The Dilepton Probe
from SIS to RHIC

Hendrik van Hees

Justus-Liebig Universität Gießen

May 13, 2011

Institut für
Theoretische Physik

Outline

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
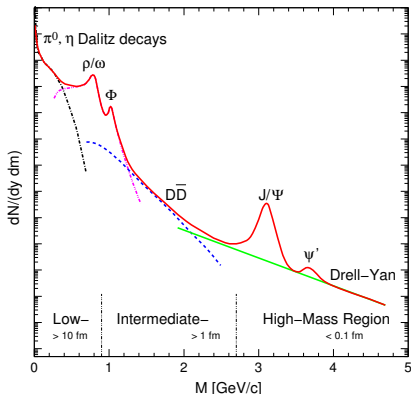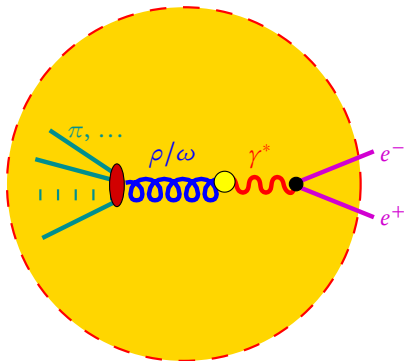 - from VM decays after thermal freezeout

Fig. by A. Drees

Vector Mesons and electromagnetic Probes

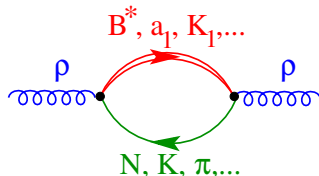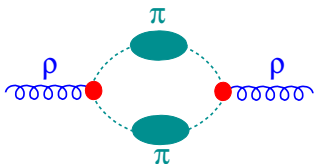- $\ell^+\ell^-$ thermal emission rates $\Leftrightarrow$ em. current-correlation function, $\Pi_{\mu\nu}$

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

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

- vector-meson dominance model:

$$\Pi_{\mu\nu} = \underset{\gamma^*}{\wedge\!\wedge\!\wedge}\!\!\overset{G_\rho}{\underset{}{\circ\!\circ\!\circ\!\circ\!\circ}}\!\!\underset{\gamma^*}{\wedge\!\wedge\!\wedge}$$
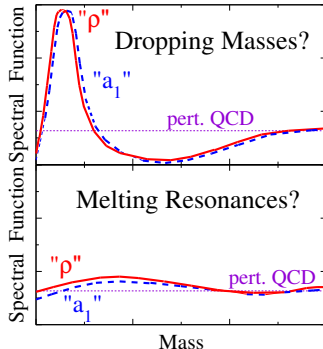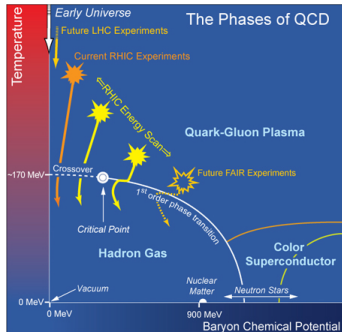
- hadronic many-body theory for vector mesons

- elementary processes $\Leftrightarrow$ cut self-energy diagrams
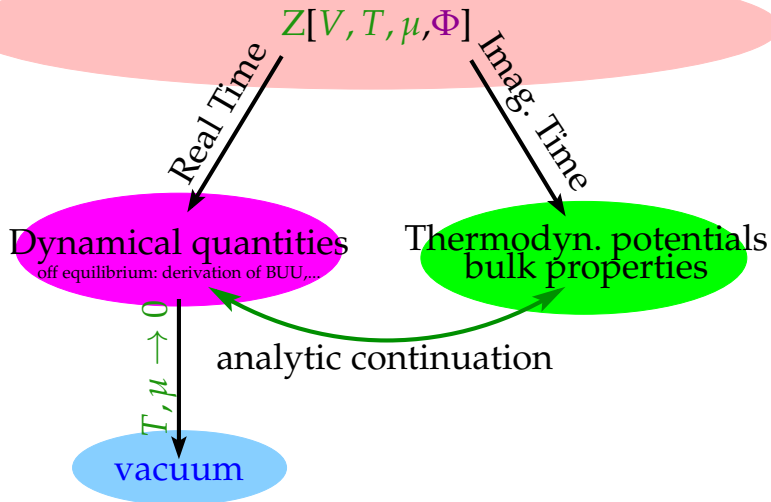
Relation to the QCD-phase diagram

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

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

Finite Temperature/Density: Idealized theory picture

- partition sum: $Z(V, T, \mu_q, \Phi) = \mathrm{Tr}\{\exp[-(\mathbf{H}[\Phi] - \mu_q \mathbf{N})/T]\}$


$$Z[V, T, \mu, \Phi]$$

Real Time

Imag. Time

Dynamical quantities
off equilibrium: derivation of BUU,...

