Dileptons in NN and AA collisions

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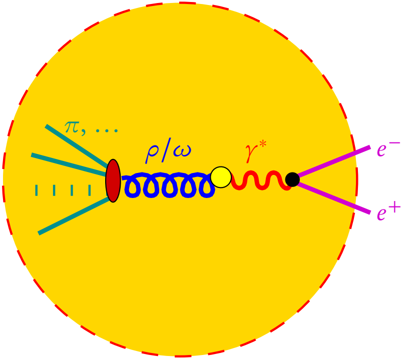
Outline

1. Electromagnetic probes in heavy-ion collisions
2. Dileptons at SIS energies (with GiBUU)
3. Dileptons at SPS and RHIC (QGP+hadronic many-body+fireball)
4. Conclusions

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



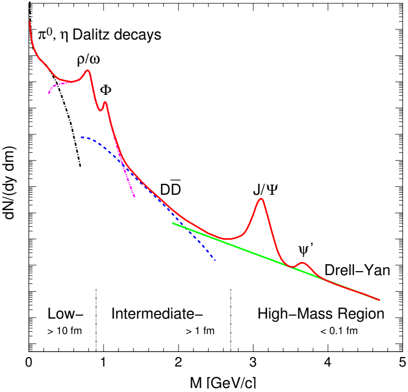


Fig. by A. Drees

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

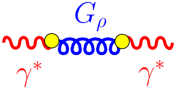
Vector Mesons and electromagnetic Probes

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

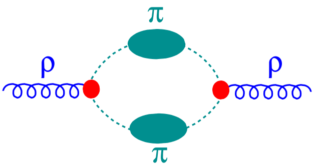
  [L. McLerran, T. Toimela 85, H. A. Weldon 90, C. Gale, J.I. Kapusta 91]

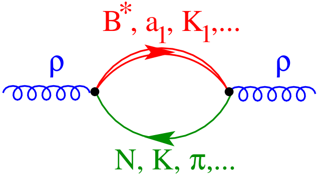
$$\frac{\mathrm{d}N_{e^+e^-}}{\mathrm{d}^4x\mathrm{d}^4q} = -g^{\mu\nu}\frac{\alpha^2}{3q^2\pi^3}\,\mathrm{Im}\,\Pi^{(\mathrm{ret})}_{\mu\nu}(q)\Big|_{q^2=M^2_{e^+e^-}} f_B(q_0)$$

- vector-meson dominance model:

$\Pi_{\mu\nu} =$ 

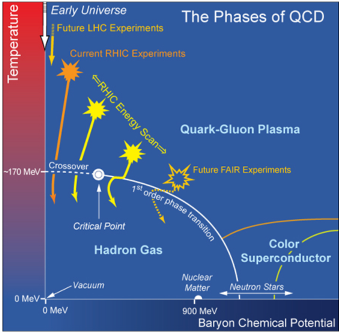
- hadronic many-body theory for vector mesons

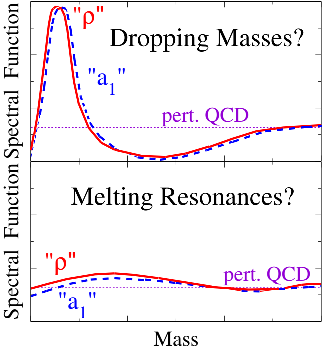




- elementary processes $\Leftrightarrow$ cut self-energy diagrams

- at high temperature/density: restoration of chiral symmetry
- Lattice QCD: $T_c^{\chi} \simeq T_c^{\text{deconf}}$

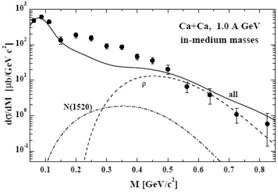




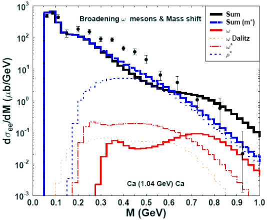
- Mechanism of chiral restoration?
- Two main theoretical ideas
  - "dropping masses": $m_{\text{had}} \propto \langle \bar{\psi} \psi \rangle$
  - "melting resonances": broadening of spectra through medium effects
  - More theoretical question: Realization of chiral symmetry in nature?

