



Dynamics of
Resonances

GSI,
18.05.2005

Motivations

Thermal
Equilibrium

π -N- Δ

vector mesons

Di-leptons

Towards
dynamics

Conserving
 Φ -functional

Gradient ap-
proximation

Quantum
Kinetic
Equation

Summary

Dynamics of Resonances in Strongly Interacting Matter (Resonance transport)

J. Knoll¹, F. Riek¹, Yu.B. Ivanov^{1,2}, D. Voskresensky^{1,3}

¹GSI

²Kurchatov Inst. (Moscow)

³Moscow Ins. for Physics and Engineering



Outline

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1 Motivations

2 Thermal Equilibrium

- The π -N- Δ system
- Vector mesons coupled to pions
- Di-lepton yields

3 Towards dynamics

- Conserving Approximations
- Φ -functional method

4 Gradient approximation

5 Quantum Kinetic Equation

5 Summary



Towards transport of broad resonances

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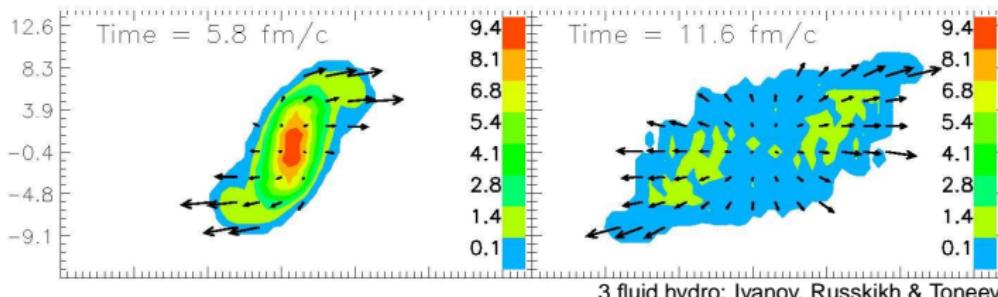
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Description of high energy nuclear collisions



3 fluid hydro: Ivanov, Russkikh & Toneev

- typical thermodynamics properties:
densities $\gg 2\rho_0$ (nucl. saturation)
 $T \in [50 - 150] \text{ MeV}$
- typical resonance width (Δ -res., ρ -meson): $\Gamma \geq 100 \text{ MeV}$
- typical collision rates: $\geq 1/2 \text{ fm/c} \sim \Gamma \geq 100 \text{ MeV}$
- \Rightarrow On-shell concepts questionable!



Towards transport of Particles and Resonance

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Boltzmann Ühling Uhlenbeck Eq.:

$$\left(\underbrace{\frac{\partial}{\partial t} + \frac{\vec{p}}{m} \frac{\partial}{\partial \vec{x}}}_{\text{free motion}} \right) f(\vec{x}, \vec{p}, t) - \underbrace{\{ U_{\text{pot}}, f \}}_{\text{mean field}} = \underbrace{C(f(\vec{x}, \vec{p}, t))}_{\text{Collision Term}}$$

$$\omega = \frac{p^2}{2m} - U_{\text{pot}}(\vec{x}, \vec{p})$$

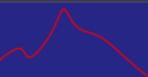
$$\int dp_1 dp_2 dp_3 \frac{d\sigma}{d\Omega} (1-f_1)(1-f_2)f_3$$

Off-Shell Propagation?:

+ loss term

$$\underbrace{f(\vec{x}, \vec{p}, t)}_{\text{3 Phase Space}} \implies \underbrace{F(\vec{x}, t; \vec{p}, \omega)}_{\text{4 Phase Space}}$$

- which equation(s)?
- is the knowledge of F sufficient?
 \implies Spectral Fct.: $A(\vec{x}, t; \vec{p}, \omega)$



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Pion modes in nuclear matter

