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Hadrons in Medium

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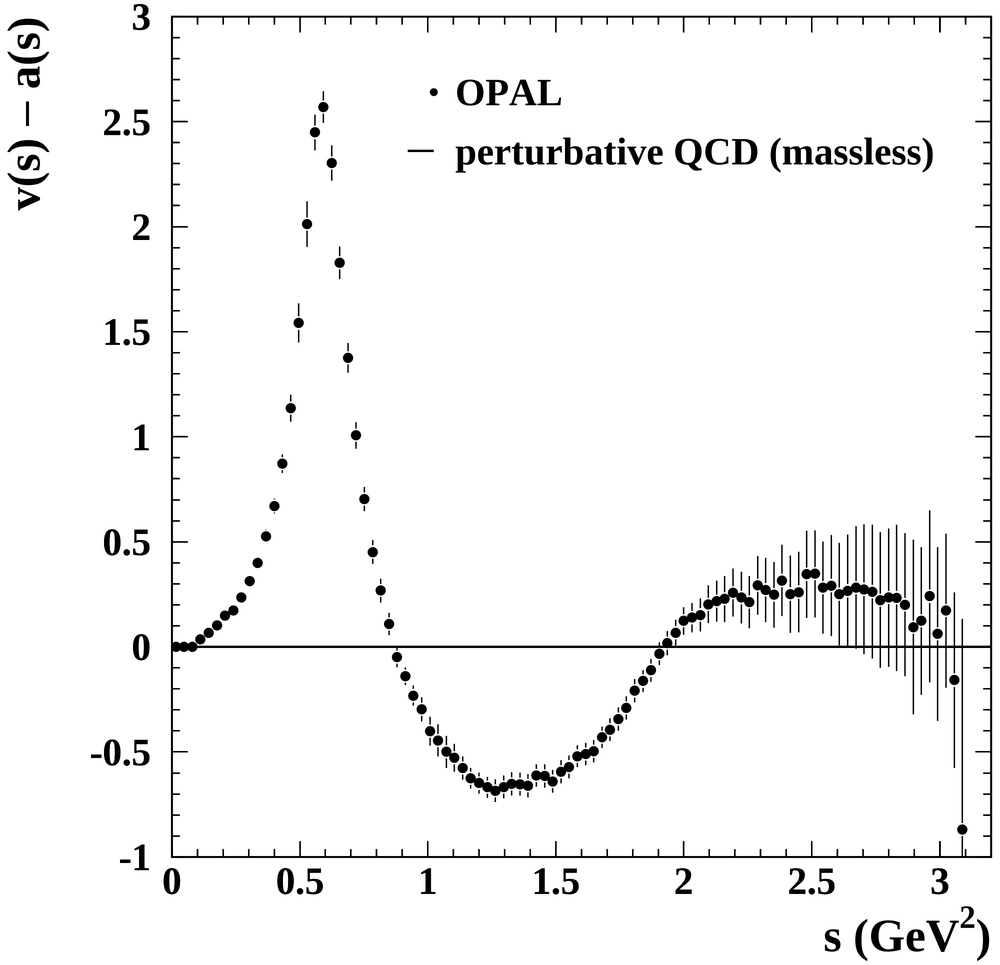
CBM workshop, ECT*, Trento, Italy, May 2006

One of the clearest signs of chiral symmetry breaking



v: $\tau \longrightarrow \nu_\tau + m\pi$

(m even)

a: $\tau \longrightarrow \nu_\tau + n\pi$

(n odd)

Eur. Phys. J. C7 (1999) 571

Motivation

- chiral restoration: spectra of vector and axial-vector currents become identical
- order parameters drop (f_π, $\langle \bar{q}q \rangle$, ...)
- What does that mean for single hadrons?
- more modest: test concepts of many-body theory

$\rightsquigarrow$ interest in in-medium changes of hadronic properties

$\rightsquigarrow$ e.g. search for dropping masses

- How to observe this?
- interesting probes: neutral vector mesons ρ^0, ω — of course not the only ones!

Contents

- Hadronic modeling
  - low-density theorem, “trivial” in-medium effects
  - required experimental input
  - how fancy is that already? (e.g. “resonance-hole”, “chiral mixing”)
- Dropping masses
  - connection to condensates
  - relation to hadronic effects? double counting?
- Further ideas related to condensates/chiral symmetry
  - QCD sum rules
  - hidden local symmetry (Bando/Harada/Kugo/Yamawaki) $\longrightarrow$ comment on ω
  - chiral quartets of baryons (Jido/Hatsuda/Kunihiro)
- Summary

Hadronic modeling

- central quantity: (in-medium) spectral function for hadron H

$$\mathcal{A}(q) = -\mathrm{Im} D(q) = -\mathrm{Im} \frac{1}{q^2 - m_H^2 - \Pi(q)}$$
$$= \frac{-\mathrm{Im}\Pi(q)}{[q^2 - m_H^2 - \mathrm{Re}\Pi(q)]^2 + [\mathrm{Im}\Pi(q)]^2}$$

- decomposition: $\Pi(q) = \Pi_{\mathrm{vac}}(q) + \Pi_{\mathrm{med}}(q)$
- linear-density ("ρT") approximation for (in-medium) self energy

$$\Pi_{\mathrm{med}}(q) = \sum_X \rho_X T_{XH}(q)$$

with medium constituents X (e.g. N, π)

- T_{XH}: (vacuum) forward scattering amplitude for $X + H$
- imaginary part of T from inelasticities $\rightsquigarrow$ data for backward reaction

Linear-density approximation (low-density theorem)

- underlying idea: probe (H) scatters on single medium constituents
- "trivial" in-medium effect
- only vacuum quantity (scattering amplitude) enters
- works if density is not too large
- break down depends on probe and medium
- what comes beyond?
- hadronic language: n-body scattering amplitudes with $n > 2$
- becomes uneconomical
- additional effects on top or only different language?
- connection to in-medium change of condensates?

