Meson and Baryon Spectral Functions and Dileptons

Hendrik van Hees

Johann Wolfgang Goethe University Frankfurt

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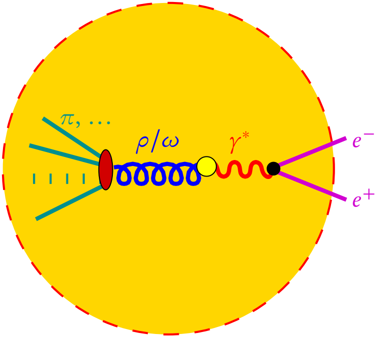
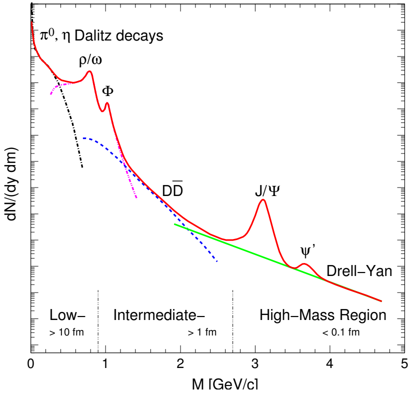
Outline

1. Motivation for electromagnetic probes $\leftrightarrow$ hadron resonances
2. Resonance model at SIS energies (with J. Weil, U. Mosel)
   - The Transport Model GiBUU
   - Baryon-resonance model at SIS energies
   - Dileptons in pp and pNb reactions at HADES
3. Dilepton production at the SPS (with R. Rapp)
   - Hadronic many-body theory
   - Dilepton emission from thermal and nonthermal sources
   - Comparison to NA60 data
4. Medium modfications of the Δ (with R. Rapp)
5. Conclusions and Outlook

Electromagnetic probes in heavy-ion collisions

- $\gamma, \ell^{\pm}$: no strong interactions
- reflect whole "history" of collision:
  - from pre-equilibrium phase
  - from thermalized medium QGP and hot hadron gas
  - from VM decays after thermal freezeout





[Fig. by A. Drees]

- vacuum and in-medium hadron properties needed!

[R. Rapp, J. Wambach, HvH, Landoldt-Börnstein, **I/23**, 4-1 (2010), arXiv: 0901.3289 [hep-ph]]

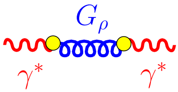
Electromagnetic Probes and Vector Mesons

- $\ell^+\ell^-$ thermal emission rates $\Leftrightarrow$ em. current-correlation function, $\Pi_{\mu\nu}$

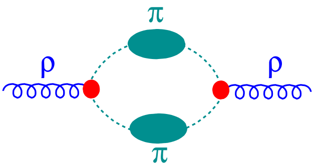
  [L. McLerran, T. Toimela 85, H. A. Weldon 90, C. Gale, J.I. Kapusta 91]

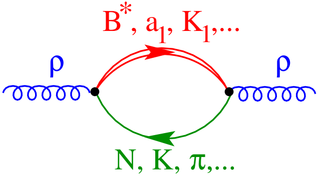
$$\frac{\mathrm{d}N_{e^+e^-}}{\mathrm{d}^4x\mathrm{d}^4q} = -g^{\mu\nu}\frac{\alpha^2}{3q^2\pi^3}\,\mathrm{Im}\,\Pi^{(\mathrm{ret})}_{\mu\nu}(q)\Big|_{q^2=M^2_{e^+e^-}} f_B(q_0)$$

- vector-meson dominance model:

$\Pi_{\mu\nu} =$ 

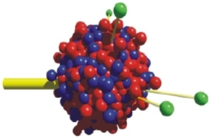
- hadronic many-body theory for vector mesons





- elementary processes $\Leftrightarrow$ cut self-energy diagrams

The GiBUU Model



GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- Boltzmann-Uehling-Uhlenbeck (BUU) framework for hadronic transport
- reaction types: pA, πA, γA, eA, νA, AA
- open-source modular Fortran 95/2003 code
- version control via Subversion
- publicly available realeases: http://gibuu.physik.uni-giessen.de
- Review: [O. Buss et al, Phys. Rept. 512, 1 (2012)]

The Boltzmann-Uehling-Uhlenbeck Equation

- time evolution of phase-space distribution functions

$$[\partial_t + (\vec{\nabla}_p H_i) \cdot \vec{\nabla}_x - (\vec{\nabla}_x H_i) \cdot \vec{\nabla}_p] f_i(t, \vec{x}, \vec{p}) = I_{\text{coll}}[f_1, \ldots, f_i, \ldots, f_j]$$

- Hamiltonian H_i
  - selfconsistent hadronic mean fields, Coulomb potential, "off-shell potential"
- collision term I_{coll}
  - two- and three-body decays/collisions
  - multiple coupled-channel problem
  - resonances described with relativistic Breit-Wigner distribution

$$\mathcal{A}(x,p) = -\frac{1}{\pi} \frac{\operatorname{Im}\Pi}{(p^2 - M^2 - \operatorname{Re}\Pi)^2 + (\operatorname{Im}\Pi)^2}; \quad \operatorname{Im}\Pi = -\sqrt{p^2}\Gamma$$