Thermodyn. potentials
bulk properties

$T, \mu \to 0$

analytic continuation

vacuum

[. . .,K. Chou, Z. Su, B. Hao, L. Yu 85, N.P. Landsmann, C.G. van Weert 87, E.A. Calzetta, B. Hu 08, . . .]
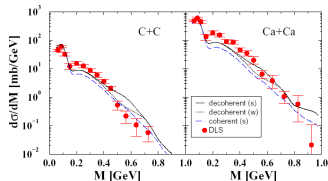
- dileptons from heavy-ion collisions at DLS at $E = 1A\ \mathrm{GeV}$

  [Porter et al, PRL **79**, 1229 (1997)]

- large enhancement at low invariant masses unexplained

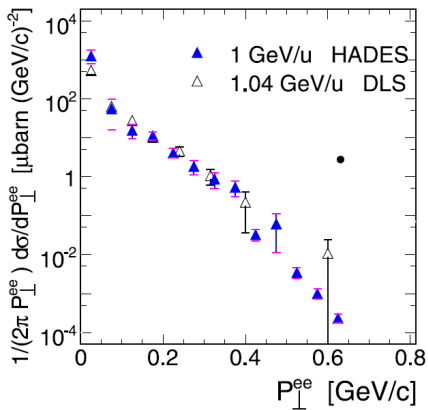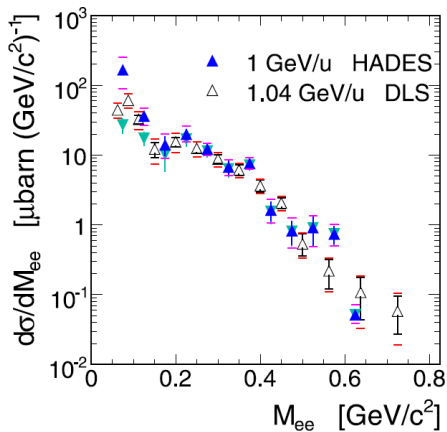- DLS puzzle
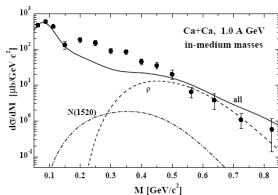
[Bratkovskaya et al (1999)]
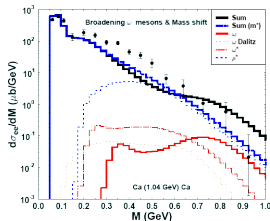
[Ernst et al (1998)]
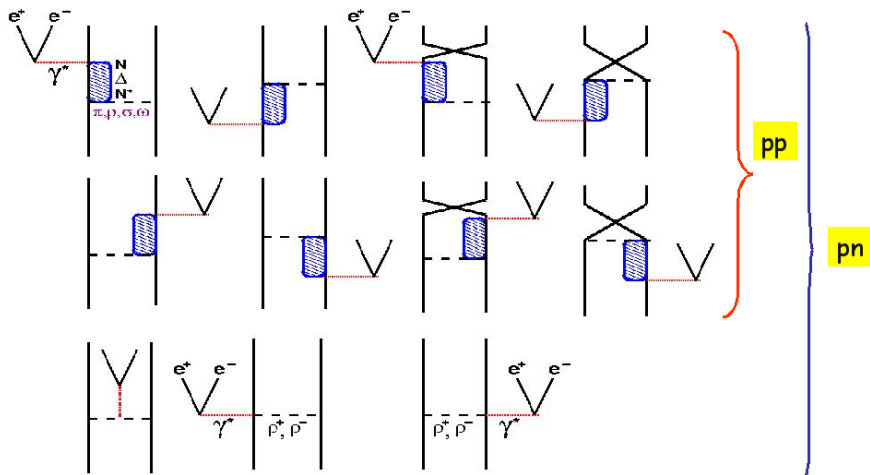
[Fuchs et al (2003)]

