Trivial and non-trivial in-medium effects

Stefan Leupold

GSI Darmstadt, Germany

CBM Forum, GSI, 27.2.2007

Motivation

- Suppose we have thermal model or transport code or …
  which describes data, e.g. dileptons
- Have we learned everything?

Motivation

- Suppose we have thermal model or transport code or . . . which describes data, e.g. dileptons
- models contain simple and more fancy things
- Have we learned everything?

Motivation

- Suppose we have thermal model or transport code or . . . which describes data, e.g. dileptons
- models contain simple and more fancy things
- Have we learned everything?
- only if we disentangle which aspects of model are really important for description of data

Motivation

- Suppose we have thermal model or transport code or . . . which describes data, e.g. dileptons
- models contain simple and more fancy things
- Have we learned everything?
- only if we disentangle which aspects of model are really important for description of data
- answer depends on experimental resolution
- might differ for same system but different probes (unified description desired)

Distinguish simple from fancy aspects:

suppose effects seen in A+A . . .

Distinguish simple from fancy aspects:

suppose effects seen in A+A . . .

- are just $N + N$ (or N+A) rescaled
  - ⇝ no medium effect
  - ⇝ "simple" to judge (maybe problem: neutron)

Distinguish simple from fancy aspects:

suppose effects seen in A+A . . .

- are just $N + N$ (or N+A) rescaled
  - ⇝ no medium effect
  - ⇝ “simple” to judge (maybe problem: neutron)
- are sequence of elementary two-body scatterings
  - ⇝ simple medium effect (scattering of secondaries, e.g. pions)

Distinguish simple from fancy aspects:

suppose effects seen in A+A ...

- are just $N + N$ (or N+A) rescaled
  - ⇝ no medium effect
  - ⇝ “simple” to judge (maybe problem: neutron)
- are sequence of elementary two-body scatterings
  - ⇝ simple medium effect (scattering of secondaries, e.g. pions)
- involve elementary N-body scatterings, $N > 2$
  - ⇝ not simple, but also not fancy

Distinguish simple from fancy aspects:

suppose effects seen in A+A . . .

- are just $N + N$ (or N+A) rescaled
  - ⇝ no medium effect
  - ⇝ “simple” to judge (maybe problem: neutron)
- are sequence of elementary two-body scatterings
  - ⇝ simple medium effect (scattering of secondaries, e.g. pions)
- involve elementary N-body scatterings, $N > 2$
  - ⇝ not simple, but also not fancy
- show collective behavior
  - potentials (mass shifts)
  - modified cross sections (screening)
  - collective excitations, level repulsion

⇝ non-trivial in-medium effects

Problems for clear distinction

try to distinguish

Two-body	N-body	collective

- not all elementary cross sections known
- comparing one model with another one
  $\hookrightarrow$ use same elementary input (cross sections)
- better gradually down-grade one model
  (sometimes not so easy to get intermediate steps...)

Problems for clear distinction

try to distinguish

Two-body N-body collective

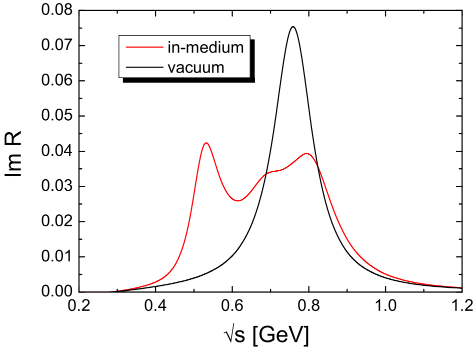
- not all elementary cross sections known
- comparing one model with another one
  $\hookrightarrow$ use same elementary input (cross sections)
- better gradually down-grade one model
  (sometimes not so easy to get intermediate steps...)

in the following: concentrate on one effect:
$\hookrightarrow$ resonance-hole excitation $\rightarrow$ fig.

- elementary two- and three-body reactions it is based on
- difference to collective behavior
- problems in distinction
- implementation in transport, thermal model, ...

Resonance-hole excitation

- dilepton rate (equilibrium) $\sim \mathrm{Im} R(q)\, n_B(q_0)$
- spectral information contained in dileptons: $\mathrm{Im} R = \mathcal{A}/q^2$



$(\vec{q} = 0, s = q^2)$

M. Post, PhD thesis, Giessen 2004

- to be multiplied by production probability (Bose factor n_B or ...)