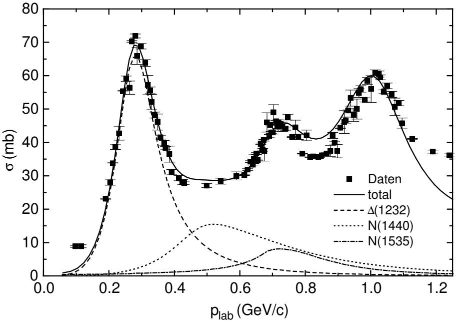
  - off-shell propagation: test particles with off-shell potential

Resonance Model

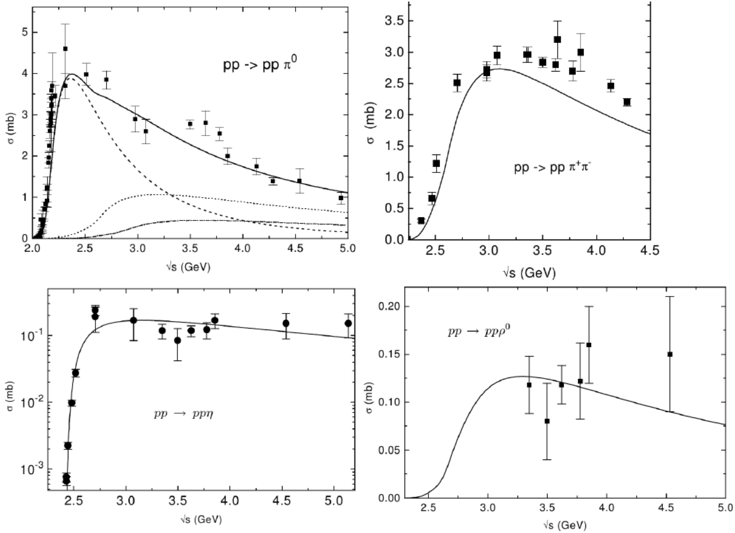
- reactions dominated by resonance scattering: $ab \to R \to cd$
- Breit-Wigner cross-section formula

$$\sigma_{ab \to R \to cd} = \frac{2s_R + 1}{(2s_a + 1)(2s_b + 1)} \frac{4\pi}{p_{\text{lab}}^2} \frac{s\Gamma_{ab \to R}\Gamma_{R \to cd}}{(s - m_R^2)^2 + s\Gamma_{\text{tot}}^2}$$

- applicable for low-energy nuclear reactions $E_{\text{kin}} \lesssim 1.1$ GeV
- example: $\sigma_{\pi^- p \to \pi^- p}$ [Teis (PhD thesis 1996), data: Baldini et al, Landolt-Börnstein **12** (1987)]



- further cross sections



Extension to HADES energies

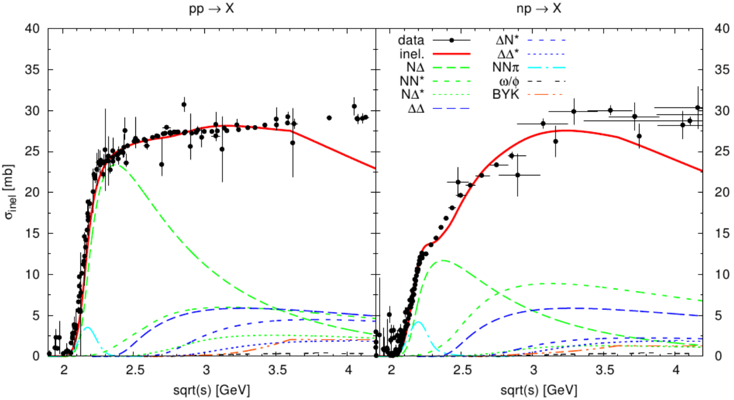
- keep same resonances (parameters from Manley analysis)

	rating	M_0 [MeV]	Γ_0 [MeV]	$\vert\mathcal{M}^2\vert/16\pi$ [mb GeV^2] NR	ΔR	branching ratio in % πN	ηN	$\pi\Delta$	ρN	σN	$\pi N^*(1440)$	$\sigma\Delta$
$P_{11}(1440)$	****	1462	391	70	—	69	—	22_P	—	9	—	—
$S_{11}(1535)$	***	1534	151	8	60	51	43	—	2_S+1_D	1	2	—
$S_{11}(1650)$	****	1659	173	4	12	89	3	2_D	3_D	2	1	—
$D_{13}(1520)$	****	1524	124	4	12	59	—	5_S+15_D	21_S	—	—	—
$D_{15}(1675)$	****	1676	159	17	—	47	—	53_D	—	—	—	—
$P_{13}(1720)$	*	1717	383	4	12	13	—	—	87_P	—	—	—
$F_{15}(1680)$	****	1684	139	4	12	70	—	10_P+1_F	5_P+2_F	12	—	—
$P_{33}(1232)$	****	1232	118	OBE	210	100	—	—	—	—	—	—
$S_{31}(1620)$	**	1672	154	7	21	9	—	62_D	25_S+4_D	—	—	—
$D_{33}(1700)$	*	1762	599	7	21	14	—	74_S+4_D	8_S	—	—	—
$P_{31}(1910)$	****	1882	239	14	—	23	—	—	—	—	67	10_P
$P_{33}(1600)$	***	1706	430	14	—	12	—	68_P	—	—	20	—
$F_{35}(1905)$	***	1881	327	7	21	12	—	1_P	87_P	—	—	—
$F_{37}(1950)$	****	1945	300	14	—	38	—	18_F	—	—	—	44_F