Dileptons at SIS energies

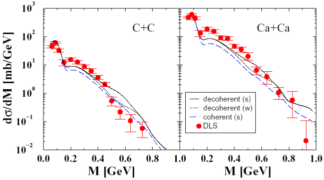
- dileptons from heavy-ion collisions at DLS at $E = 1A\,\mathrm{GeV}$
  [Porter et al, PRL **79**, 1229 (1997)]
- large enhancement at low invariant masses unexplained
- DLS puzzle



[Bratkovskaya et al (1999)]



[Ernst et al (1998)]



[Fuchs et al (2003)]

- DLS measurement confirmed by HADES!

Motivation for Transport Models

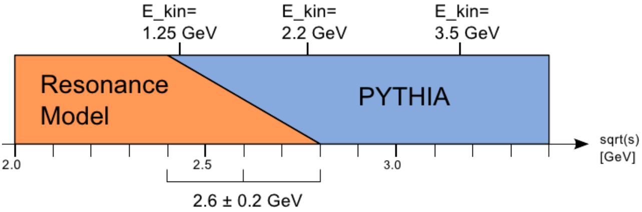
- description of various nuclear reactions within one framework
  - pA, γA, eA, νA, AA
- time evolution of system $\Rightarrow$ need dynamical approach
- transport models well suited for Monte-Carlo simulations (test-particle approach)
- strongly interacting many-body system: "medium modifications" of hadrons
- challenging task: description of broad resonance-like excitations
  - off-shell transport with consistent dynamical evolution of spectral properties
  - conservation laws
  - thermodynamic consistency
- in this talk: GiBUU model [O. Buss et al arXiv: 1106.1344 [hep-ph]; accepted@Phys. Rept.]
  - dileptons in pp and pNb collisions (HADES)
  - work with J. Weil, K. Gallmeister,...

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
  - selfcons. hadronic mean fields, Coulomb pot., "off-shell pot."
- collision term I_{coll}
  - two- and three-body decays/collisions
  - multiple coupled-channel problem
  - at low reaction energies: resonance model
  - at high reaction energies: (modified) PYTHIA
  - new: extend resonance model to cover whole HADES range

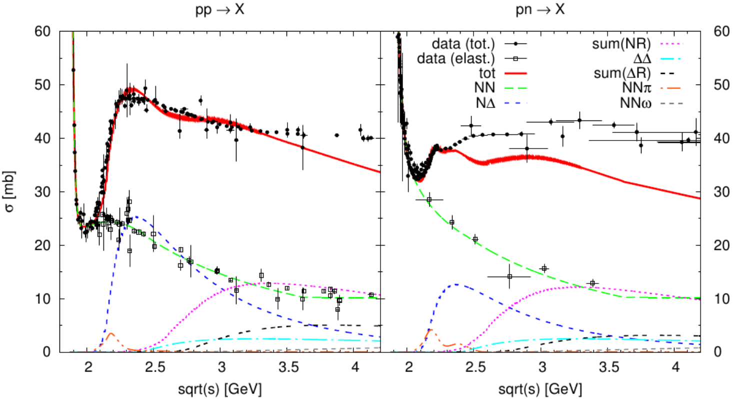


Resonance Model

- 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 [Teis (PhD thesis 1996)]

