} = \frac{f_\pi^*}{f_\pi} \simeq 0.8$$

2) Many-Body approaches: Rapp, Friman, Post, Mosel, etc.

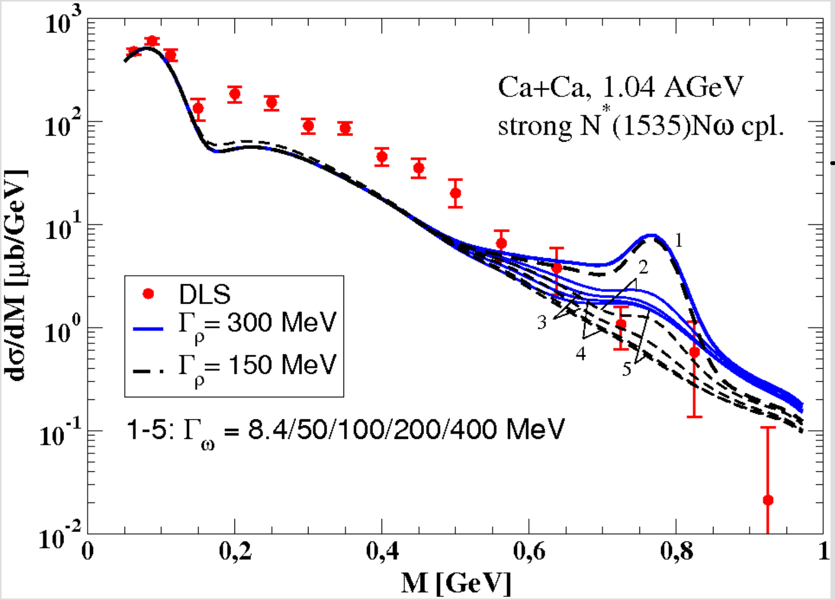
- effective models for meson-baryon interactions
- in-medium self-energies

Medium effects: Collisional Broadening

Collisional broadening: $\Gamma_V^{tot} = \Gamma_V + \Gamma_V^{coll}$

$dB(\mu, M)^{R\rightarrow NV} = \frac{d\Gamma^R_{NV}(\mu,M)}{\Gamma_R(\mu)}$ - increases with meson width

$B(\mu)^{R\rightarrow Ne^+e^-} \sim B(\mu)^{R\rightarrow NV} \frac{\Gamma_{V\rightarrow e^+e^-}}{\Gamma_V^{tot}}$ - decreases due to increased meson width



- different mass region than DLS Puzzle
- adjust collisional widths to data:

$\Gamma_\rho^{coll} \simeq 150$ MeV

$\Gamma_\omega^{coll} \simeq 100 \div 200$ MeV at $1.5\rho_0$

- similar conclusions from C+C at 1 AGeV and in agreement other

theoretical estimates (Klingl& Weise)

Comparison with HADES

Density dependent widths:

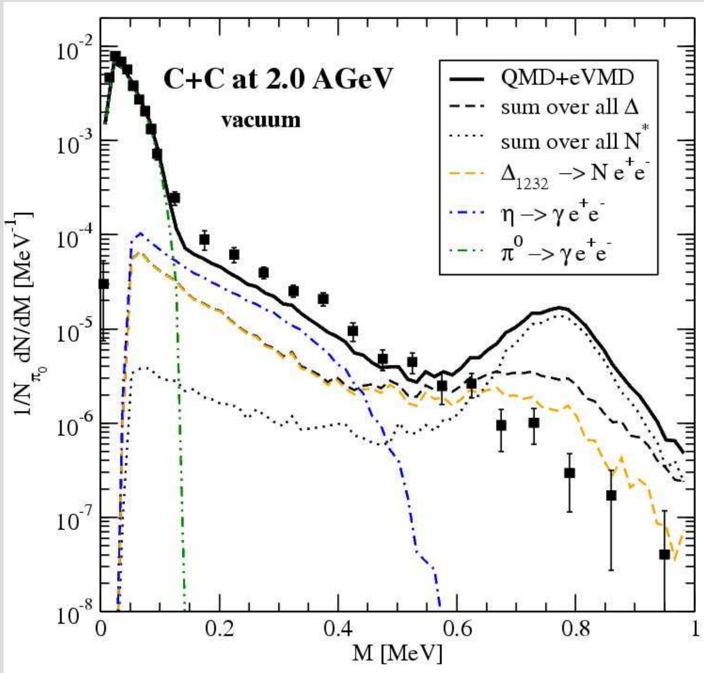
$$\Gamma_V^{tot} = \Gamma_V^{vac} + \rho/\rho_0\,\Gamma_V^{coll}$$