- production channels in Teis: $NN \to N\Delta$, $NN \to NN^*, N\Delta^*$, $NN \to \Delta\Delta$
- extension to $NN \to \Delta N^*, \Delta\Delta^*$, $NN \to NN\pi$, $NN \to NN\rho, NN\omega, NN\pi\omega, NN\phi$, $NN \to BYK$ $(B = N, \Delta,\ Y = \Lambda, \Sigma)$

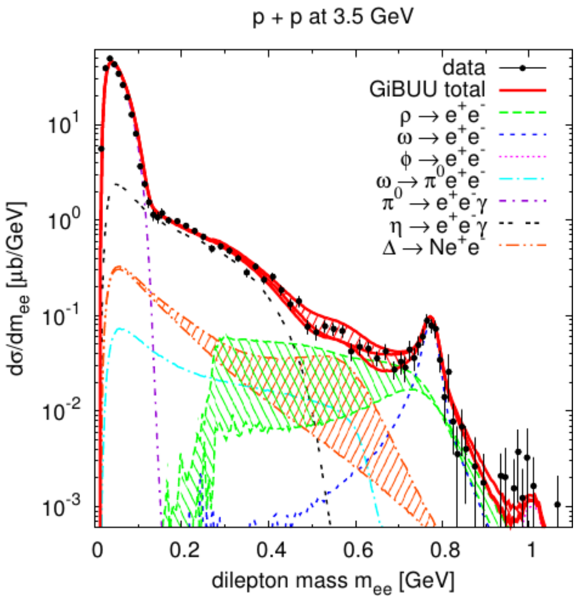
Extension to HADES energies

- good description of total pp, pn (inelastic) cross section



- dilepton sources
  - Dalitz decays: $\pi^0, \eta \to \gamma \ell^+ \ell^-$; $\omega \to \pi^0 \ell^+ \ell^-$, $\Delta \to N \ell^+ \ell^-$
  - $\rho, \omega, \phi \to \ell^+ \ell^-$: invariant mass $\ell^+ \ell^-$ spectra $\Rightarrow$ spectral properties of vector mesons

p p at HADES ($E_{\text{kin}} = 3.5$ GeV)



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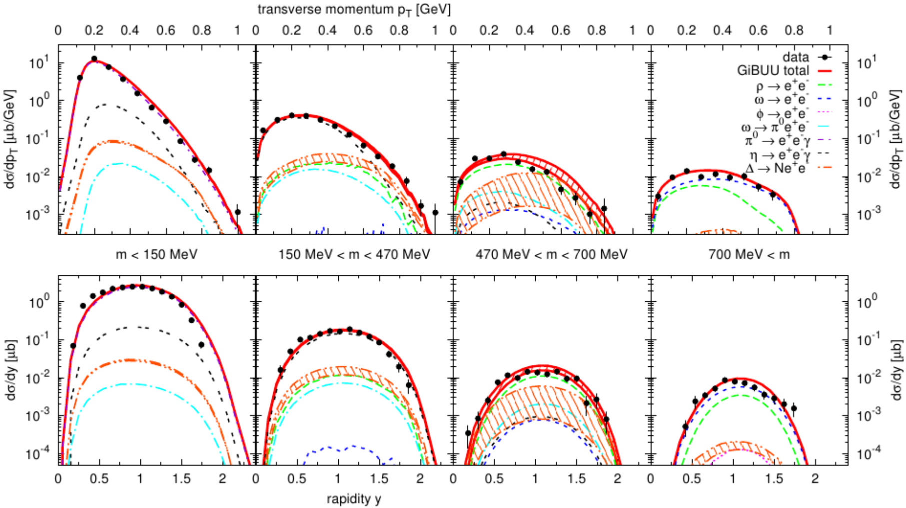
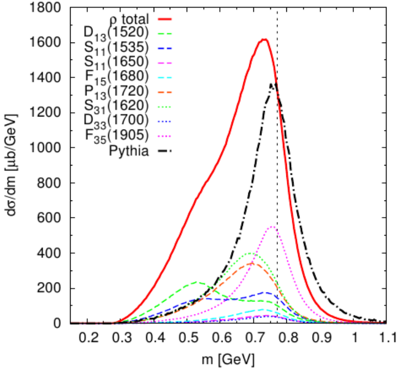
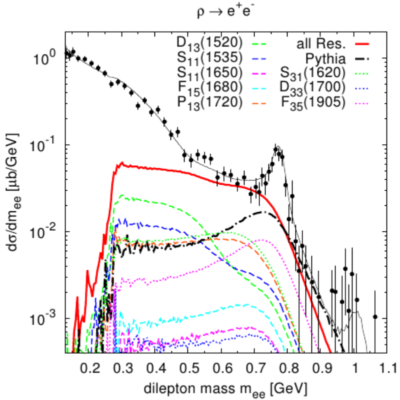


“ρ meson” in pp

- production through hadron resonances
  $NN \to NR \to NN\rho$, $NN \to N\Delta \to NN\pi\rho$