Problems for clear distinction

try to distinguish

Two-body N-body collective

- not all elementary cross sections known
- comparing one model with another one
  $\hookrightarrow$ use same elementary input (cross sections)
- better gradually down-grade one model
  (sometimes not so easy to get intermediate steps...)

in the following: concentrate on one effect:
$\hookrightarrow$ resonance-hole excitation $\rightarrow$ fig.

- elementary two- and three-body reactions it is based on
- difference to collective behavior
- problems in distinction
- implementation in transport, thermal model, ...

Table of Contents

Two-body scattering events

- suppose effects seen in A+A are just sequence of elementary two-body scatterings

$\rightsquigarrow$ simple medium effect

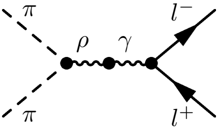
- but includes already:
  - $N + N \to N + N + \ell^+ \ell^-$
  - $\pi + \pi \to \ell^+ \ell^-$
  - $\pi + N \to N + \ell^+ \ell^-$

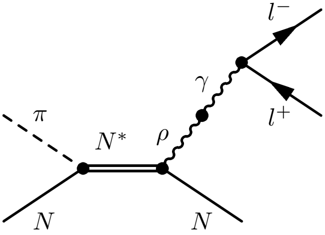
Two-body scattering events

- suppose effects seen in A+A are just sequence of elementary two-body scatterings

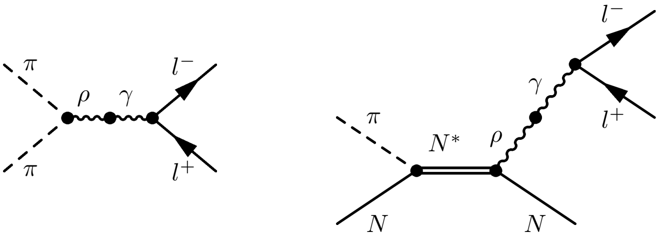
⇝ simple medium effect

- but includes already:
  - $N + N \to N + N + \ell^+\ell^-$
  - $\pi + \pi \to \rho \to \ell^+\ell^-$
  - $\pi + N \to N^* \to N + \ell^+\ell^-$ (Dalitz decay of resonance)





Two-body scattering events – everything settled?

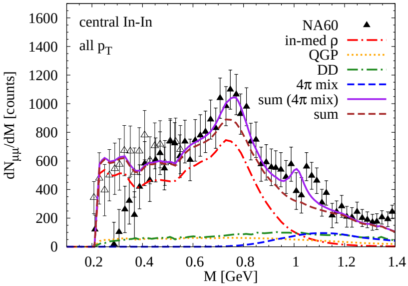


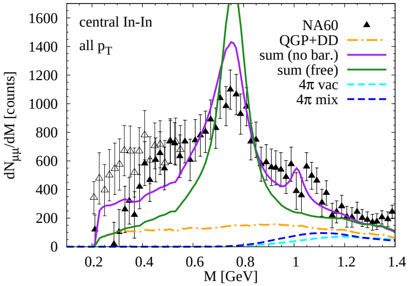
- $N + N \to N + N + \ell^+\ell^-$ measurable
- $\pi + \pi \to \ell^+\ell^-$ from inverse reaction
- $\pi + N \to N + \ell^+\ell^-$?

⇝ can sizably contribute at low invariant masses → fig.

Importance of baryons

full calculation ↔ without baryons

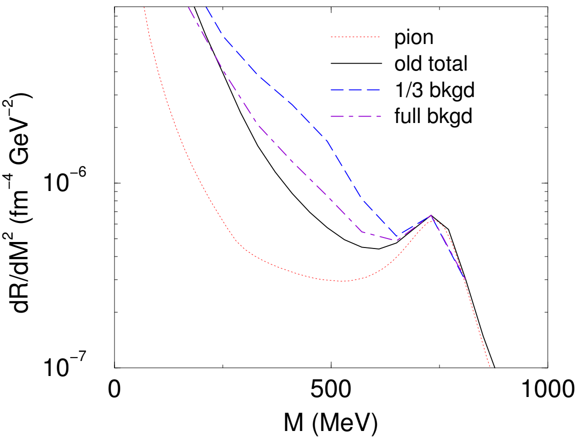




van Hees/Rapp, Phys.Rev.Lett.97:102301,2006

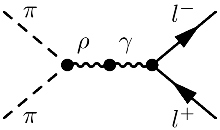
- How fancy is that?
- Just elementary $\pi + N \to N + \ell^+\ell^-$ with thermal weight?