Nucl. Phys. A 740(2004)287
with Felix Riek

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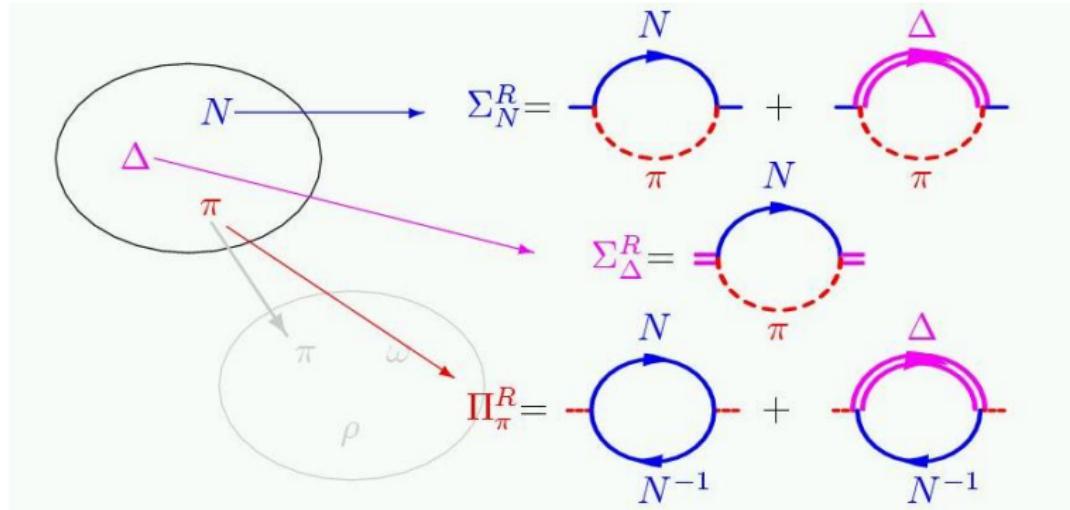
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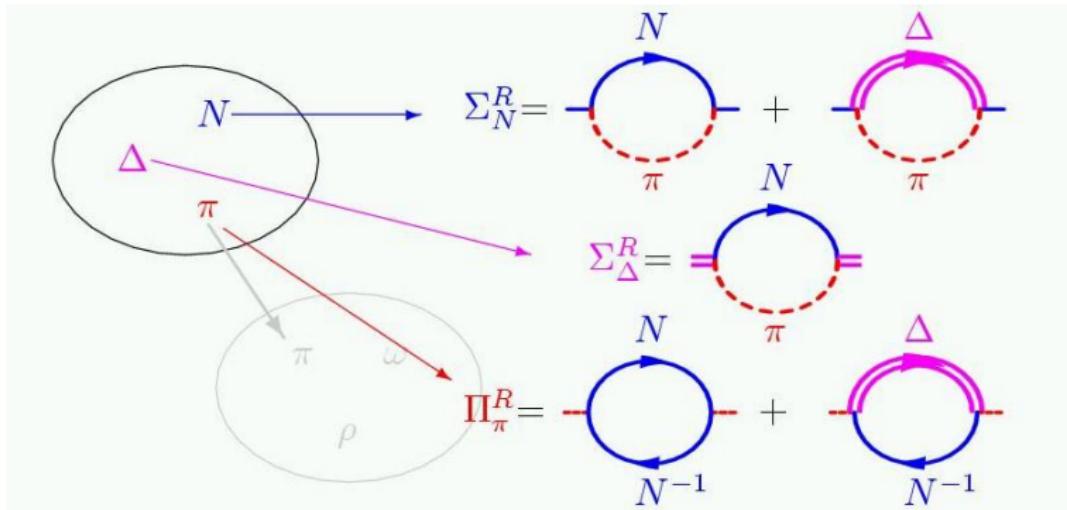
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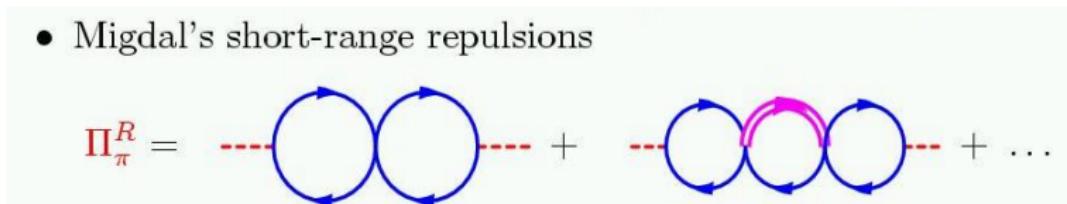
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- Migdal's short-range repulsions





Pion spectral-function

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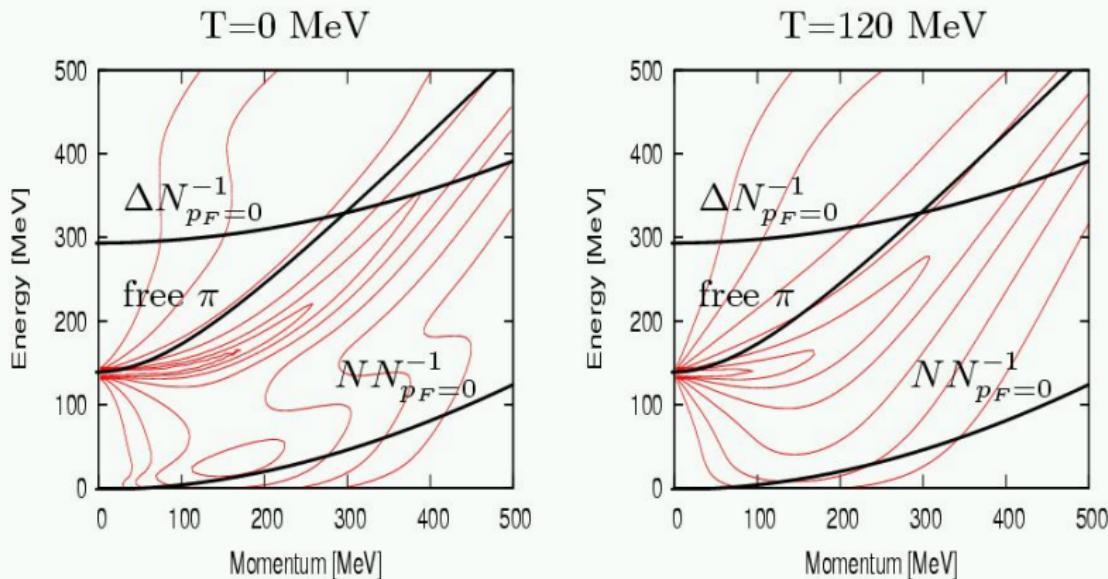
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- broad π spectral function
- 2 components: pion & particle-hole branches