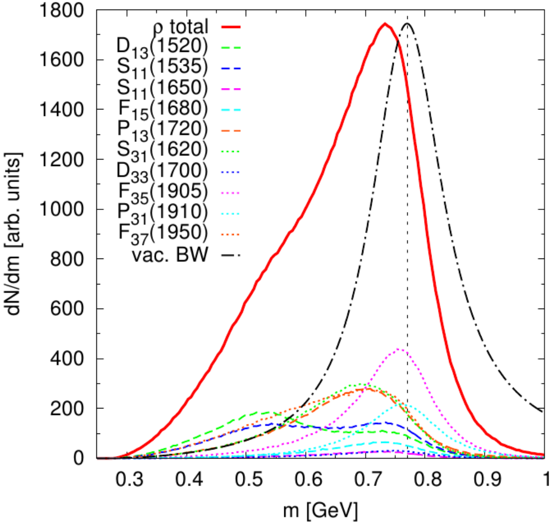


Dileptons in GiBUU

- uses strict vector-meson dominance ($J^\mu_{\text{had. em.}} \propto V^\mu$)
- Resonance model in Teis: $NN \rightarrow NR, \Delta\Delta$;
  extension $NN \rightarrow RR$ ($m_R \lesssim 2$ GeV)
- Teis: describes exclusive π, 2π, ρ, η production
  extension: $\pi\eta$, $\pi\rho$, 3π, 2η, 2ρ,...
- lack of experimental data $\Rightarrow$ fit to PYTHIA $\Rightarrow$ $\pi\rho$, $\pi\eta$ dominant for HADES energies $\sqrt{s_{\text{max}}} = 3.2$ GeV
- $NN \rightarrow \Delta R \rightarrow (N\pi)(\eta N), (N\pi)(\rho N)$ new production channels
  $NN \rightarrow \Delta S_{11}(1535) \rightarrow NN\pi\eta$, $NN \rightarrow \Delta N^* \rightarrow NN\pi\rho$ with
  $N^* \in \{D_{13}(1520), S_{11}(1650), F_{15}(1680), P_{13}(1720)\}$;
  $NN \rightarrow \Delta\Delta^* \rightarrow NN\pi\rho$ with $\Delta^* \in \{S_{31}(1620), D_{33}(1700), F_{35}(1905)$

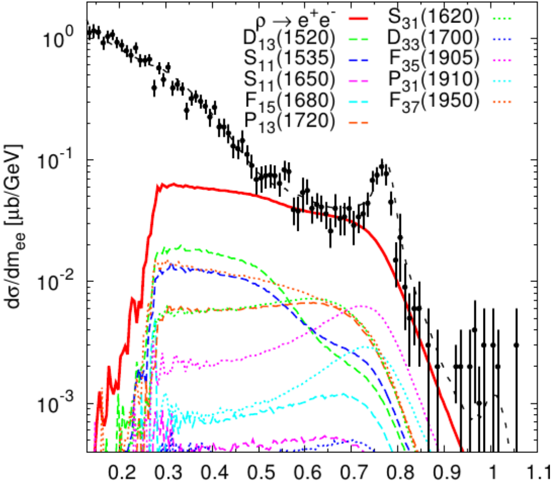
ρ-production spectrum

- mass spectrum for $\rho \to e^+e^-$ production in 3.5 GeV pp collisions ($\sqrt{s} = 3.18$ GeV)