Connection to change of condensates? Speculative!

- change of vacuum structure possibly triggered by excluded volume (percolation)
- medium constituents carry chirally restored phase in their interior
- outside: chirally broken phase
- increasing density $\rightsquigarrow$ percolation
- purely geometrical effect
- covered by linear-density approximation
- other effects on top?
- if hadronic many-body states form complete set of states

$\rightsquigarrow$ all in-medium effects related to hadronic many-body scattering amplitudes

- maybe more economical: connection of in-medium properties to condensates
- so far no direct relations from first principles $\rightsquigarrow$ model dependence

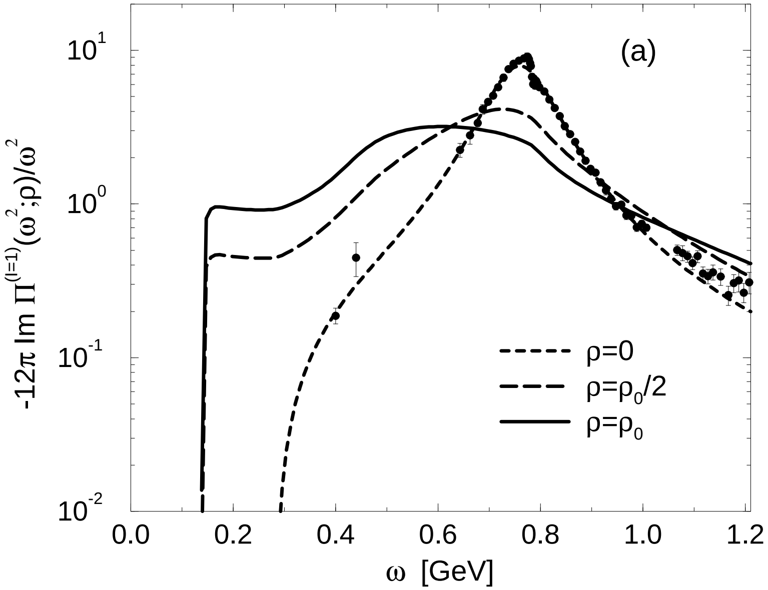
Forward scattering amplitude

$$\Pi(q) = \sum_X \rho_X T_{XH}(q)$$

- everything well under control for low densities?
- in principle yes: need “only” vacuum scattering amplitudes T_{XH}
- in practice no: H can be unstable

$\rightsquigarrow$ no H beam, no direct access on scattering amplitude

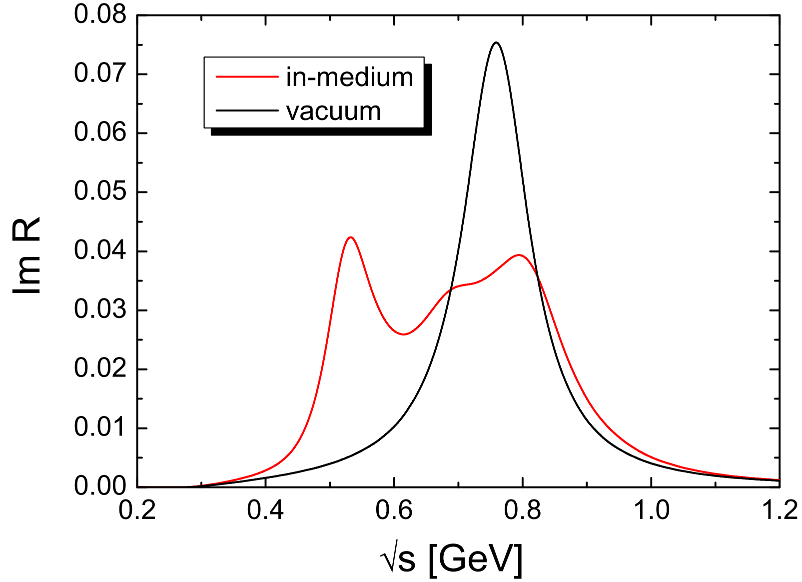
- sizable model dependences
- e.g. for ρ meson in cold nuclear matter $\rightsquigarrow$ figs.



Klingl/Kaiser/Weise,

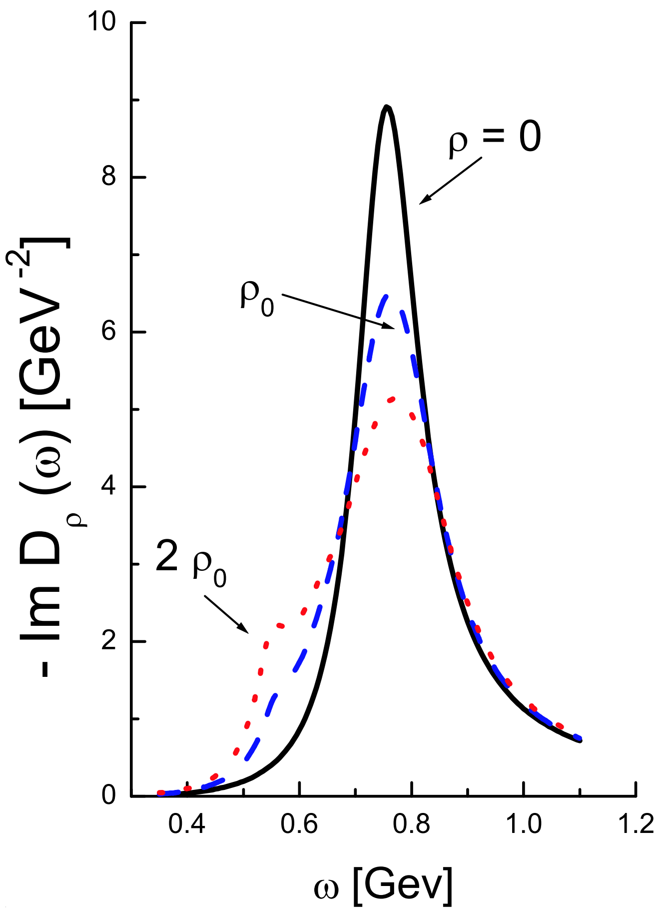
NPA 624 (1997) 527

(note: log plot!)