Pion spectral-function

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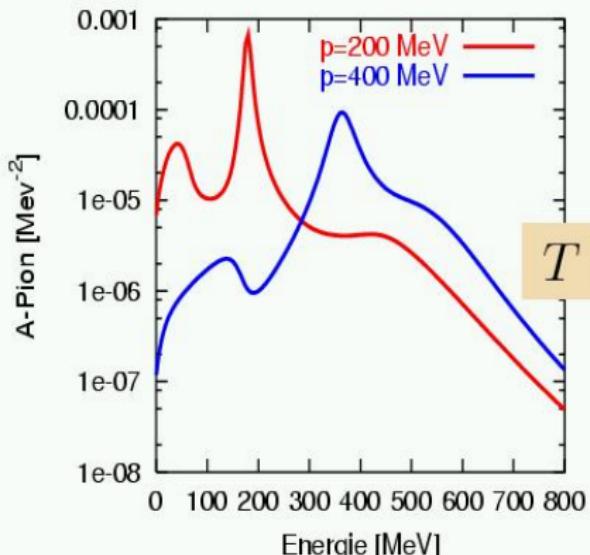
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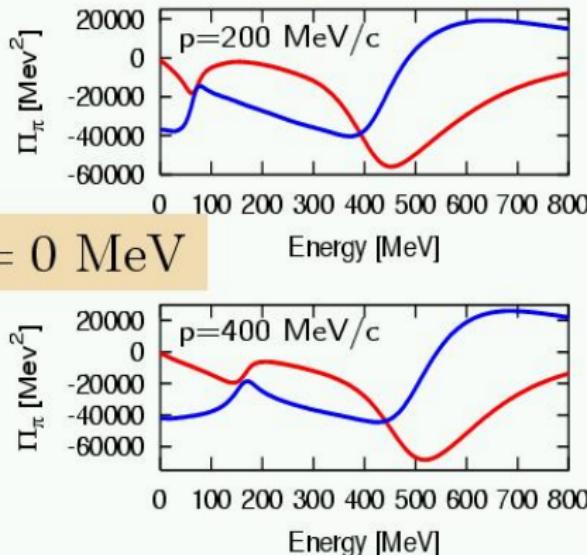
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Spectral Function



$T = 0 \text{ MeV}$



- broad π spectral function
- 2 components: pion & particle-hole branches



Pion spectral-function

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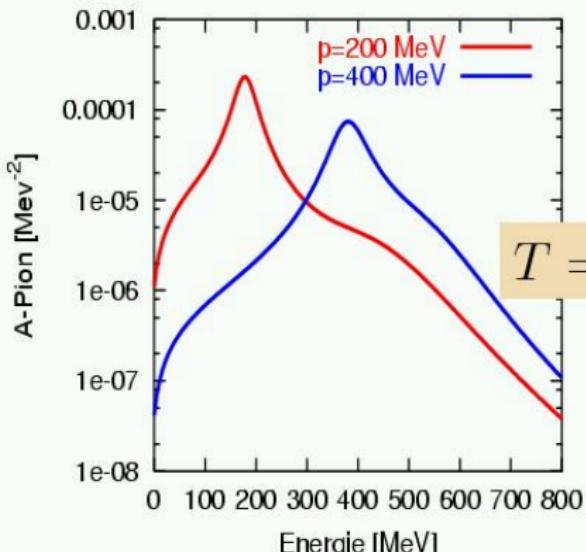
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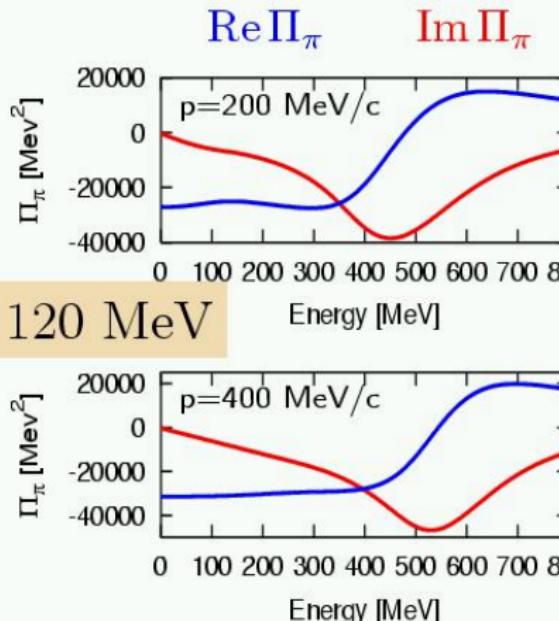
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Spectral Function



$T = 120 \text{ MeV}$



- broad π spectral function
- 2 components: pion & particle-hole branches



Vector mesons coupled to pions

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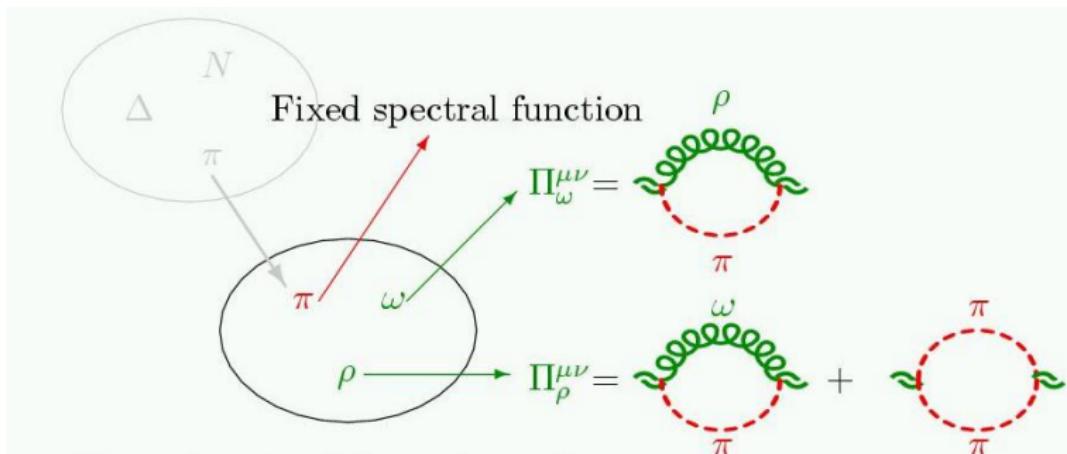
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freezing the in-medium pion cloud of the π -N- Δ system