Γ_ρ^{coll} =100 MeV, Γ_ω^{coll} =115 MeV at ρ_0

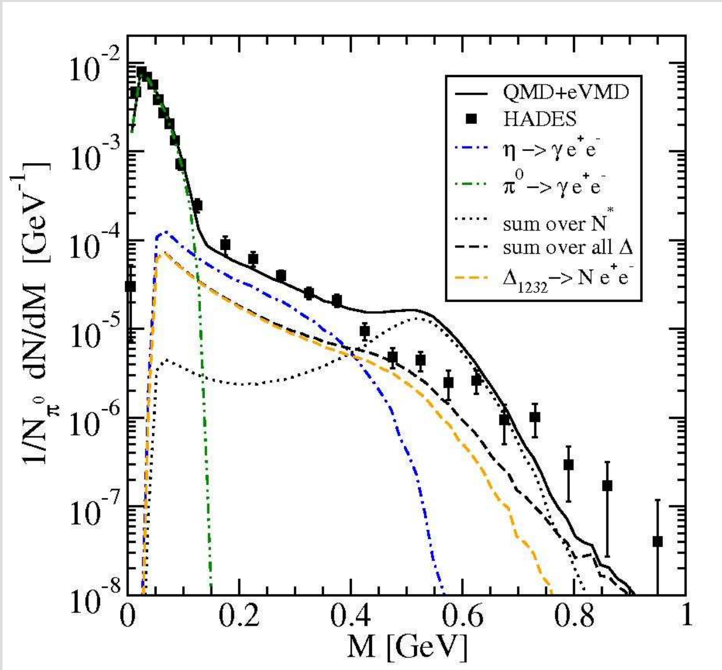
Brown-Rho scaling:

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

Vacuum:



Medium:



Many-body approach

Spin 1 particle in vacuum

$$D^0_{\mu\nu}(p) = \frac{-g_{\mu\nu} + \frac{p_\mu p_\nu}{p^2}}{p^2 - m^2 + i\varepsilon} + \frac{1}{m^2}\,\frac{p_\mu p\nu}{p^2}$$

use Lorentz covariance to write self-energy

$$\Sigma_{\mu\nu}(p,n) = g_{\mu\nu}\,\Sigma_1(p,n) + p_\mu\,p_\nu\,\Sigma_2(p,n) + n_\mu\,n_\nu\,\Sigma_3(p,n) + p_\mu\,n_\nu\,\Sigma_4(p,n)$$

use gauge invariance $p_\mu\,\Sigma^{\mu\nu} = 0$ to simplify

$$\text{in vacuum} \quad : \quad \Sigma_{\mu\nu} = P^T_{\mu\nu}(p)\,\Sigma_{vac}(p)$$

$$\text{in medium} \quad : \quad \Sigma_{\mu\nu} = T_{\mu\nu}\,\Sigma^T(p) + L_{\mu\nu}\,\Sigma^L(p)$$

Solve Dyson-Schwinger equation for spin-1 particle

$$D_{\mu\nu}(p) = -\frac{L_{\mu\nu}(p)}{p^2 - m_0^2 - \Sigma^L(p^2)} - \frac{T_{\mu\nu}(p)}{p^2 - m_0^2 - \Sigma^T(p^2)} + \frac{1}{m_0^2}\,\frac{p_\mu p\nu}{p^2}$$

In-medium spectral functions for vector mesons

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

In-medium self-energies from eVMD

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:

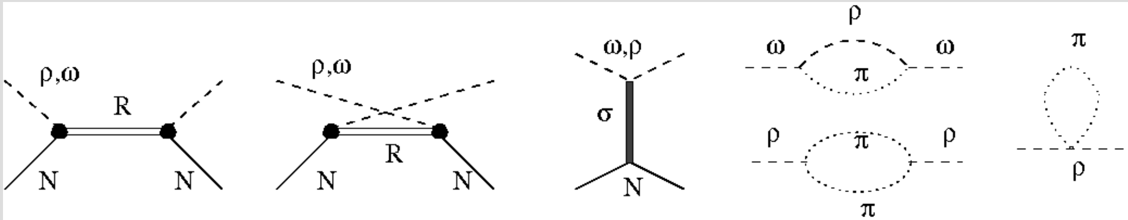
ρNN and ωNN: Bonn nucleon-nucleon potential model