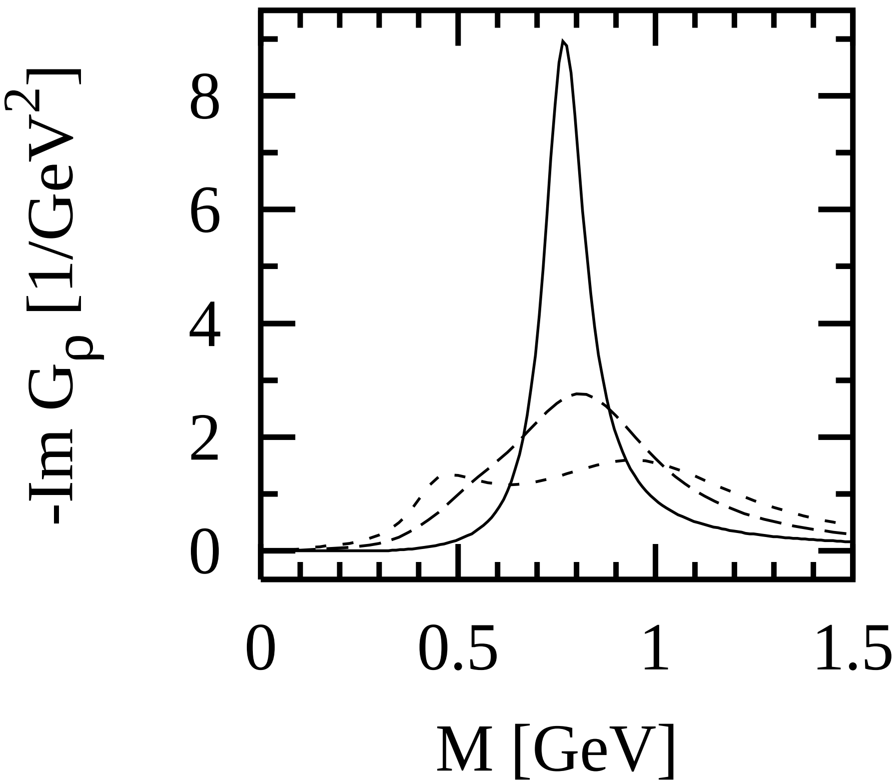
Post/Leupold/Mosel,

NPA 741 (2004) 81



Lutz/Wolf/Friman,

NPA 706 (2002) 431



vacuum: solid, ρ_0: long dashed,

$2\rho_0$: short dashed

Urban/Buballa/Rapp/Wambach,

NPA 641 (1998) 433

How fancy is linear-density approximation?

- simple toy model for dilepton production $\sim n_B(q)\mathcal{A}_\rho(q)/q^2$
  - mediated by ρ meson (VMD)
  - ρ meson couples to 2π and resonance-hole (RN^{-1})

$\rightsquigarrow$ $\mathcal{A}_\rho(q) =$

$$\frac{-\mathrm{Im}\Pi_{2\pi}(q) - \mathrm{Im}\Pi_{RN^{-1}}(q)}{[q^2 - m_\rho^2 - \mathrm{Re}\Pi_{2\pi}(q) - \mathrm{Re}\Pi_{RN^{-1}}(q)]^2 + [\mathrm{Im}\Pi_{2\pi}(q) + \mathrm{Im}\Pi_{RN^{-1}}(q)]^2}$$

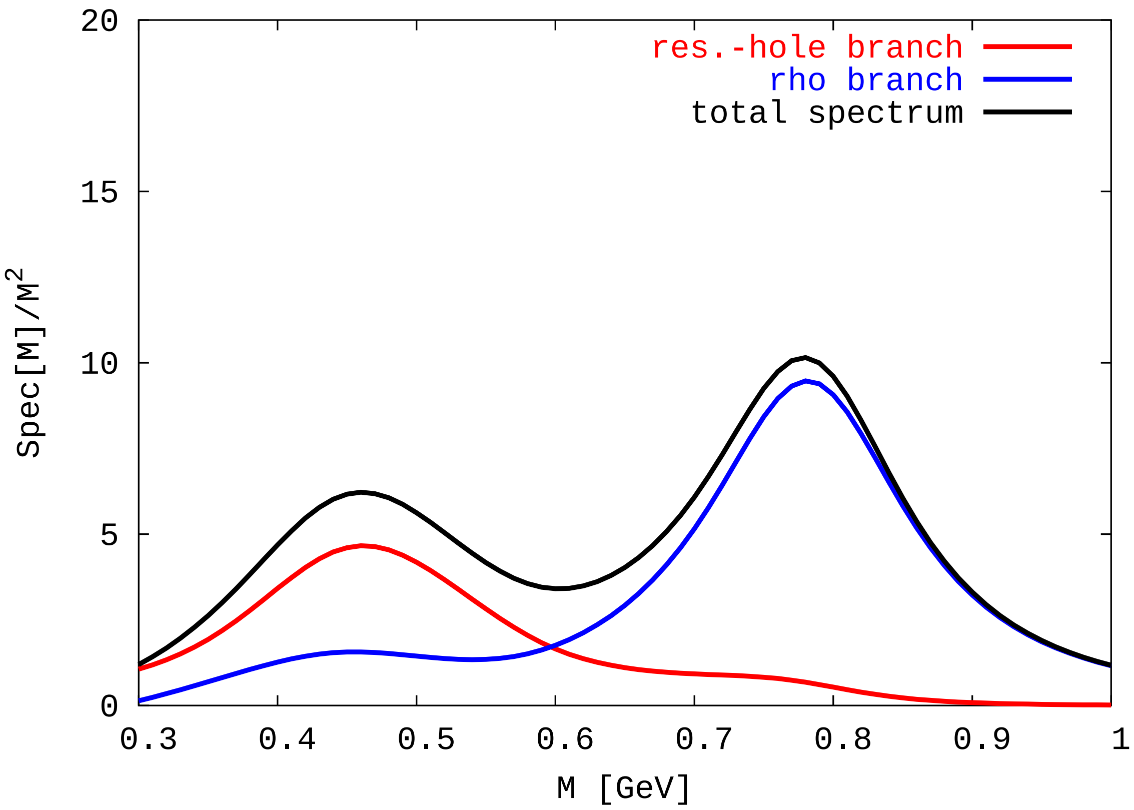
(note: $\Pi_{RN^{-1}} = \rho_N T_{\rho N \to R \to \rho N}$)