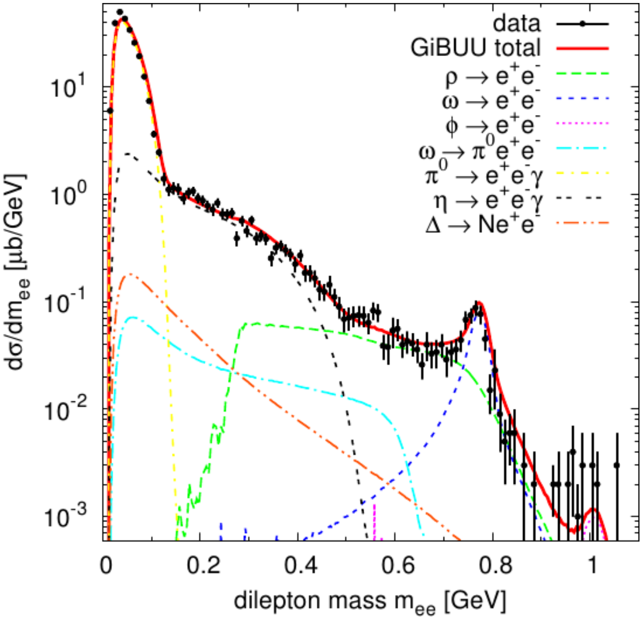


ρ-production spectrum

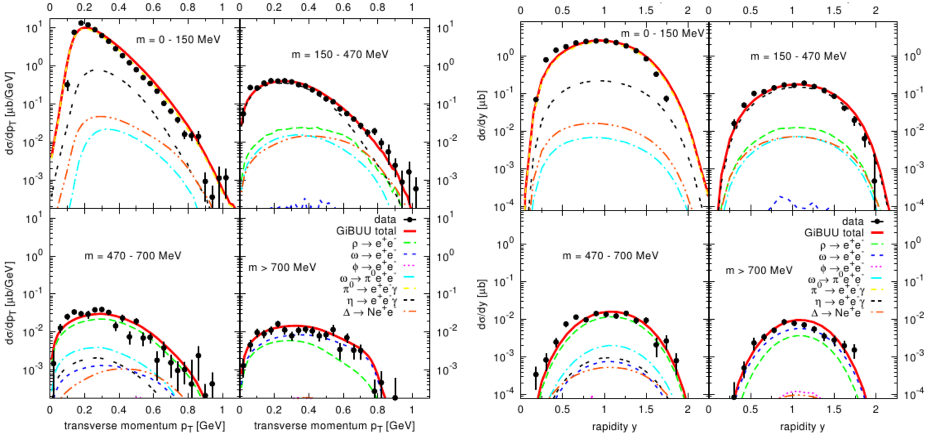
- mass spectrum for ρ production in 3.5 GeV pp collisions ($\sqrt{s} = 3.18$ GeV)



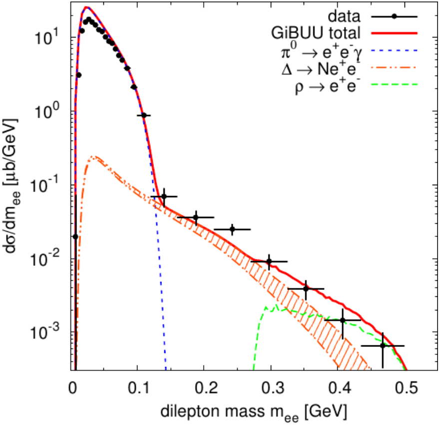
Dileptons in 3.5 GeV pp collisions

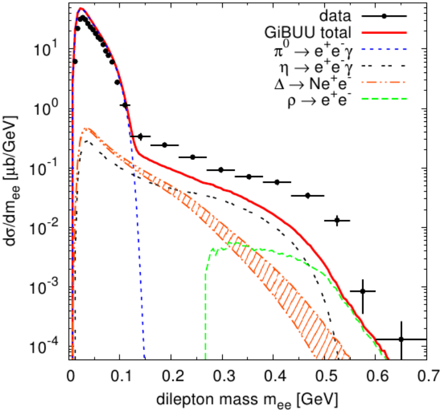


Dileptons in 3.5 GeV pp collisions



Dileptons in 1.25 GeV pp collisions

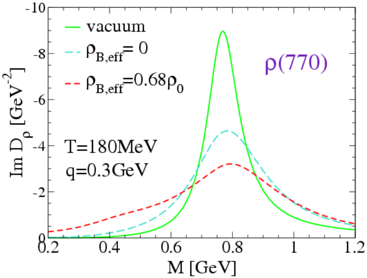


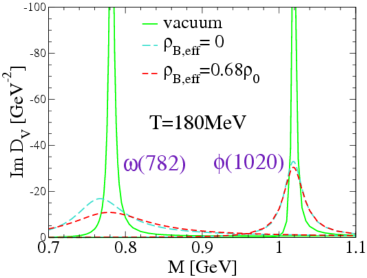


- pp well described
- pn from dp
- trouble for pn (work in progress)

Dileptons at SPS and RHIC

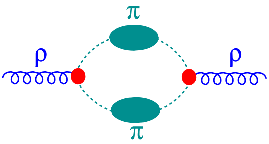
- radiation from thermal sources: Hadronic many-body theory

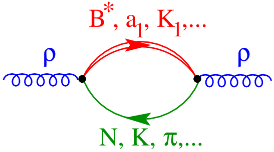




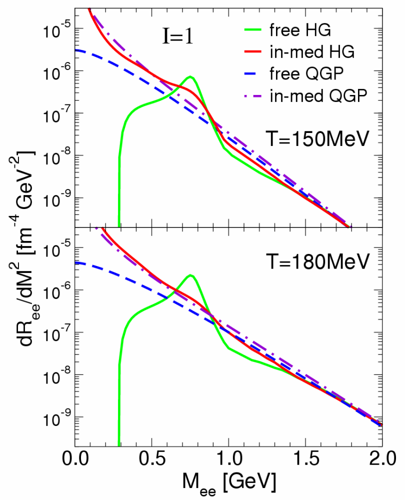
[R. Rapp, J. Wambach 99]