3) Sigma meson exchanges:

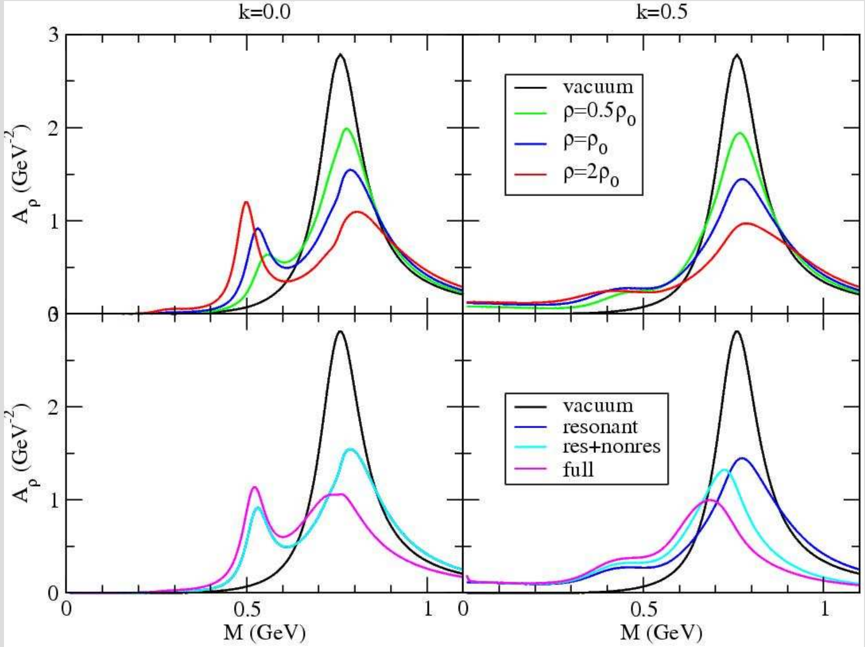
$g_{\rho\rho\sigma}$: from the decay $\rho^0 \rightarrow \rho^0\sigma \rightarrow \pi^+\pi^-\pi^+\pi^-$

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

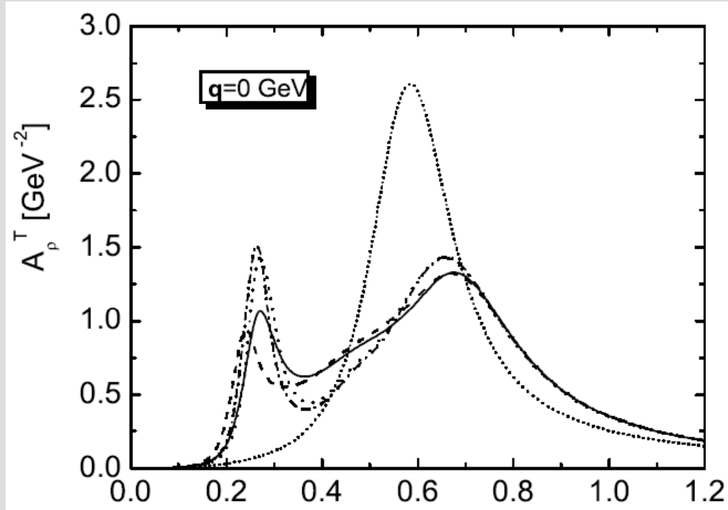
4) Vacuum self-energies parametrize results of $\rho\pi\pi$ interaction for ρ and of the effective Gell-Mann-Sharp-Wagener for the ω



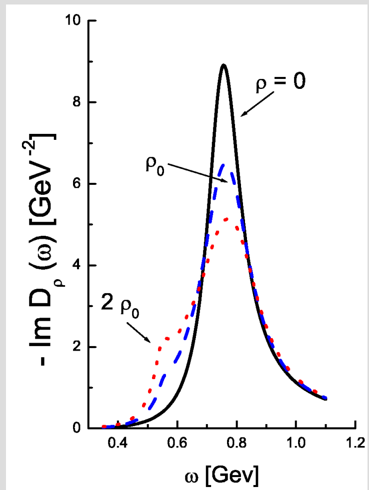
In-medium spectral functions: ρ meson



secondary peak: N*(1520), N*(1535), Δ(1620)