- appearance of density in denominator causes non-elementary effect:

$\rightsquigarrow$ corresponding elementary reactions:

$$\frac{-\mathrm{Im}\Pi_{2\pi}(q) - \mathrm{Im}\Pi_{RN^{-1}}(q)}{[q^2 - m_\rho^2 - \mathrm{Re}\Pi_{\mathrm{vac}}(q)]^2 + [\mathrm{Im}\Pi_{\mathrm{vac}}(q)]^2}$$

in-medium ρ meson spectral information



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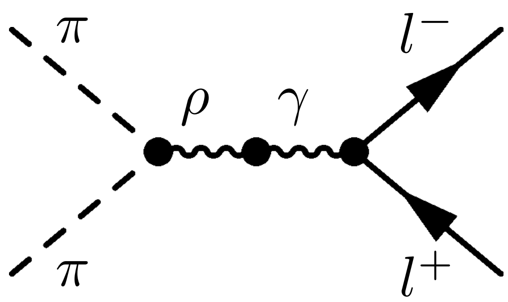
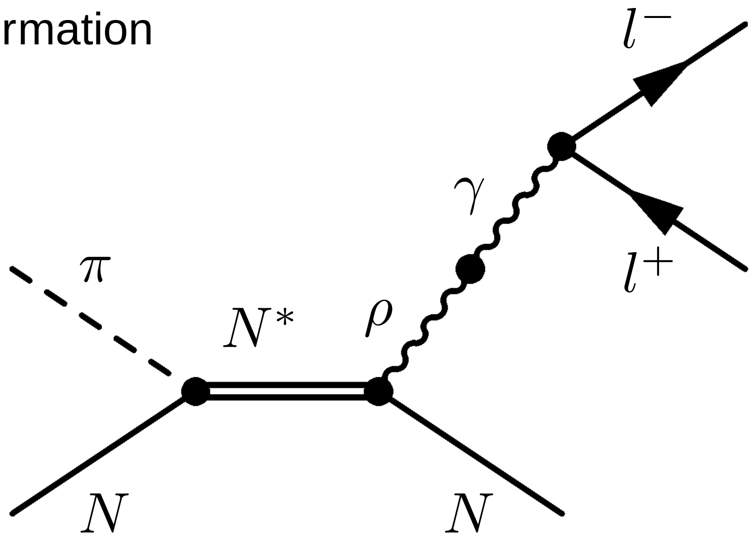
$$= \frac{\mathrm{Im}\Pi_{2\pi}(q)}{\mathrm{Im}\Pi_{\mathrm{vac}}(q)}\,\mathcal{A}_\rho^{\mathrm{vac}} + \frac{\mathrm{Im}\Pi_{RN^{-1}}(q)}{\mathrm{Im}\Pi_{\mathrm{vac}}(q)}\,\mathcal{A}_\rho^{\mathrm{vac}}$$