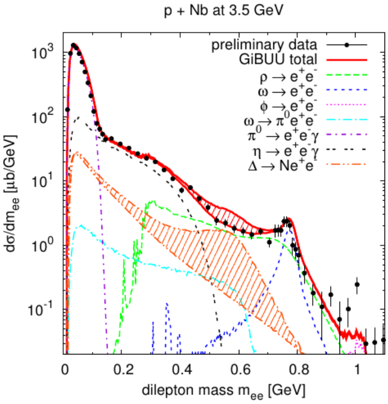


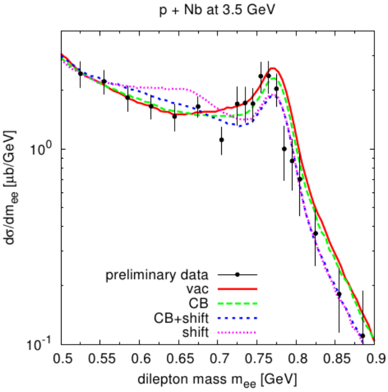


- “ρ”-line shape “modified” already in elementary hadronic reactions
- due to production mechanism via resonances

p Nb at HADES (3.5 GeV)

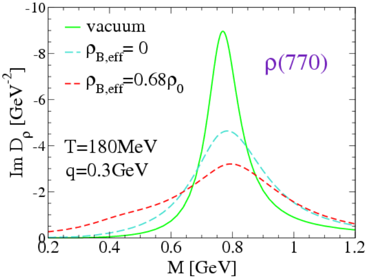
- medium effects built in transport model
  - binding effects, Fermi smearing, Pauli blocking
  - final-state interactions
  - production from secondary collisions
- sensitivity on medium effects of vector-meson spectral functions?

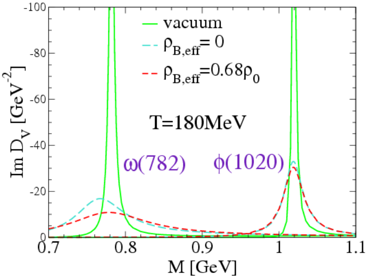




Dileptons at the SPS: Hadronic many-body theory

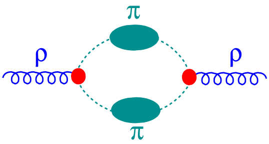
- radiation from thermal sources: Hadronic many-body theory

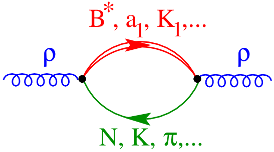




[R. Rapp, J. Wambach 99]

- baryon effects important
- $n_B + n_{\bar{B}}$ relevant quantity (not net-baryon density)!





Sources of dilepton emission in heavy-ion collisions

1. initial hard processes: Drell Yan
2. "core" $\Leftrightarrow$ emission from thermal source [McLerran, Toimela 1985]

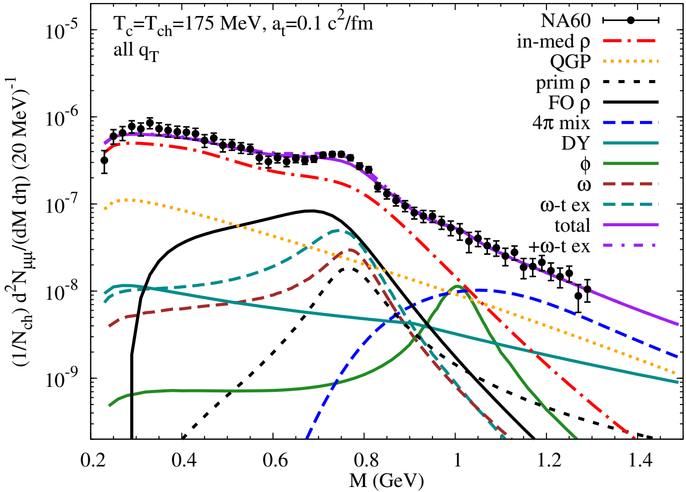
$$\frac{1}{q_T}\frac{\mathrm{d}N^{(\text{thermal})}}{\mathrm{d}M\mathrm{d}q_T} = \int \mathrm{d}^4x \int \mathrm{d}y \int M\mathrm{d}\varphi \frac{\mathrm{d}N^{(\text{thermal})}}{\mathrm{d}^4x\mathrm{d}^4q}\text{Acc}(M, q_T, y)$$

   use cylindrical thermal fireball with QGP, mixed and hadronic phase
3. "corona" $\Leftrightarrow$ emission from "primordial" mesons (jet-quenching)
4. after thermal freeze-out $\Leftrightarrow$ emission from "freeze-out" mesons [Cooper, Frye 1975]

$$N^{(\text{fo})} = \int \frac{\mathrm{d}^3q}{q_0} \int q_\mu \mathrm{d}\sigma^\mu f_B(u_\mu q^\mu/T)\frac{\Gamma_{\text{meson}\to\ell^+\ell^-}}{\Gamma_{\text{meson}}}\text{Acc}$$

M spectra (in p_T slices)