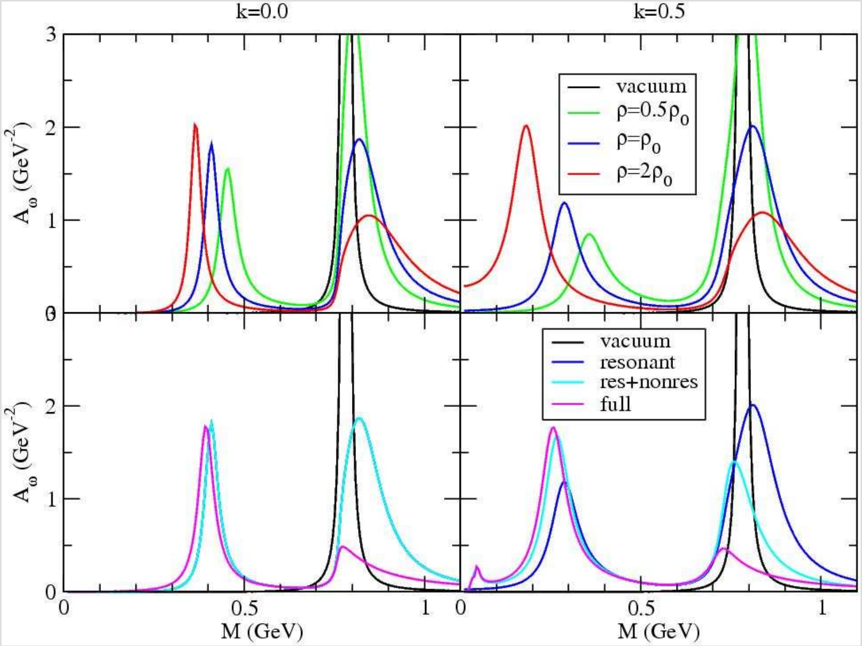


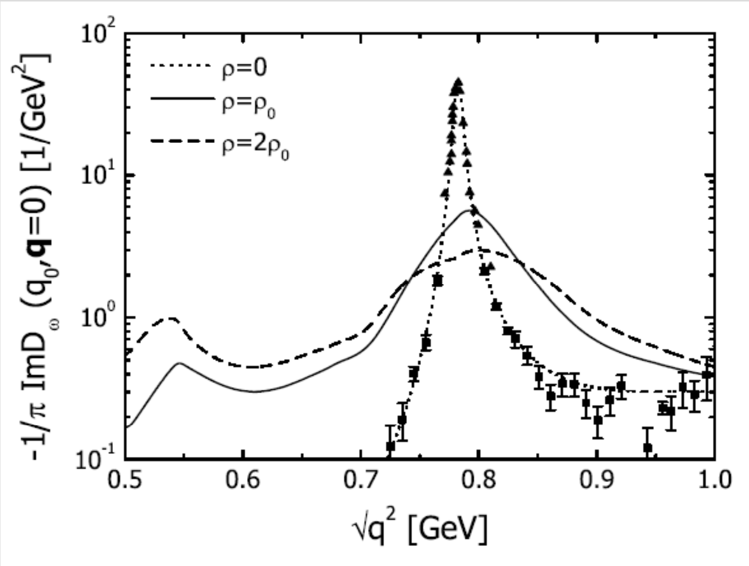
Post *et al.*, NPA 741, 81 (2004)



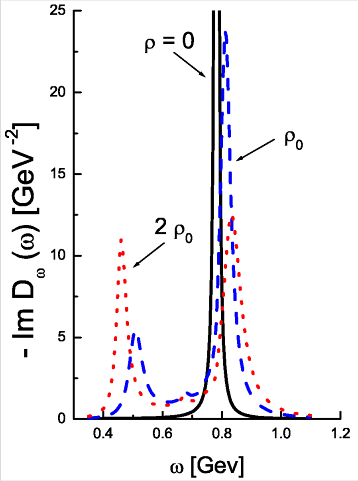
M. Lutz *et al.*, NPA 706, 431 (2002)