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





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"

Sources of dilepton emission in heavy-ion collisions

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

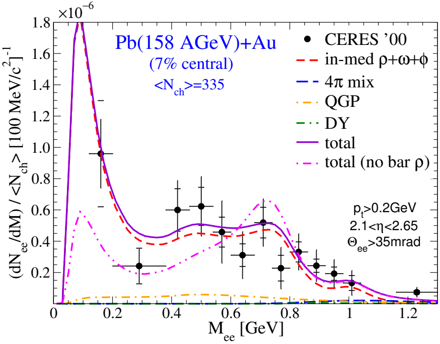
$$\frac{1}{q_T}\frac{\mathrm{d}N^{(\text{thermal})}}{\mathrm{d}M\mathrm{d}q_T} = \int \mathrm{d}^4x \int \mathrm{d}y \int M\mathrm{d}\varphi \frac{\mathrm{d}N^{(\text{thermal})}}{\mathrm{d}^4x\mathrm{d}^4q}\mathrm{Acc}(M, q_T, y)$$

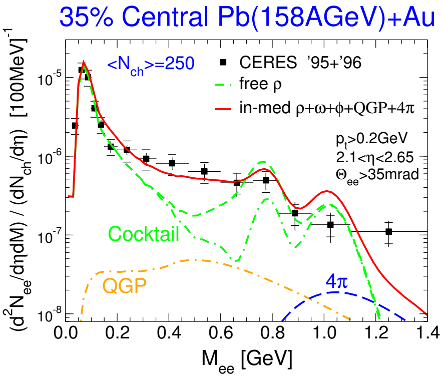
   use cylindrical thermal fireball with QGP, mixed and hadronic phase
3. "corona" ⇔ emission from "primordial" mesons (jet-quenching)
4. after thermal freeze-out ⇔ emission from "freeze-out" mesons [Cooper, Frye 1975]

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

CERES/NA45 dielectron spectra

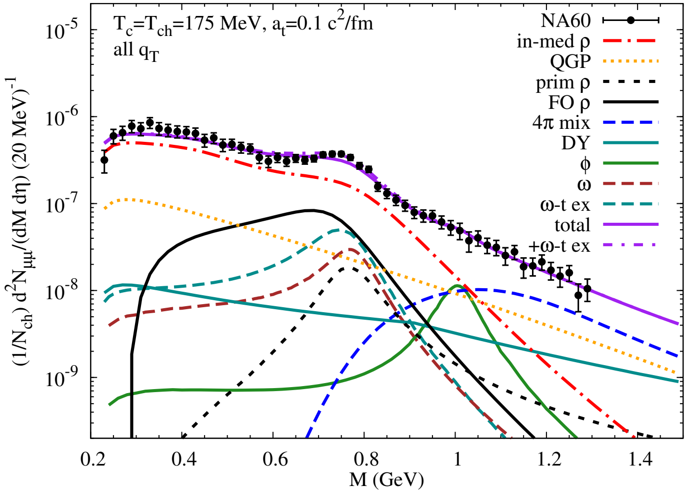
- good agreement also for dielectron spectra in 158 GeV Pb-Au
- low-mass tail from baryon effects





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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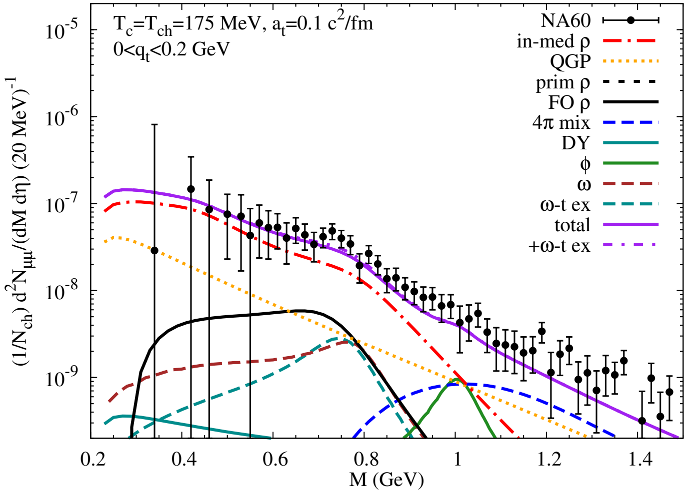