- norm corrected by $\sim$3% due to centrality correction (min-bias data: $\langle N_{\rm ch}\rangle = 120$, calculation $N_{\rm ch} = 140$)



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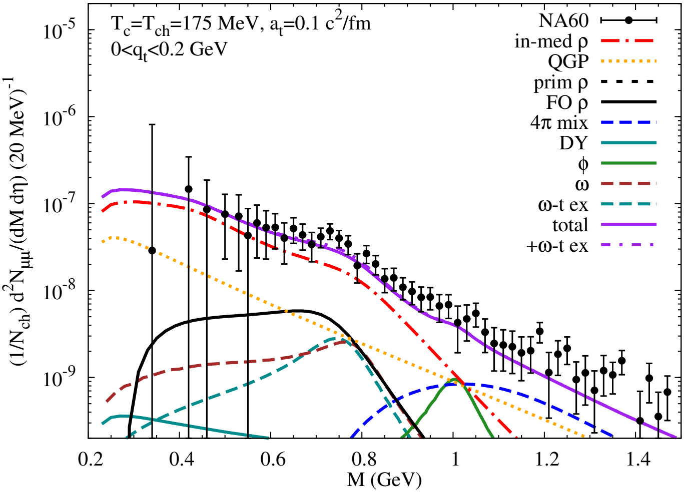

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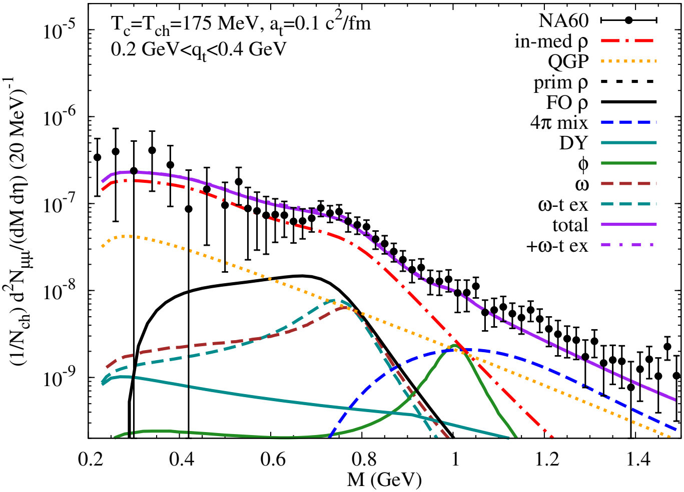

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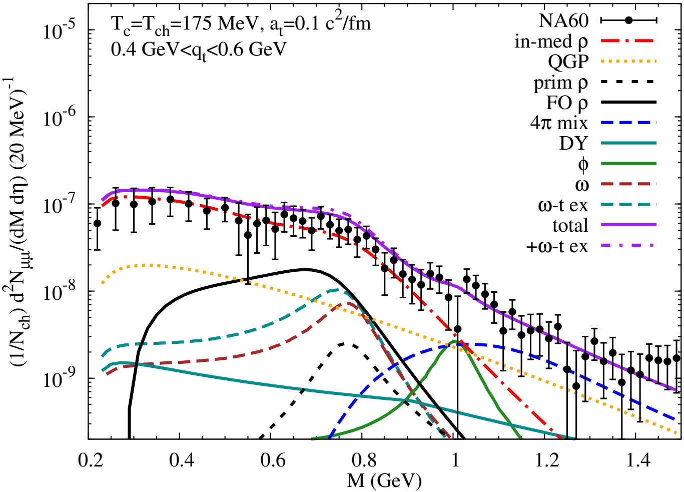

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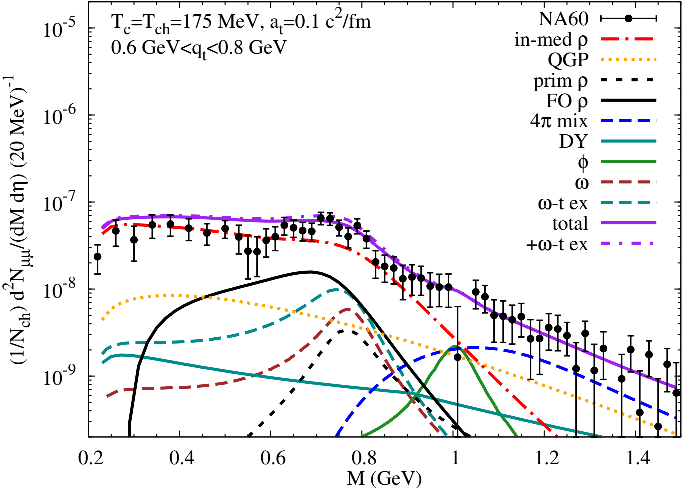

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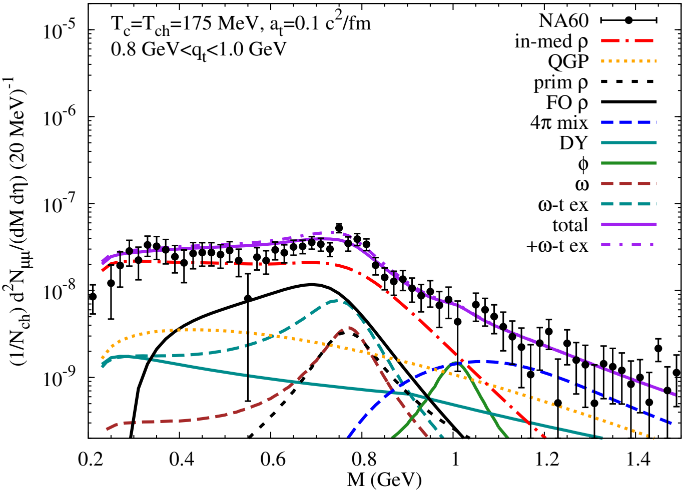