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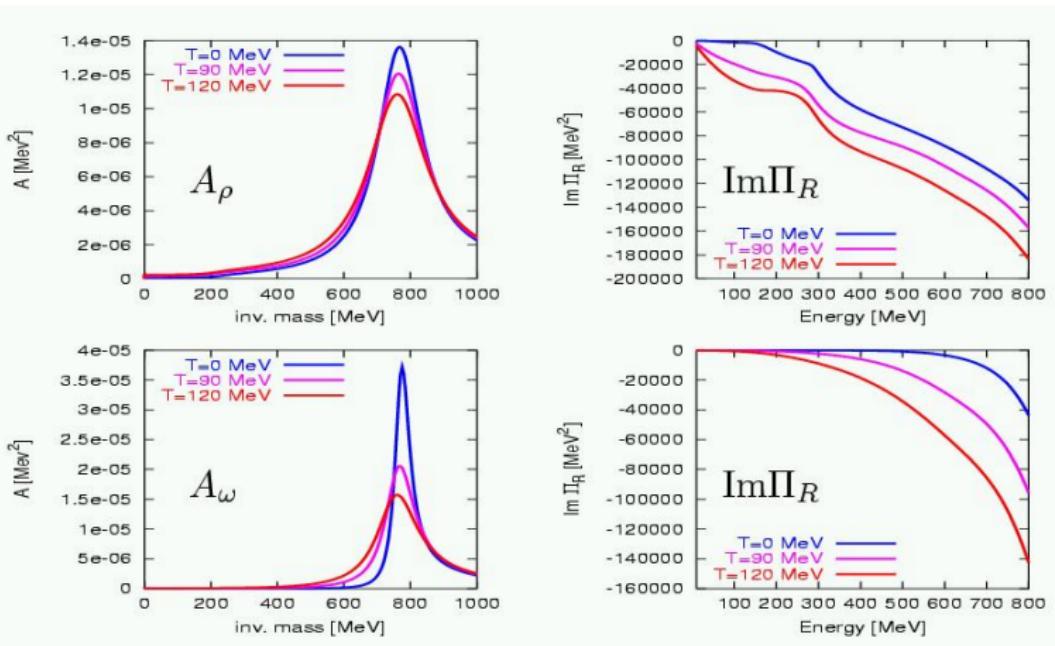
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- neglecting real parts of self-energy
- \Rightarrow broadening of both vector meson spectral functions



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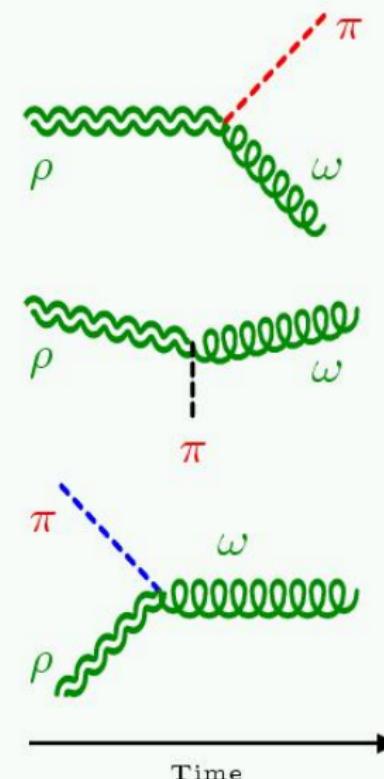
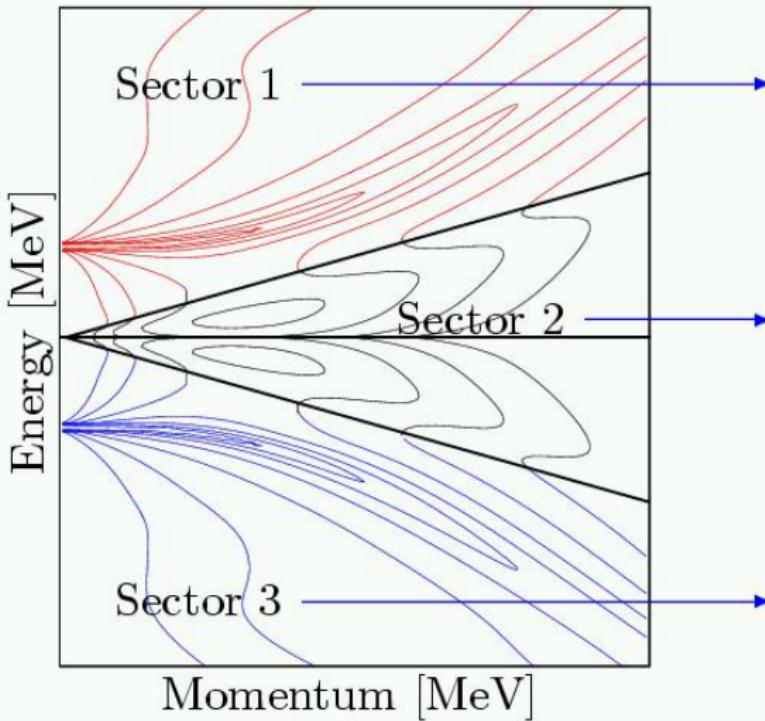
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Pion spectral function