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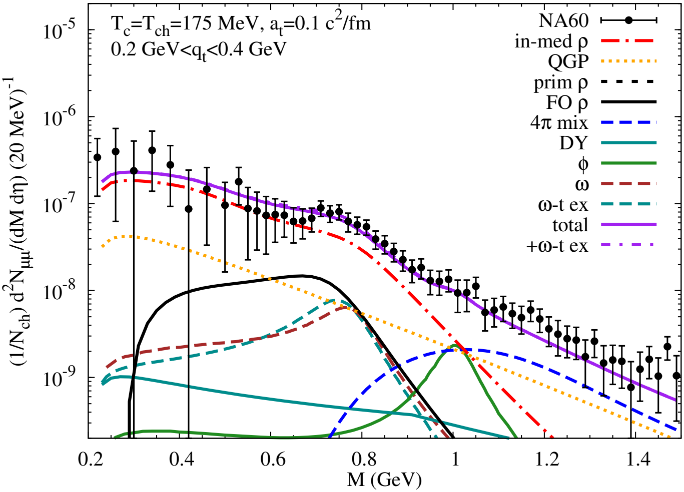

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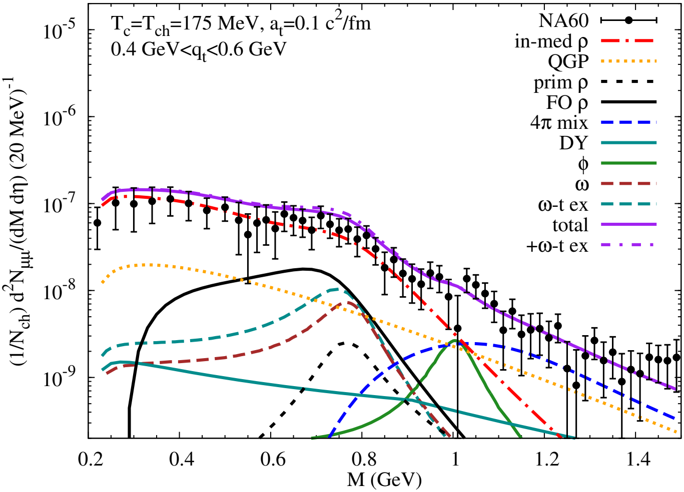

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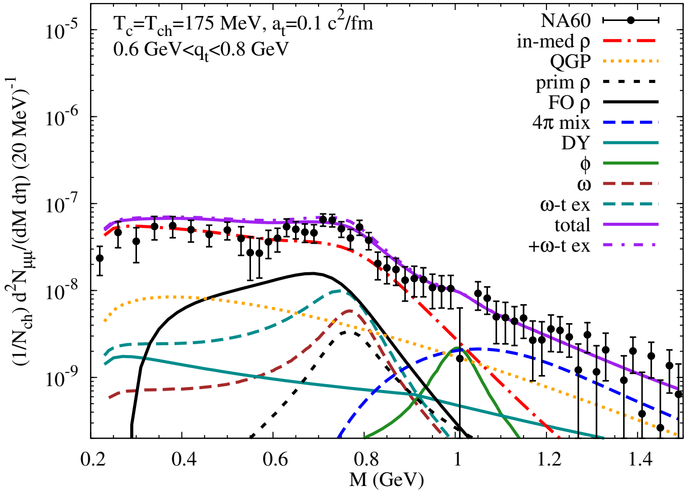