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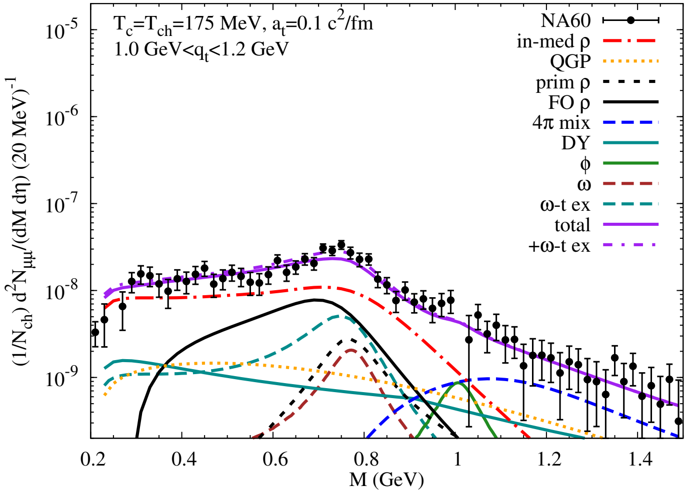

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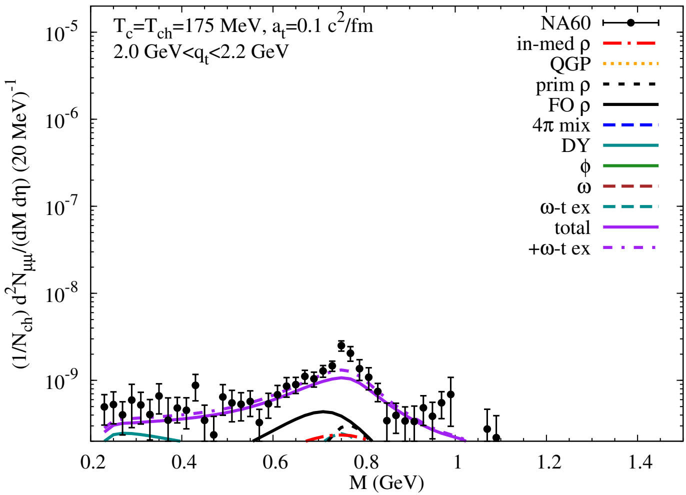

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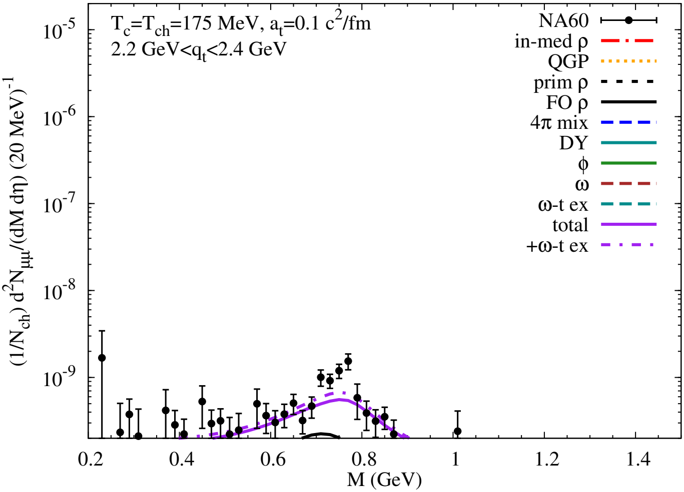
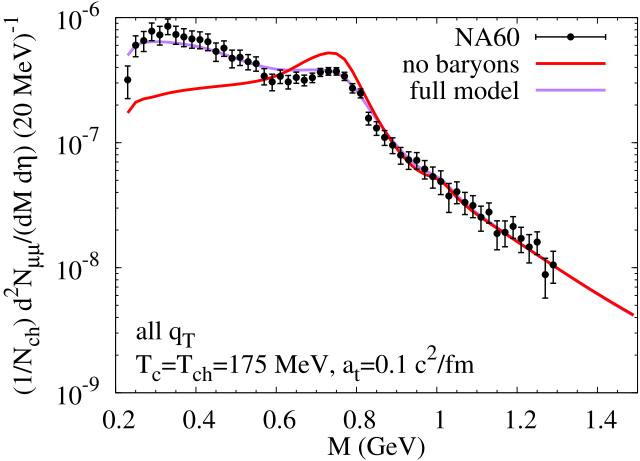
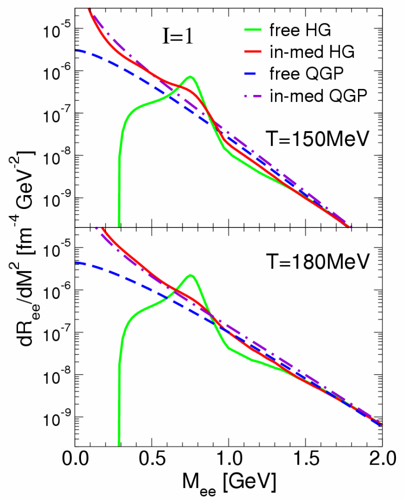


- baryonic interactions important!
- in-medium broadening
- low-mass tail!