Di-leptons from vector mesons

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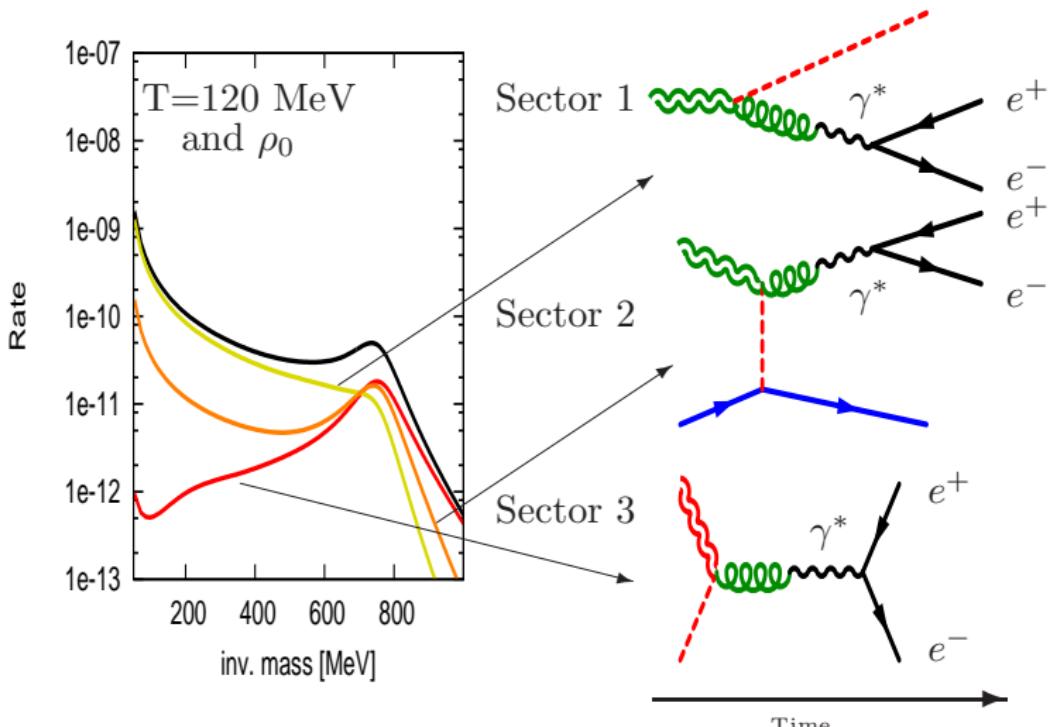
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Dileptons - decay of the ω -meson





Di-leptons from vector mesons

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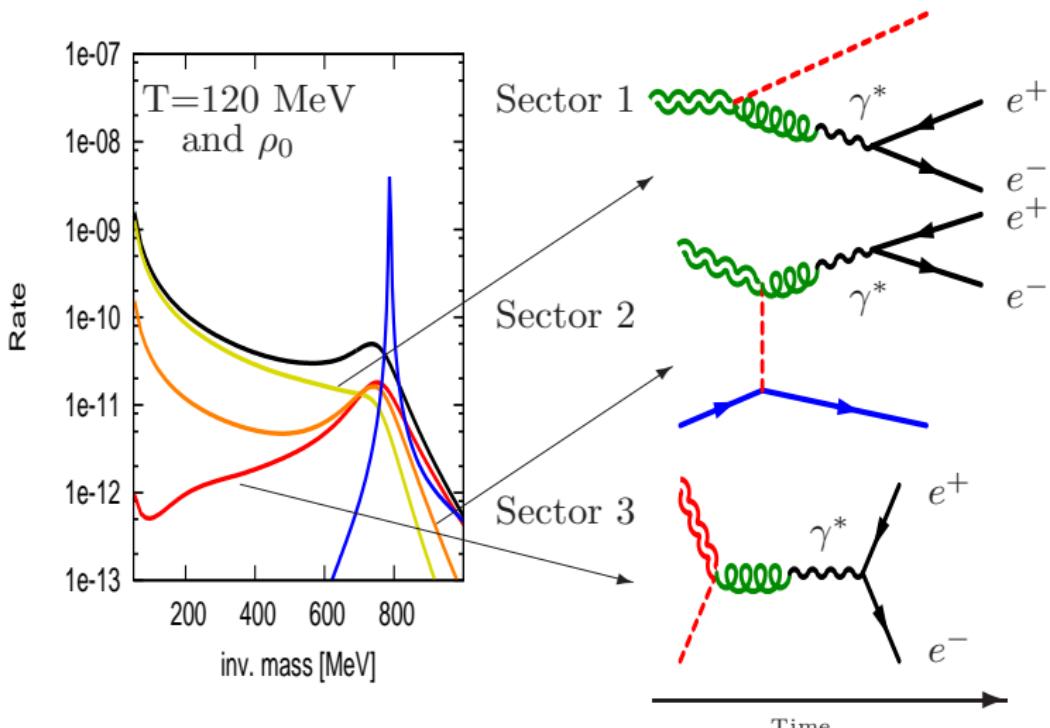
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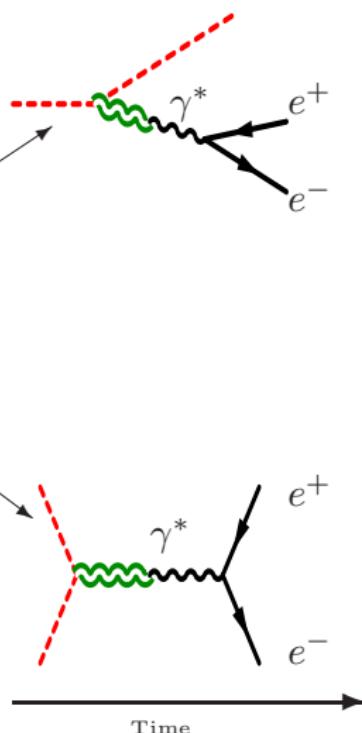
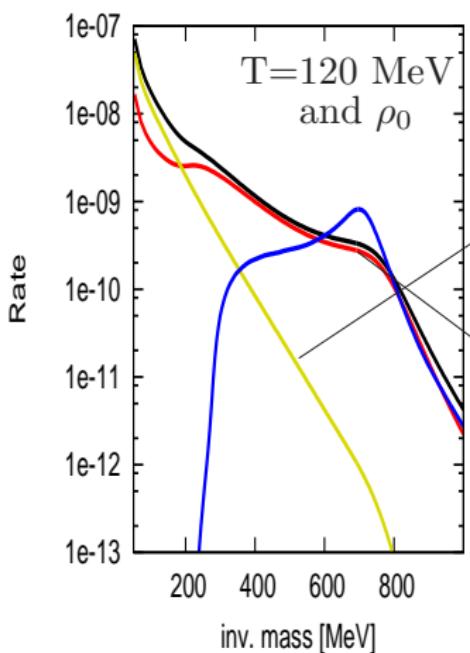
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Dileptons - decay of the ρ -meson