Experimental confirmation

- DLS measurement confirmed by HADES at GSI

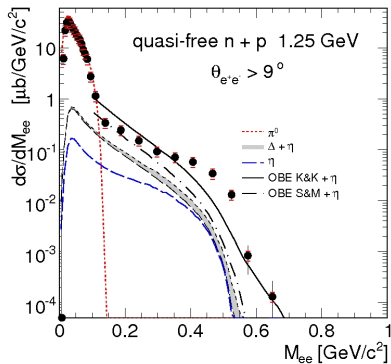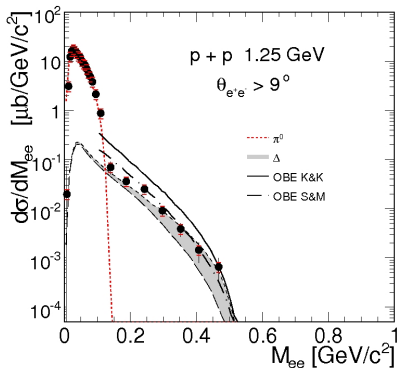[Sudol et al, EPJC **62**, 81 (2009)]

Theoretical "HADES Puzzle"

- one-boson-exchange model by Shyam/Mosel
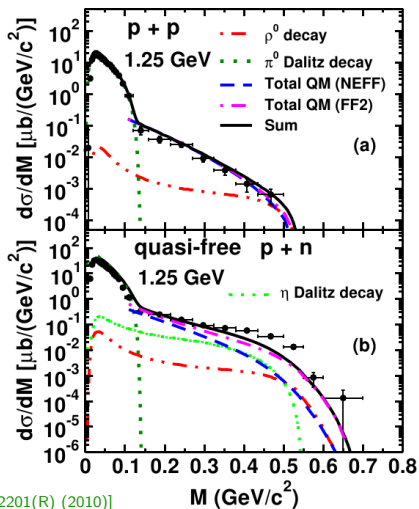- Bremsstrahlung in pp and pn collisions

Theoretical "HADES Puzzle"

- elementary pp- and pn-cross sections
- discrepancy between models (KK vs. SM);
  only difference: pseudo-scalar vs. pseudo-vector couplings
  (should be on-shell equivalent!)
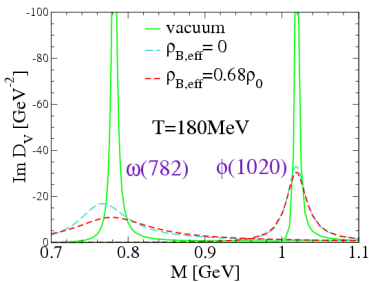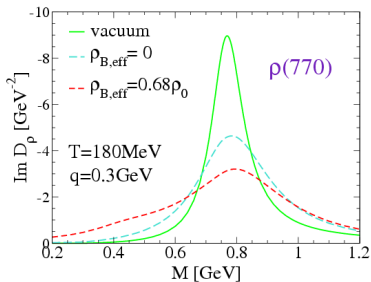- discrepancy of between theory and experiment in pn bremsstrahlung

Most recent update

[R. Shyam, U. Mosel, PRC **82**, 062201(R) (2010)]

- crucial for pn: nucleon- and π-form factors
  (50% VMD+50% direct quarks)

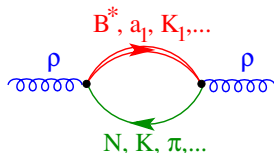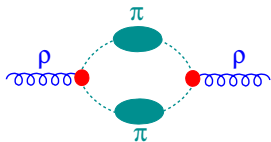 [G. E. Brown, M. Rho, and W. Weise, Nucl. Phys. A 454, 669 (1986)]

Dileptons at SPS and RHIC
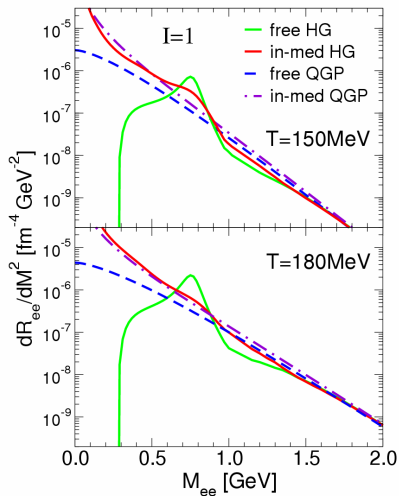
- radiation from thermal sources: Hadronic many-body theory