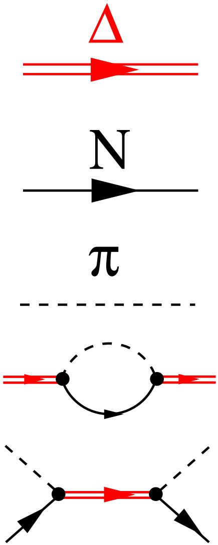
Dilepton rates: Hadron gas $\leftrightarrow$ QGP

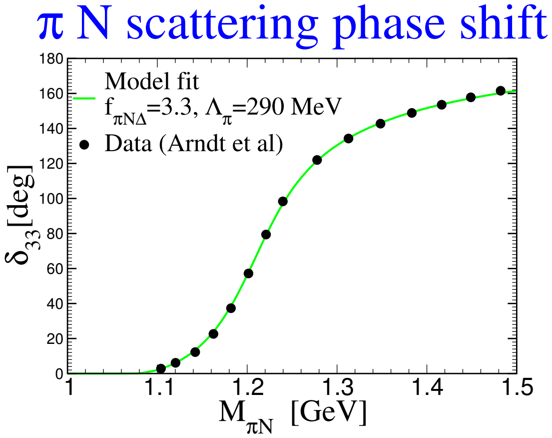


- in-medium hadron gas matches with QGP
- similar results also for γ rates
- "quark-hadron duality"!?
- consistent with chiral-symmetry restoration
- "resonance melting" rather than "dropping masses"

Medium modfications of the Δ

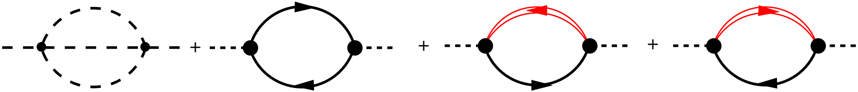
[HvH, R. Rapp, Phys. Lett. B **606**, 59 (2005); J. Phys. G **31**, S203 (2005)]



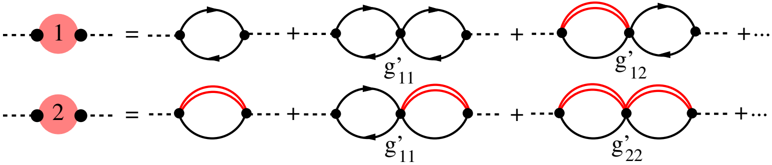


Medium modifications of pions and nucleons

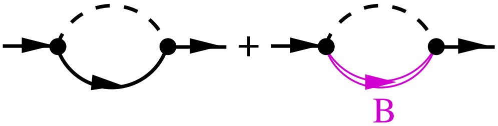
- pions: nucleon and Δ-hole excitations

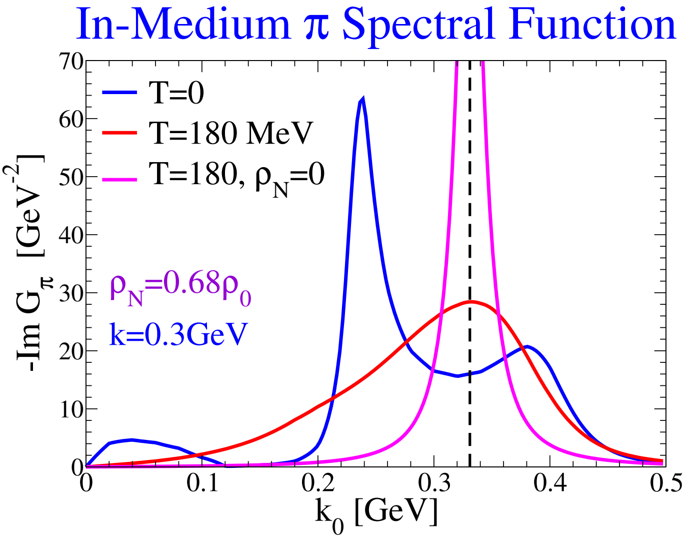


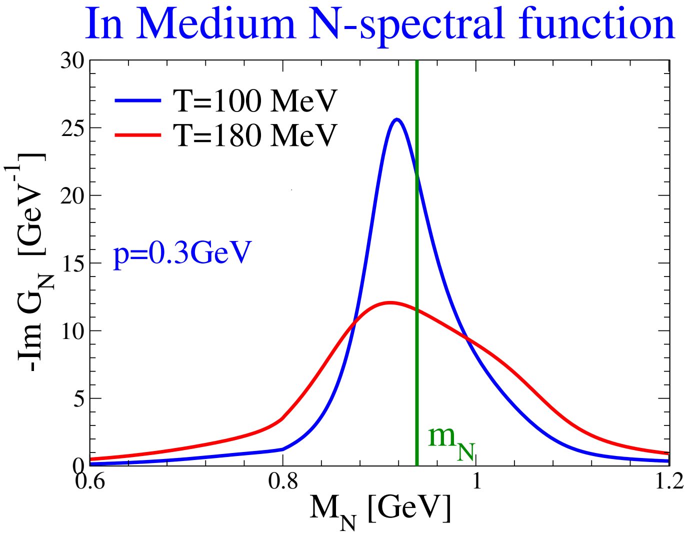
- short-range correlations: Migdal resummation