Conserving approximations

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Summary

How to come to a closed, consistent scheme?

respecting conservation laws
avoiding double counting
keeping the causality structure
the retarded relations and
detailed balance



Conserving approximations

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Summary

- **Perturbation Theory fails:**

- secular behavior at long times
 - higher order diagramms plagued by singularities
- Cure by cut-offs or appropriate resummations

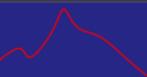
- **Partial resummation schemes:**

- Simplest: mean (classical) field and Dyson (Kadanoff-Baym) Eqs.

Φ -derivable method (2PI)

Luttinger-Ward '61
Baym 62'
Cornwall-Jackiw-Tomboulis '74

for classical fields
and two-point functions (Green fcts)



Conserving approximations

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- General aim: equation of motion for

⇒ Classical Fields ϕ_α (one-point fcts.)
⇒ Propagators G_α (two-point fcts.)

which are: $\left\{ \begin{array}{l} \text{self consistent} \\ \text{conserving (Charge, Energy,} \\ \quad \text{Momentum, Symmetries, ...)} \\ \text{Thermodyn. consistent} \end{array} \right.$

$$(\partial^\mu \partial_\mu + m^2) \phi_\alpha = J_\alpha \quad (\text{Cl. Field Eq})$$

$$v^\mu \partial_\mu G_\alpha = G_\alpha \odot \Sigma_\alpha - \Sigma_\alpha \odot G_\alpha \quad (\text{K.B. Eq})$$

Diagrammatic generating functional $\Phi(\phi_\alpha, G_\alpha)$ with

$$J_\alpha(x) = \frac{\delta \Phi}{\delta \phi_\alpha(x)}; \quad \Sigma_\alpha(x, y) = \mp \frac{\delta \Phi}{\delta G_\alpha(y, x)}$$

Φ : connected two-particle irred. closed diagrams
⇒ Conserving & Thermodyn. Consistent Appx.



Invariances of $\Phi \Rightarrow$ Conservation laws

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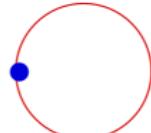
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Conserved Noether current:

$$v^\mu = \begin{cases} 2 p^\mu & \text{rel.} \\ (1, \frac{\vec{p}}{m}) & \text{non-rel.} \end{cases}$$

$$J^\mu(X) = e \int \frac{d^4 p}{(2\pi)^4} v^\mu \underbrace{f(X, p) A(X, p)}_{F(X, p)} = \bullet$$


Space-time invariance: $x \rightarrow x + \xi$: E-M-tensor

$$\Theta^{\mu\nu}(X) = \underbrace{\int \frac{d^4 p}{(2\pi)^4} v^\mu p^\nu F(X, p)} + g^{\mu\nu} (\mathcal{E}^{\text{int}}(X) - \mathcal{E}^{\text{pot}}(X))$$

$\Theta^{00}(X)$: **single particle energies**

$$\mathcal{E}^{\text{int}}(x) = -\langle \mathcal{L}(x) \rangle = \frac{\delta \Phi}{\delta \lambda(x)} \quad \text{Interaction Energy Density}$$

$$\begin{aligned} \mathcal{E}^{\text{pot}}(x) &= \frac{1}{2} \left\langle \frac{\partial \mathcal{L}}{\partial \phi(x)} \phi(x) \right\rangle && \text{Single Particle Potential Energy Density} \\ &= \int \frac{d^4 p}{(2\pi)^4} [\text{Re } \Sigma^R(X, p) F(X, p) + \text{Re } G^R(X, p) \Gamma^{\text{in}}(X, p)] \end{aligned}$$