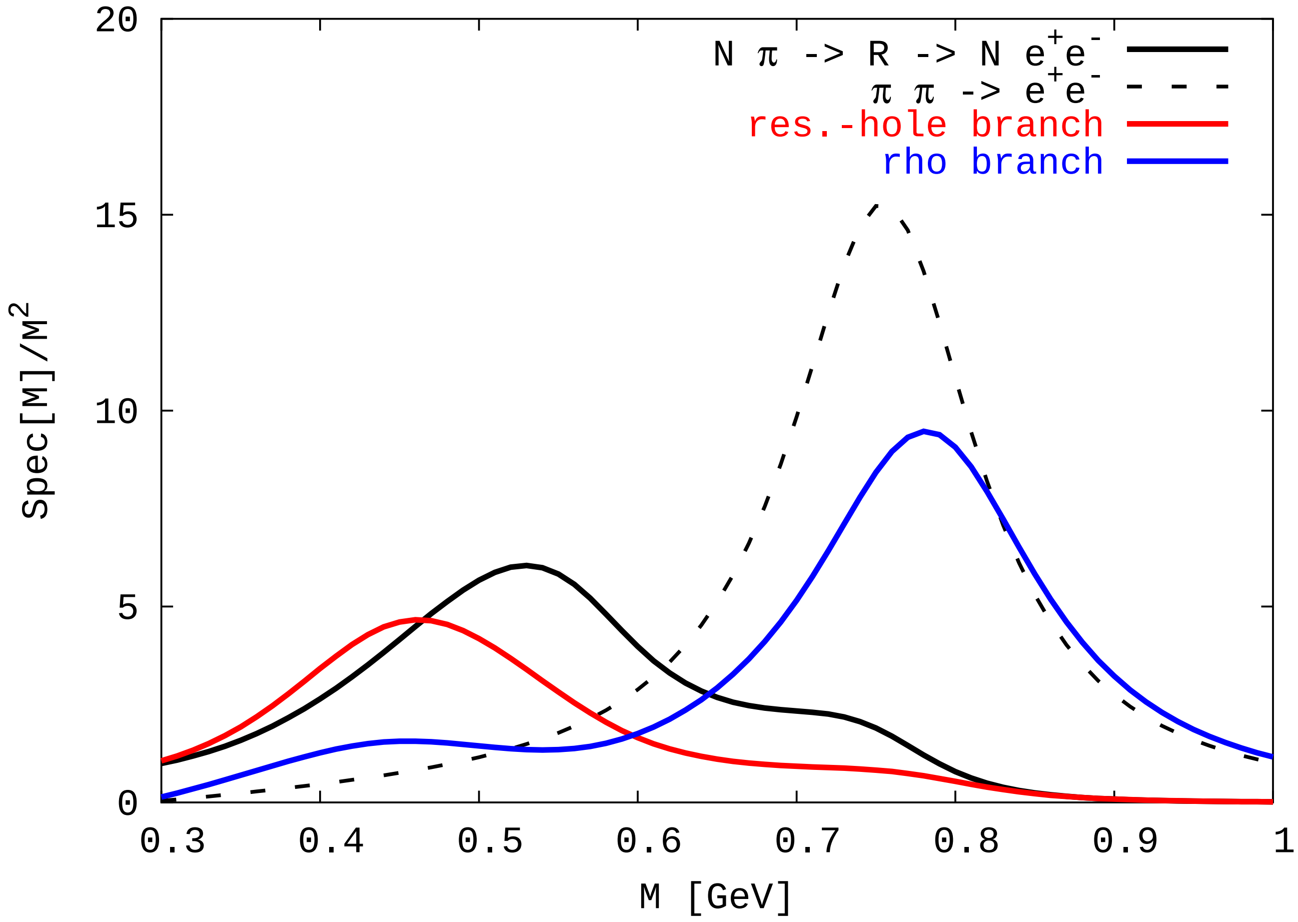
i.e. branching ratios times spectral information





$\hookrightarrow$ data required!

Elementary reactions versus full in-medium spectrum (at $\vec{q} = 0$!)



Conclusions from simple toy model

- structures already present in elementary reactions
- "denominator effect": level repulsion and overall depletion
- elementary reactions should be measured

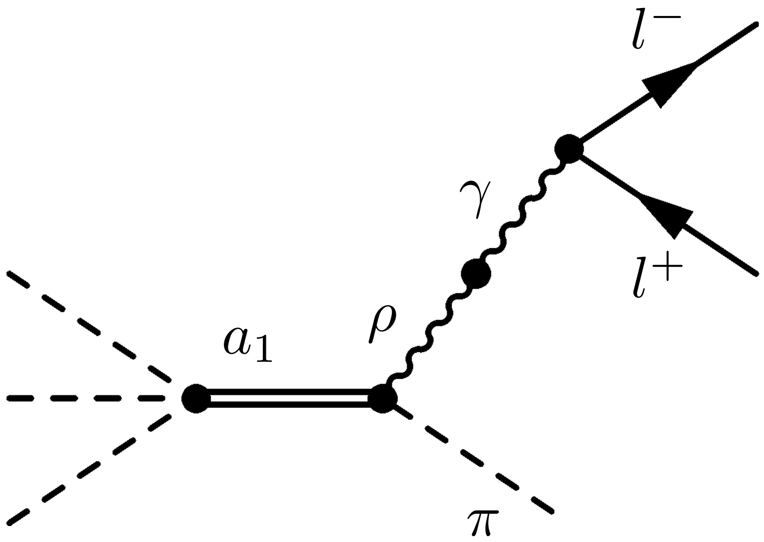
$\rightsquigarrow$ πN to dileptons, not only NN

(in latter resonance structure more smeared out, phase space)

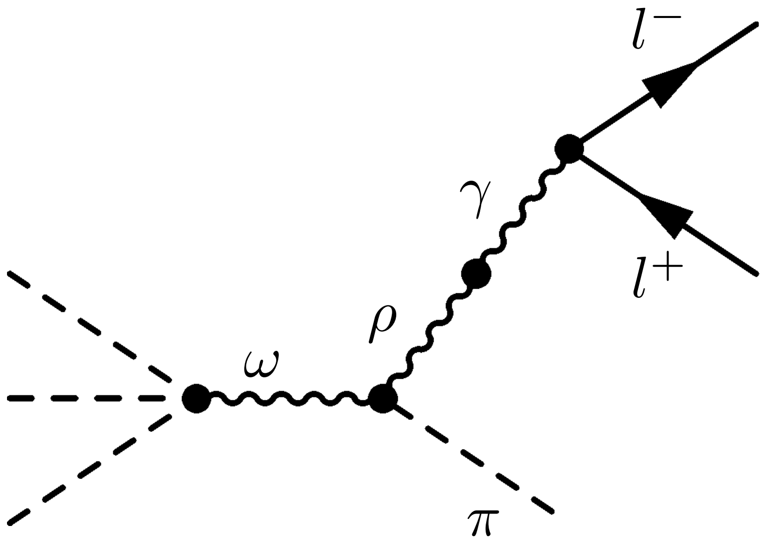
- note: "elementary" reactions are genuine in-medium (π in initial state)

How fancy is linear-density approximation? Part II

- chiral mixing (s-wave)



- similar non-chiral effect (p-wave)