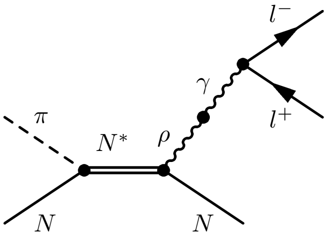
Importance of elementary πN contribution



- Steele, Zahed, Phys.Rev.D60:037502,1999
- note: ρ-meson peak unchanged

Two-body scattering events – everything settled?





- $\pi + N \to N + \ell^+\ell^-$?

⇝ problem: not all cross sections known

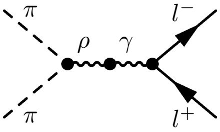
⇝ can learn about $\pi + N \to N + \ell^+\ell^-$ cross sections!

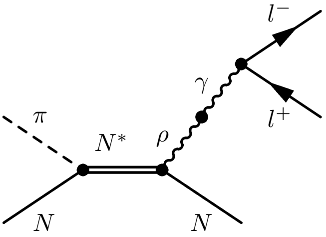
- complementary to pion beam (slow = thermal pions)
- “bread and butter” for transport (⇝ “traditional transport”)

Collective effects – toy model

(at least) in equilibrium possible:

- take elementary processes

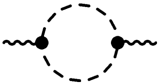


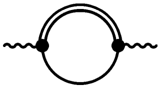


- include them in ρ-meson self energy $\Pi(q)$

⇝ linear-density approximation

↪ density of N's accompanying ρ-meson! (detailed balance)





- compare result to elementary two-body reactions

ρ-meson spectral function

- self energy $\Pi(q) = \Pi_{2\pi}(q) + \Pi_{N^*N^{-1}}(q)$
- spectral function

$$\mathcal{A}(q) = -\mathrm{Im}\frac{1}{q^2 - m_\rho^2 - \Pi(q)}$$

$$= \frac{-\mathrm{Im}\Pi(q)}{[q^2 - m_\rho^2 - \mathrm{Re}\Pi(q)]^2 + [\mathrm{Im}\Pi(q)]^2}$$

$$= -\frac{\mathrm{Im}\Pi_{2\pi}(q)}{[\ldots]^2 + [\ldots]^2} - \frac{\mathrm{Im}\Pi_{N^*N^{-1}}(q)}{[\ldots]^2 + [\ldots]^2}$$

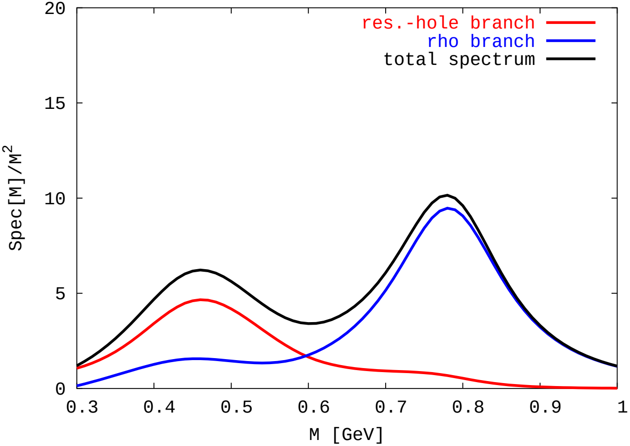
- how to get back elementary two-body reactions? (=traditional transport)

$\rightsquigarrow$ replace in denominator $\Pi \to \Pi_{\mathrm{vac}} \approx \Pi_{2\pi}$