The interacting N - Δ - π - ρ - ω system

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Lagrangian:

$$\mathcal{L}_{\text{int}} = \text{Diagram 1} + \text{Diagram 2} + \text{Diagram 3}$$

Diagram 1: A vertex where a nucleon (N) emits a pion (pi) and a rho meson (rho), which then interact with another nucleon (N) and a pion (pi).
Diagram 2: A vertex where a nucleon (N) emits a pion (pi) and an omega meson (omega), which then interact with another nucleon (N) and a pion (pi).
Diagram 3: A vertex where a nucleon (N) emits a pion (pi) and a rho meson (rho), which then interact with another nucleon (N) and an omega meson (omega).

closed Diagrams:

$$\Phi = \text{Diagram 4} + \text{Diagram 5} + \text{Diagram 6}$$

Diagram 4: A loop with a rho meson (rho) loop inside, with external pions (pi) and internal pions (pi).
Diagram 5: A loop with an omega meson (omega) loop inside, with external pions (pi) and internal pions (pi).
Diagram 6: A loop with a rho meson (rho) loop inside, with external nucleons (N) and internal pions (pi).

Meson self-energies:

$$\Pi_\rho = \text{Diagram 7} + \text{Diagram 8}$$

Diagram 7: A loop with a rho meson (rho) loop inside, with external pions (pi) and internal pions (pi).
Diagram 8: A loop with an omega meson (omega) loop inside, with external pions (pi) and internal pions (pi).

$$\Pi_\omega = \text{Diagram 9}$$

Diagram 9: A loop with a rho meson (rho) loop inside, with external pions (pi) and internal pions (pi).

$$\Pi_\pi = \text{Diagram 10} + \text{Diagram 11} + \text{Diagram 12}$$

Diagram 10: A loop with a rho meson (rho) loop inside, with external pions (pi) and internal pions (pi).
Diagram 11: A loop with an omega meson (omega) loop inside, with external pions (pi) and internal pions (pi).
Diagram 12: A loop with a rho meson (rho) loop inside, with external nucleons (N) and internal pions (pi).



Towards transport dynamics

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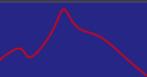
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How to come to a
closed and consistent
Transport scheme?

which is conserving
respects detailed balance
treats broad spectral widths
keeps the causality structure
and the retarded relations

Consistent Gradient approximation of K-B Equations
in Φ -derivable approximation



Generalized gradient apprx.

Ann. Phys. (NY) 293 (2001) 126

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Taylor expanded with respect to $X = (x_1 + x_2)/2$

$$G\left(\frac{x_i + x_j}{2}, p\right) \approx \underbrace{G(X, p)}_{\text{local}} + \underbrace{\frac{1}{2} \left[(x_i^\mu - x_1^\mu) + (x_j^\mu - x_2^\mu) \right] \frac{\partial}{\partial X^\mu} G(X, p)}_{\text{gradient terms}}$$

$$\overline{\overline{i \quad j}} = \frac{1}{2} (\partial_i + \partial_j) G(i, j) \longrightarrow \partial_X G(X, p)$$

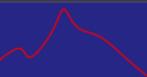
$$\overline{i \quad j} = -i (x_i - x_j) \longrightarrow -(2\pi)^4 \frac{\partial}{\partial p} \delta(p)$$

For any two-point function:

$$M(X, p) \approx \left(1 + \frac{i}{2} \diamond\right) M^{\text{local}}(X, p)$$

$$\diamond \{M(1, 2)\} = \diamond \begin{array}{|c|c|} \hline & M \\ \hline 1 & 2 \\ \hline \end{array} = \begin{array}{c} 3 \\ \text{---} \\ 4 \end{array} + \begin{array}{c} 3 \\ \text{---} \\ 4 \end{array}$$

$$M'(1, 2; 3, 4) = \mp \frac{\delta M(1, 2)}{\delta i G(4, 3)}.$$



Gradient Diagram Rules

Ann. Phys. (NY) 293 (2001) 126

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Addition rule:

$$1 \xrightarrow{3} = 1 \xrightarrow{2} + 2 \xrightarrow{3} \quad \text{and} \quad \bullet \circlearrowleft = 0$$

Convolution rule:

$$\begin{aligned} \diamond \left\{ \begin{array}{c} A \\ \diamond \\ B \end{array} \right\} &= \begin{array}{c} \bullet \circlearrowleft \\ A \\ \partial_X B \end{array} + \begin{array}{c} \partial_X A \\ \bullet \circlearrowleft \\ B \end{array} \\ &+ \begin{array}{c} A \\ \diamond \\ \diamond B \end{array} + \begin{array}{c} \diamond A \\ \diamond \\ B \end{array} \\ &= \{A(X, p), B(X, p)\} \\ &\quad + A(X, p) \diamond [B(X, p)] + \diamond [A(X, p)] B(X, P) \end{aligned}$$



$$v^\mu \partial_\mu F(X, p) = (1 + \frac{i}{2} \diamond) \left\{ C_{(\text{loc})}^{-+}(X, p) \right\}$$

local (non-gradient) right side: Collision term \rightarrow detailed balance!

$$\begin{aligned} \mp C_{(\text{loc})}^{-+} &= \text{diagram} & - &\quad \text{---} \quad \text{---} \\ &= \text{value} & \underbrace{\Gamma_{\text{in}}(X, p) \tilde{F}(X, p)}_{\text{gain}} &- \underbrace{\Gamma_{\text{out}}(X, p) F(X, p)}_{\text{loss}} \end{aligned}$$