- the important aspect (cf. also kaon potentials):
  strength of chiral mixing is dictated by chiral symmetry breaking
- note: easy for thermal hadronic model (calculate collisional loss of ρ),
  complicated for transport (dilepton production from three-body initial state)

Dropping Masses

- includes effects beyond linear-density approximation
- propose model which links elementary hadronic parameters (bare masses, coupling constants) e.g. with quark condensate (Brown/Rho)

$$\frac{m_{H,\text{med.}}}{m_{H,\text{vac.}}} = \left(\frac{\langle \bar{q} q \rangle_{\text{med.}}}{\langle \bar{q} q \rangle_{\text{vac.}}} \right)^{\alpha}$$

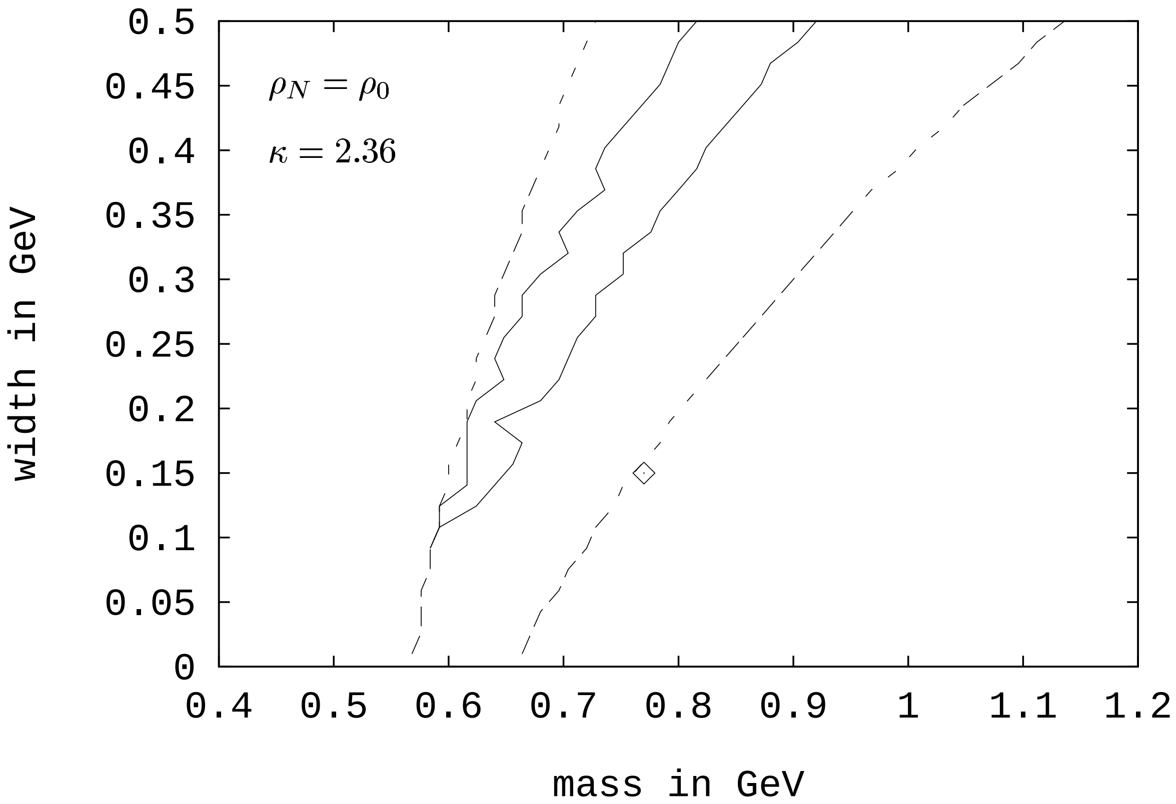
- α might be density/temperature dependent
- oversimplified? at low densities in conflict with low-density theorem

$\leadsto$ should be fused with standard many-body effects

- different, economic language for hadronic higher-order many-body effects?
- alternative: resummation techniques, self consistency
- or additional effects on top of hadronic effects?

Further ideas I: QCD sum rules

- no prediction for mass shift
- but constraints for hadronic models
- relation to four-, not two-quark condensates



Leupold/Peters/Mosel

NPA 628 (1998) 311

Further ideas II: Hidden local symmetry

- vector mesons treated as gauge bosons of local chiral symmetry

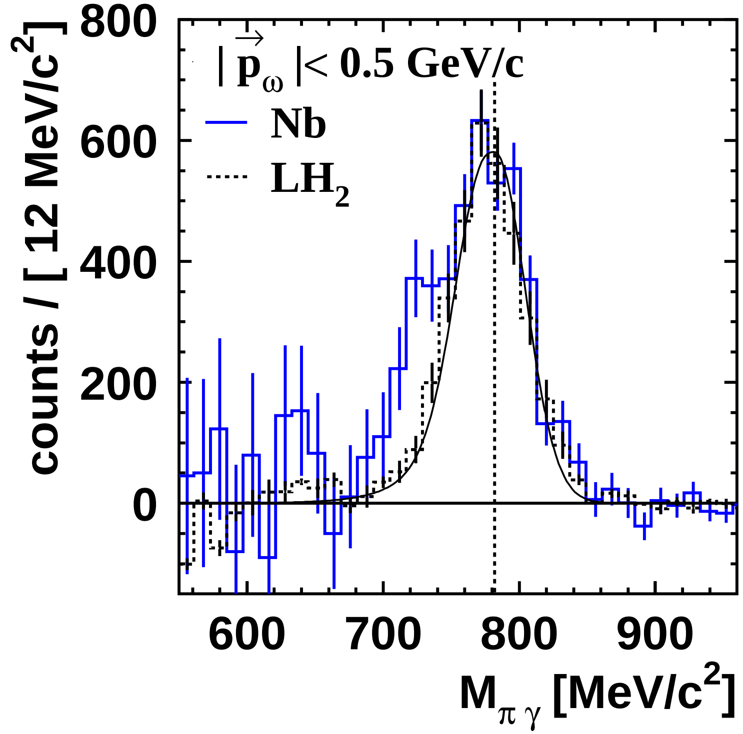
$\rightsquigarrow$ vector meson masses generated by chiral symmetry breaking (Higgs mechanism)