In-medium spectral functions: ω meson





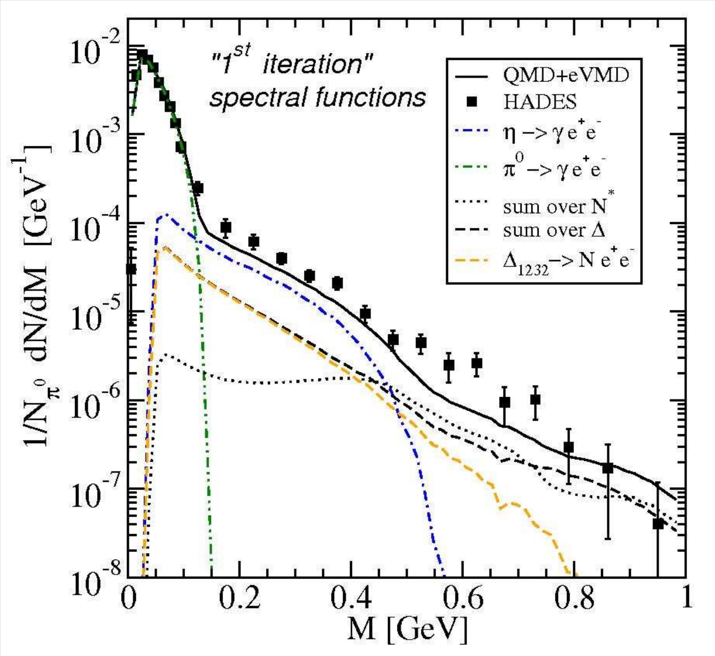
Muehlich *et al.*, NPA 780, 187 (2006)

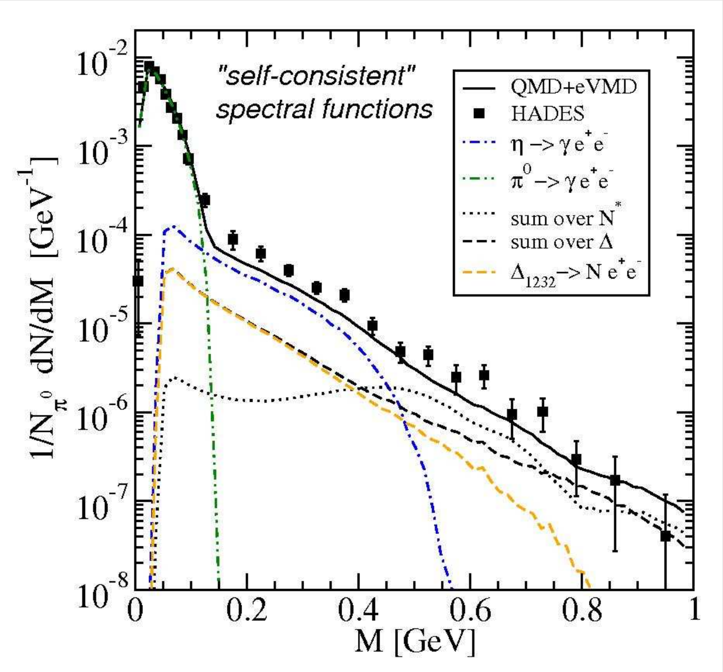


secondary peak: N*(1535), N*(1520)

M. Lutz *et al.*, NPA 706, 431 (2002)

Dilepton Spectra & HADES





-iteration of meson and resonance spfs important

-omitted contribution: nucleon-nucleon bremsstrahlung

-issues: poorly known $RN\omega$ couplings

-under investigation: C+C @ 1.0 AGeV and elementary reactions

Summary and Outlook

- Used eVMD to describe in-medium vector meson properties
- Qualitative/quantitative agreement between various many body approaches
- Brown-Rho mass scaling of vector meson masses seems to be excluded
- Preliminary comparison with HADES dilepton data: collisional effects might suffice do describe data
- No effect? of partial chiral symmetry restoration on vector mesons

Spectral function approach

propagator scalar particle:

$$\int d^4 \exp^{ipx} \langle\Omega|T\Phi(x)\Phi(0)|\Omega\rangle = \int_0^\infty \frac{dM^2}{2\pi} A(M^2) \frac{i}{p^2 - M^2 + i\varepsilon}$$
$$= \frac{iZ}{p^2 - m^2 + i\varepsilon} + \int_{4m^2}^\infty \frac{dM^2}{2\pi} A(M^2) \frac{i}{p^2 - M^2 + i\varepsilon}$$

Example: scalar particle with decay widths Γ

$$\frac{i}{p^2 - m^2 + im\Gamma} \quad \rightarrow \quad A(p^2) \quad = \quad \frac{1}{\pi} \frac{m\Gamma}{(p^2 - m^2)^2 + \Gamma^2}$$

In general: full propagator is obtained by solving a Dyson-Schwinger equation

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