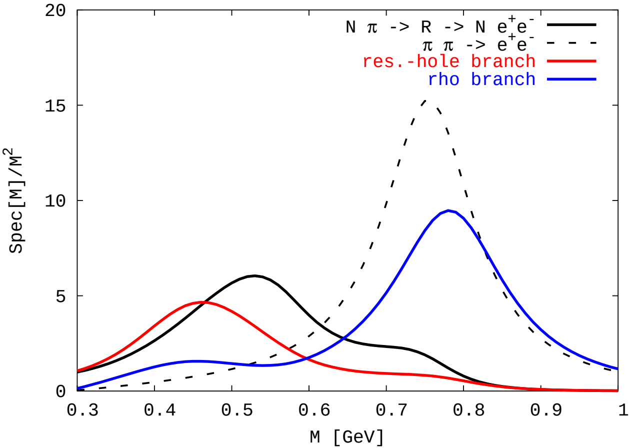
Spectral information including collective effects

Decomposition:

- genuine ρ-meson branch (2π)
- resonance-hole branch



Two-body contributions versus collective effects



$(\vec{q} = 0)$

- sum of colored curves (collective effects) <u>different</u> from sum of black curves (two-body reactions)
- especially: level repulsion, depletion of ρ-meson peak

Two-body contributions versus collective effects

- collective effects different from two-body reactions
- especially: level repulsion, depletion of ρ-meson peak
- but: strength at low invariant masses already from two-body reactions

$\rightsquigarrow$ need good resolution to distinguish

Two-body contributions versus collective effects

- collective effects different from two-body reactions
- especially: level repulsion, depletion of ρ-meson peak
- but: strength at low invariant masses already from two-body reactions

$\rightsquigarrow$ need good resolution to distinguish

- why are results different at all?

$\hookrightarrow$ after all “linear-density approximation”

$\rightsquigarrow$ additional effects from three-body reactions!

- are there always collective effects?

Are there always collective effects?

- so far: equilibrium considerations

↪ also possible for non-equilibrium?

- technical answer:
  collective effects emerge by putting self energy in denominator

$$\mathcal{A}(q) = -\mathrm{Im}\frac{1}{q^2 - m_\rho^2 - \Pi(q)}$$

↪ in principle also possible for non-equilibrium situations

Are there always collective effects?

- so far: equilibrium considerations

↪ also possible for non-equilibrium?

- technical answer:
  collective effects emerge by putting self energy in denominator

$$\mathcal{A}(q) = -\mathrm{Im}\frac{1}{q^2 - m_\rho^2 - \Pi(q)}$$

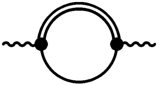
↪ in principle also possible for non-equilibrium situations

- but: not only a technical question!

↪ physical interpretation of denominator effect?

Physical interpretation of denominator effect

$$\mathcal{A}(q) = -\mathrm{Im}\frac{1}{q^2 - m_\rho^2 - \Pi(q)}$$

- contribution to ρ-meson self energy Π: 
- interpretation: multiple scattering on medium constituents

- not correct, if medium changes rapidly in time

↪ does system stay together/stay unchanged long enough?

↪ cf. works of C. Greiner/Schenke

Effects from N-body scattering

Why are results from two-body scatterings different from collective effects even at low densities?
$\hookrightarrow$ perform serious linear-density expansion:

- $\Pi = \Pi_{2\pi} + \Pi_{N*N^{-1}}$
- $\Pi_{2\pi} \approx \Pi_{\mathrm{vac}}$ (apart from Bose enhancement)
- $\Pi_{N*N^{-1}}$ linear in nucleon density

$$\mathcal{A}(q) = -\mathrm{Im}\frac{1}{q^2 - m_\rho^2 - \Pi(q)}$$

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

- so far: replace in denominator $\Pi \to \Pi_{\mathrm{vac}} \approx \Pi_{2\pi}$
- now: serious expansion

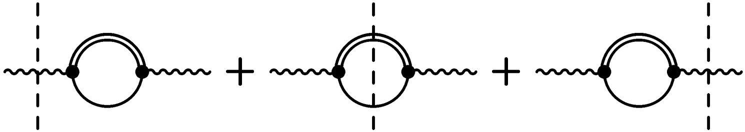
Serious linear-density expansion

- serious expansion:

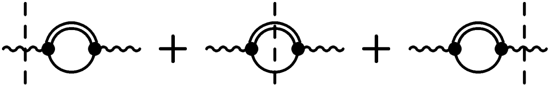
$$\mathcal{A}(q) = -\mathrm{Im}\frac{1}{q^2 - m_\rho^2 - \Pi_{2\pi}(q) - \Pi_{N^*N^{-1}}(q)}$$

$$\to \mathcal{A}_{\mathrm{vac}}(q) - \mathrm{Im}\left[\left(\frac{1}{q^2 - m_\rho^2 - \Pi_{\mathrm{vac}}(q)}\right)^2 \Pi_{N^*N^{-1}}(q)\right]$$

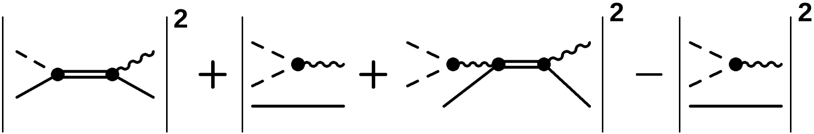
- graphical representation:
  (have to cut propagator, not only self energy!)



Subtle interference effects



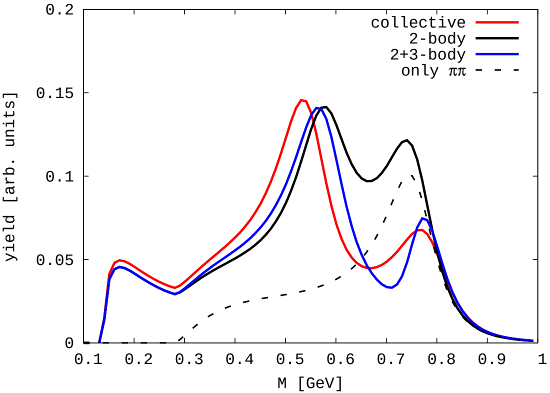
- in terms of elementary scattering diagrams:
  (not displayed: ρ-meson finally decays to dileptons)



- subtle interferences of three-body reactions!
- note: still within linear-density approximation:

$\hookrightarrow$ one nucleon accompanies ρ-meson/dileptons

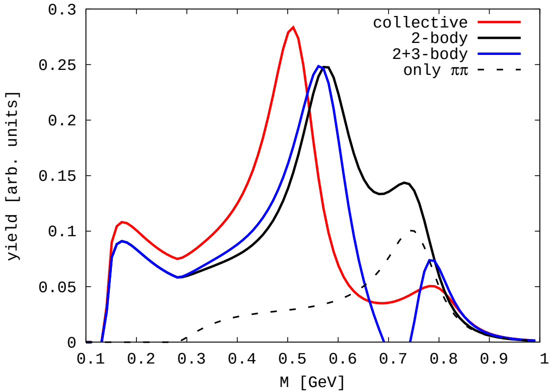
Compare various effects



- - only $\pi\pi$
— 2-body
— 2+3-body
— collective

- low-mass enhancement similar
- no depletion of ρ-meson peak in pure two-body reactions
- but depletion already when including three-body reactions

Compare various effects – higher densities



density doubled

- - only $\pi\pi$
— 2-body
— 2+3-body
— collective

differences between collective and three-body effects:

- collective effects show enhancement at lower masses

↪ level repulsion

- yields in part negative for three-body effects

↪ signals limit of applicability of linear-density approximation

How to implement N-body effects?

- problem (same as before):
  transition amplitudes often unknown
- for 3 $\rightarrow$ 2 reactions: back reaction helps
- thermal models: detailed balance relates

$$X_1 + X_2 + X_3 + \ldots \rightarrow Y + \ell^+ \ell^-$$

  to (semi-)two-body reaction

$$\gamma^* + Y \rightarrow X_1 + X_2 + X_3 + \ldots$$

- transport: in principle N-body reactions can be included (rates instead of geometric cross sections)
- do not forget interferences

Summary

try to distinguish

Two-body N-body collective

- experiment: need proper resolution
- low-mass enhancement not neccessarily sign of anything beyond two-body reactions (if $\pi N \to$ dileptons sizable)
- depletion of rho peak important issue (cf. also review by Rapp/Wambach)
- transport and thermal models: use same elementary cross sections before drawing conclusions about fancy things
- thermal models: compare with and without collective effects, with and without interferences/N-body effects
- transport: two-body standard, N-body doable, collective effects only possible with “offshell transport”