$\rightsquigarrow$ vector mesons become massless at chiral restoration

$\rightsquigarrow$ dropping masses

- but only for vector mesons, not for all hadrons (maybe for nucleon as chiral soliton???)
- ω meson is not necessary as gauge boson, but in SU(3) member of vector meson nonet
- note: also here relation to four-, not two-quark condensates

Experimental signifi cance for dropping ω mass



Trnka et al (CBELSA/TAPS), PRL 94 (2005) 192303

Further ideas III: Chiral quartets of baryons

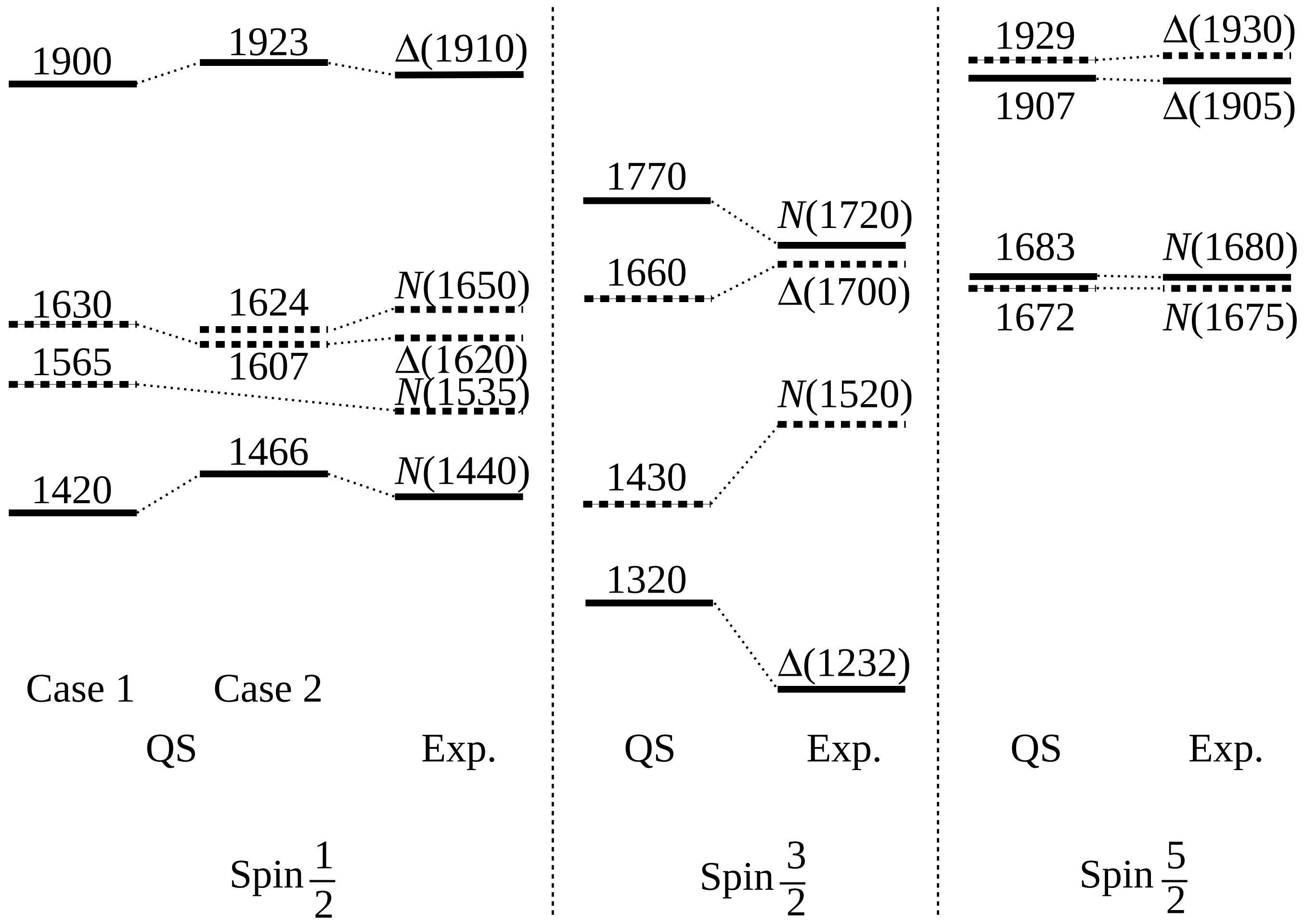
- for linear realization of chiral symmetry:

$\rightsquigarrow$ sort baryons in chiral multiplets,
e.g. $\Delta(1232)$, $N(1520)$, $\Delta(1700)$, $N(1720)$

$\rightsquigarrow$ mass splitting by symmetry breaking

- Jido/Hatsuda/Kunihiro, PRL 84 (2000) 3252
- degeneracy at chiral restoration
- observable?