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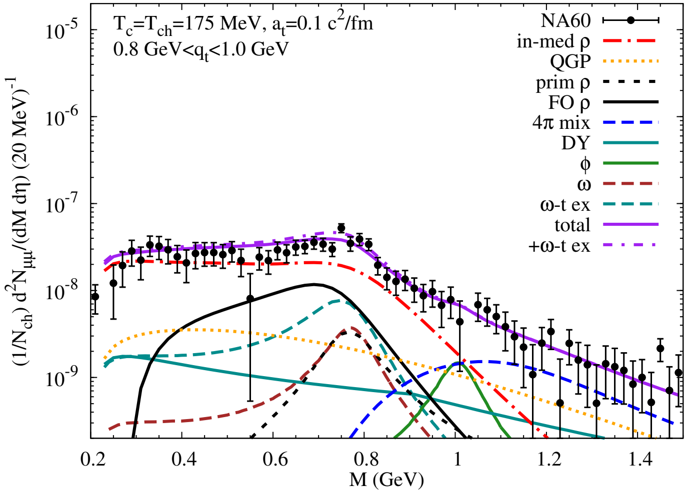

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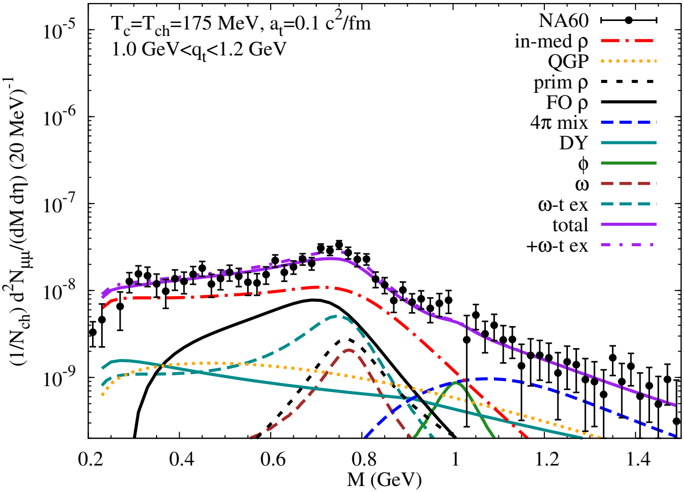

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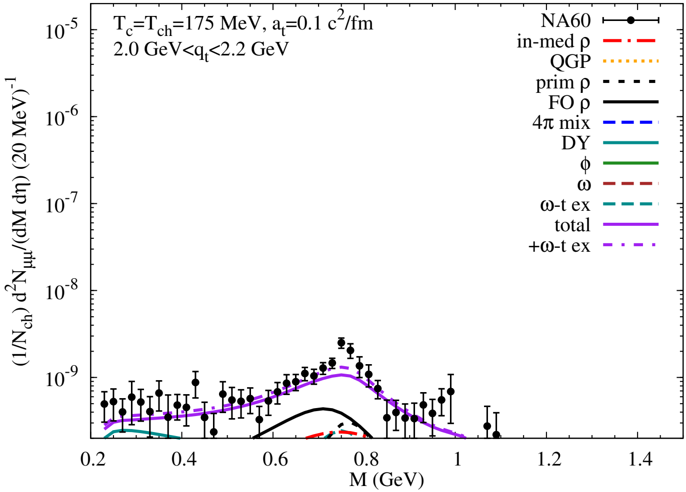