- nucleons: πN and πB,
  B=Δ(1232), $N^*(1440)$, $N^*(1535)$, $\Delta^*(1600)$, $\Delta^*(1620)$
- coupling constants fitted to partial decay widths $B \to \pi N$




In-Medium π Spectral Function
T=0
T=180 MeV
T=180, ρN=0
ρN=0.68ρ0
k=0.3GeV
-Im Gπ [GeV-2]
k0 [GeV]
0
10
20
30
40
50
60
70
0
0.1
0.2
0.3
0.4
0.5

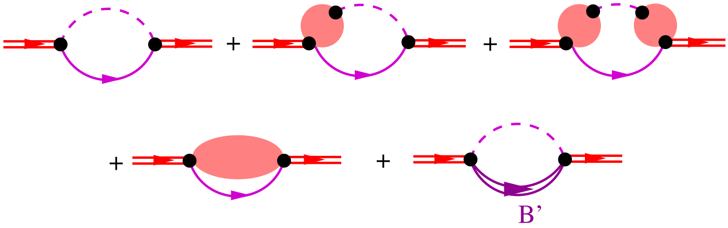


T=100 MeV, ϱ_N=0.12ϱ_0, μ_π=96 MeV

T=180 MeV, ϱ_N=0.68ϱ_0, μ_π=0

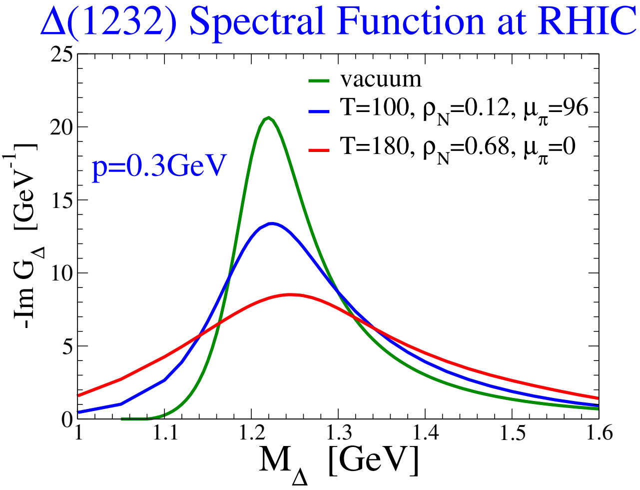
Medium Modifications of the Δ

- same diagram as in vacuum with dressed pion- and nucleon propagators
- vertex corrections: same resummed Migdal loops as for the pion
- 4-fermion vertices: same Migdal parameters as for the pion

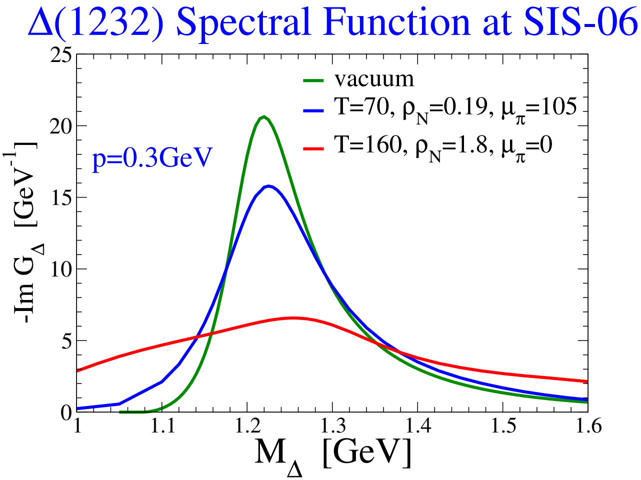


- $B' = \Delta(1232)$, $N^*(1440)$, $N^*(1520)$, $\Delta^*(1600)$, $\Delta^*(1620)$, $N^*(1700)$, $\Delta^*(1700)$

Medium Modifications of the Δ



Medium Modifications of the Δ



Conclusions and Outlook

- dilepton spectra $\Leftrightarrow$ in-medium em. current correlator
- SIS energies
  - GiBUU for pp, pn with resonance model for all HADES energies
  - np still a problem?
  - p Nb, AA work in progress
  - similar study within UrQMD in progress (with S. Endres, M. Bleicher)
- SPS and RHIC energies
  - excess yield dominated by radiation from thermal sources
  - baryons essential for in-medium properties of vector mesons
  - melting vector mesons with little mass shift
  - "quark-hadron duality" of $\ell^+\ell^-$ rates around T_c
  - compatible with chiral symmetry restoration!
  - studies in UrQMD(+hydro hybrid) model (with S. Endres, M. Bleicher) $\Rightarrow$ see talk by Marcus Bleicher
- Medium modifications of the Δ