chiral quartets



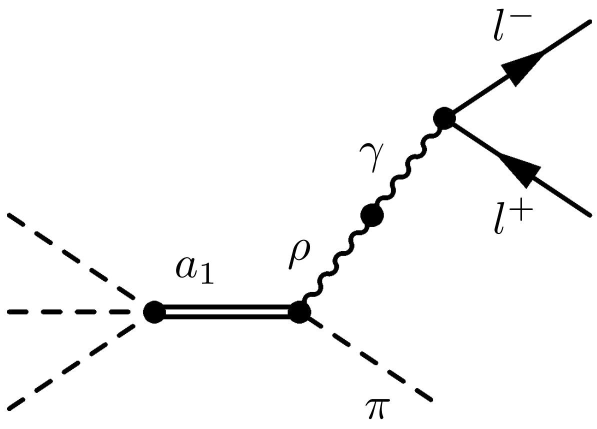
Jido/Hatsuda/Kunihiro, PRL 84 (2000) 3252

Summary and Outlook

- hadronic modeling, standard many-body effects, low-density theorem
- dropping mass models, relation to condensates

  (two-quark, four-quark, gluon condensates?)
- connections between them unclear
- maybe standard effects are enough (percolation)
- sizable model dependences in hadronic models
- qualitatively most effects already there in standard (in-medium) reactions
- n-body reactions ($n > 2$) might be important for dilepton production
- data on elementary processes necessary (πN to dileptons)
- stronger connections between hadronic models and QCD required!

How important can three-body reactions be?



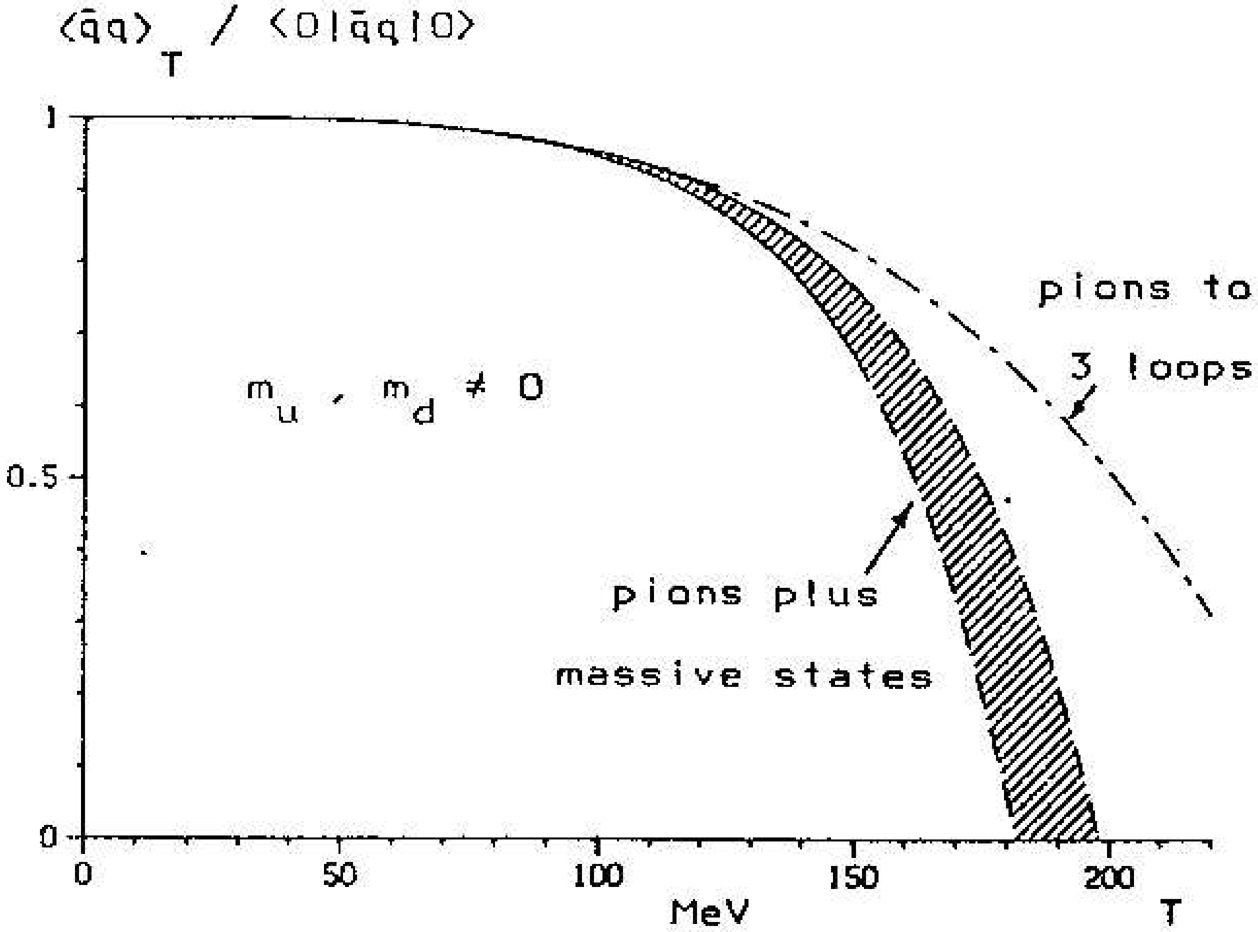
- clear statement possible for thermal system:

⇝ dilepton yield $\sim n_B(q)\mathcal{A} \approx e^{-q_0/T}\mathcal{A}$

$$\rightarrow e^{-q_0/T}\,\mathrm{Im}\Pi_{\rho\pi\rightarrow a_1} \sim e^{-q_0/T}\,e^{-E_\pi/T} = e^{-E_{\pi 1}/T}\,e^{-E_{\pi 2}/T}\,e^{-E_{\pi 3}/T}$$

- If you regard $\pi\rho \rightarrow a_1(\rightarrow 3\pi)$ as important for spectral function and therefore for dileptons (e.g. above $q^2 > 1$ GeV^2)

⇝ include $3\pi \rightarrow a_1 \rightarrow \pi\rho$ in transport



drop of quark condensate with temperature (Gerber/Leutwyler, NPB 321 (1989) 387)