3-momentum

$$f(X, \vec{p}) \frac{d^3 \vec{p}}{(2\pi)^3} \implies F(X, p) \frac{d^4 p}{(2\pi)^4} = f(X, p) A(X, p) \frac{d^4 p}{(2\pi)^4}$$

4-momentum

$$\begin{aligned} \Gamma(X, p) &\equiv -2\text{Im } \Sigma^R(X, p) = \Gamma_{\text{loss}}(X, p) \pm \Gamma_{\text{gain}}(X, p) \\ A(X, p) &\equiv -2\text{Im } G^R \end{aligned}$$

Retarded eq.

$$G^R(X, p) = \frac{1}{p^2 - m^2 - \text{Re } \Sigma^R(X, p) + i\Gamma(X, p)/2}$$



Gradients & conservation laws

Ann. Phys. (NY) 293 (2001) 126

Dynamics of
Resonances

GSI,
18.05.2005

Motivations

Thermal
Equilibrium
 π -N- Δ
vector mesons

Di-leptons

Towards
dynamics
Conserving
 Φ -functional

Gradient ap-
proximation

Quantum
Kinetic
Equation

Summary

$$v^\mu \partial_\mu F(X, p) - \{\text{Re } \Sigma^R, F\} + \{\text{Re } G^R, \Gamma^{\text{in}}\} - C^{(\text{non-loc})} = C^{(\text{loc})}$$

dragflow
group velocity

backflow from
fluctuations, gain & non-local terms
from internal gradients in Σ

- \Rightarrow conserved Noether currents and E-M-tensor (\rightarrow EoS)

$$\partial_\mu \sum_a \int \frac{d^4 p}{(2\pi)^4} e_a v^\mu F(X, p) = \partial_\mu J^\mu(X) = 0$$

$$\Theta^{\mu\nu}(X) = \int \frac{d^4 p}{(2\pi)^4} v^\mu p^\nu F(X, p) + g^{\mu\nu} \left(\mathcal{E}_{\text{int}}^{(\text{loc})}(X) - \mathcal{E}_{\text{pot}}^{(\text{loc})}(X) \right)$$

$$\mathcal{E}^{\text{pot}}(x) = \int \frac{d^4 p}{(2\pi)^4} [\text{Re } \Sigma^R(X, p) F(X, p) + \text{Re } G^R(X, p) \Gamma^{\text{in}}(X, p)]$$

- Relation to Delay Times (P. Danielewicz)
drag flow: forward delay other gradients: scattering delay



Towards Quantum Transport

Nucl.Phys.A 672 (2000) 313
Ann. Phys. (NY) 293 (2001) 126

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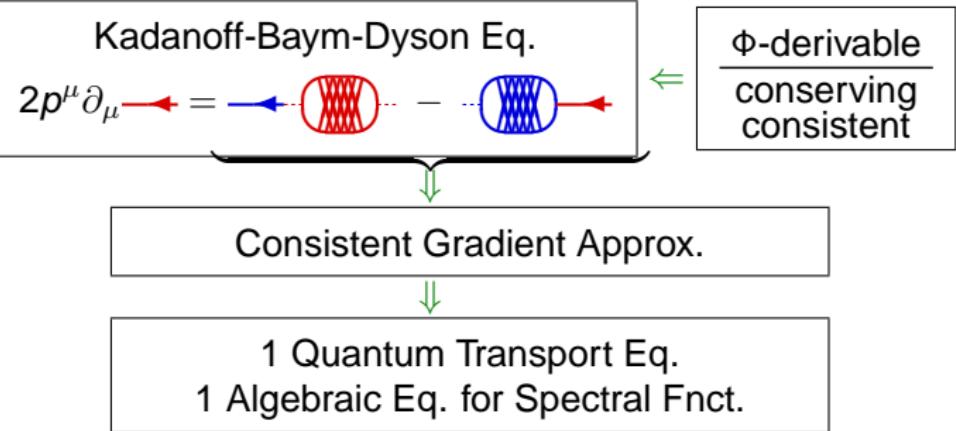
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Summary



Merits:

- ♣ A self-consistent & conserving transport scheme
- ♣ Allows to include Classical Fields (Soft Modes)
- ♣ Includes all QM Effects that are included in Equilibrium
- ♣ No Limitation to small Widths
- ♣ Delay-time, Drag & Back Flow, Memory & non-local Effects
- ♣ Non-equilibrium Entropy-current & H-Theorem
- ♠ Limitation to slow Space-time variations inherent to **all** transport schemes



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Summary

Limitations:

- ♠ Test-particle simulation unsettled
Problem: backflow;
approx. treatment: Botermans-Malfliet
used by W. Cassing & S. Leupold
- ♠ Problems with Symmetries on Correlator Level
 - a) violation of Goldstone modes,
 - b) violation of Gauge Invariance Transversality of the polarization tensor (vector bosons)

general cure: next higher vertex eq.: Bethe-Salpeter eq.
(generally untractable)

special repair:

⇒ a) supplement a symmetry restoring term to Φ

Y.B. Ivanov, J.K. & F. Riek, Phys.Rev.D71:105016,2005; hep-ph/0506157

⇒ b) use only spatial components of $\Pi^{\mu\nu}$ (short relaxation)
and construct a 4-transverse tensor by projection
methods

H. van Hees & J.K., Nucl. Phys. A683(2001)369