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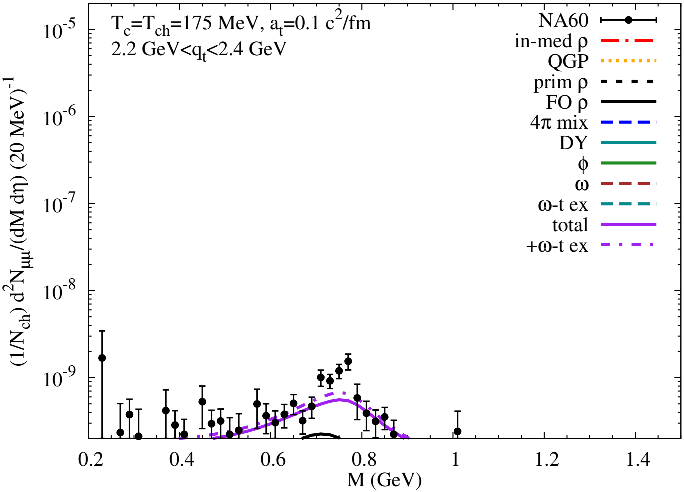
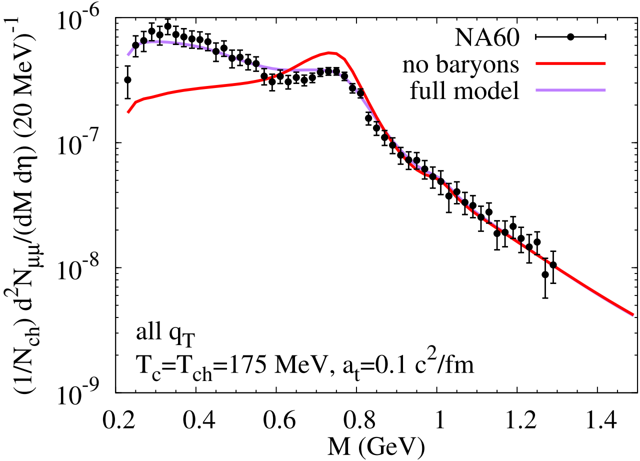
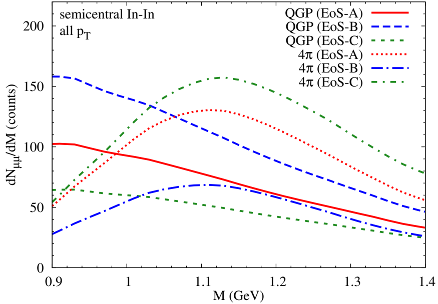


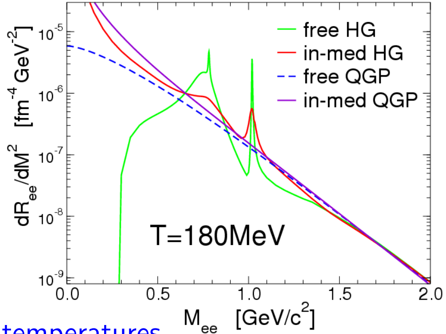
Importance of baryon effects

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



IMR: QGP vs. multi-pion radiation

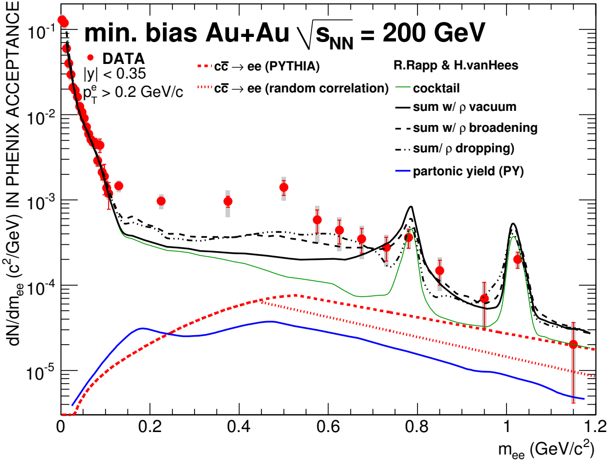




- different critical and freeze-out temperatures
  $T_c = 160 \ldots 190$ MeV, $T_{\text{chem}} = 160 \ldots 175$ MeV
- M- and p_T spectra comparably well described!
- reason: T vs. volume $\Rightarrow$ maximal $l^+ l^-$ emission for
  $T = T_{\max} = M/5.5$
- hadronic and partonic radiation "dual" for $T \sim T_c$
  compatible with chiral-symmetry restoration!
- inconclusive whether hadronic or partonic emission in IMR!

Dileptons@RHIC: (Another) new Puzzle?

- huge enhancement in the LMR unexplained yet!



model: Rapp, HvH

[A. Adare et al (PHENIX), PRC **81**, 034911 (2010)]

Conclusions and Outlook

- dilepton spectra ⇔ in-medium em. current correlator
- SIS energies
  - GiBUU for pp, pn with resonance modell for all HADES energies
  - pn still a problem (work in progress)
  - p Nb, AA work in progress
  - similar study within UrQMD in progress (with S. Endres)
- 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
  - IMR well described by scenarios with radiation dominated either by QGP or multi-pion processes (depending on EoS)
  - "quark-hadron duality" of $\ell^+\ell^-$ rates around T_c
  - compatible with chiral symmetry restoration!
  - new puzzle @ RHIC?!?
  - studies in UrQMD+hydro hybrid model planned (with S. Endres)