[R. Rapp, J. Wambach 99]

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

- 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" $\Leftrightarrow$ emission from thermal source [McLerran, Toimela 1985]

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

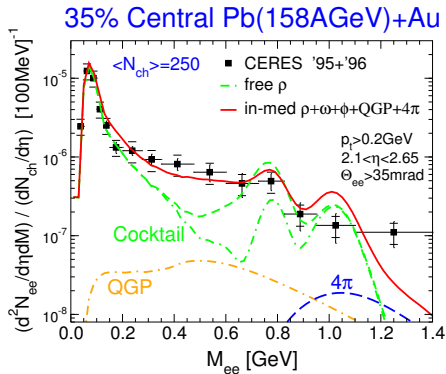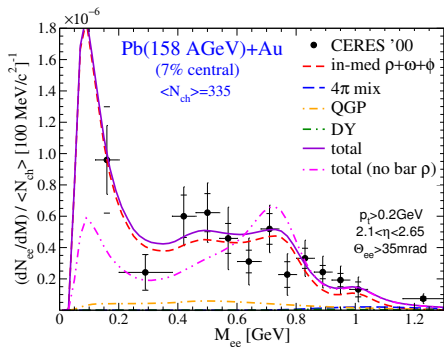   use cylindrical thermal fireball with QGP, mixed and hadronic phase
3. "corona" $\Leftrightarrow$ emission from "primordial" mesons (jet-quenching)
4. after thermal freeze-out $\Leftrightarrow$ emission from "freeze-out" mesons
   [Cooper, Frye 1975]

$$N^{(\text{fo})} = \int \frac{\mathrm{d}^3q}{q_0} \int q_\mu \mathrm{d}\sigma^\mu f_B(u_\mu q^\mu/T)\frac{\Gamma_{\mathsf{meson}\to\ell^+\ell^-}}{\Gamma_{\mathsf{meson}}}\mathsf{Acc}$$
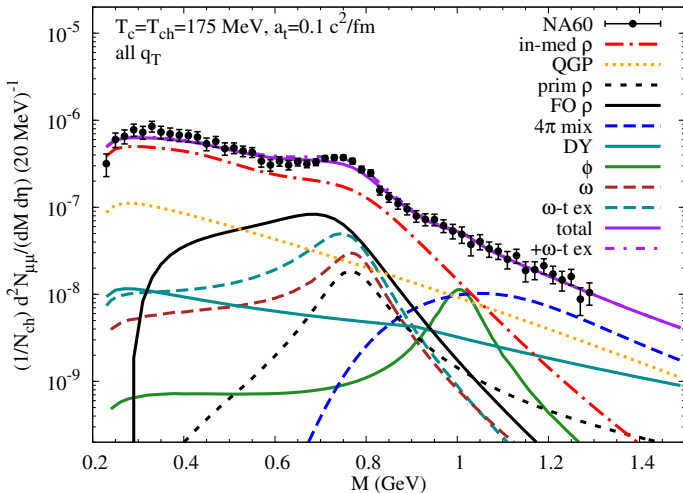
CERES/NA45 dielectron spectra

- 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: $\langle N_{ch} \rangle = 120$, calculation $N_{ch} = 140$)

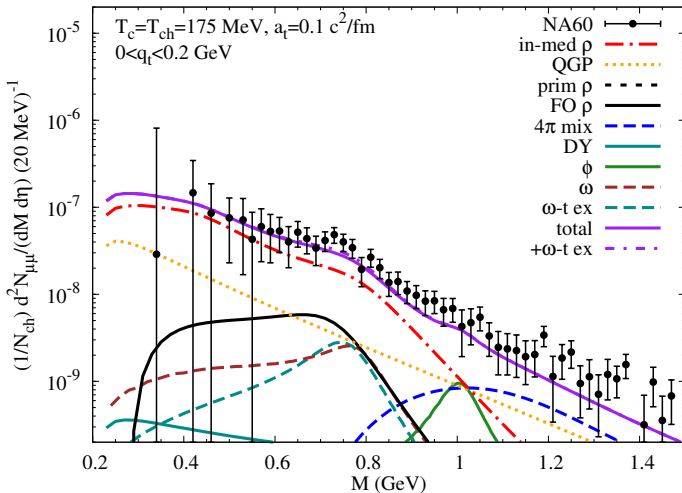# M spectra (in p_T slices)

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

M spectra (in p_T slices)

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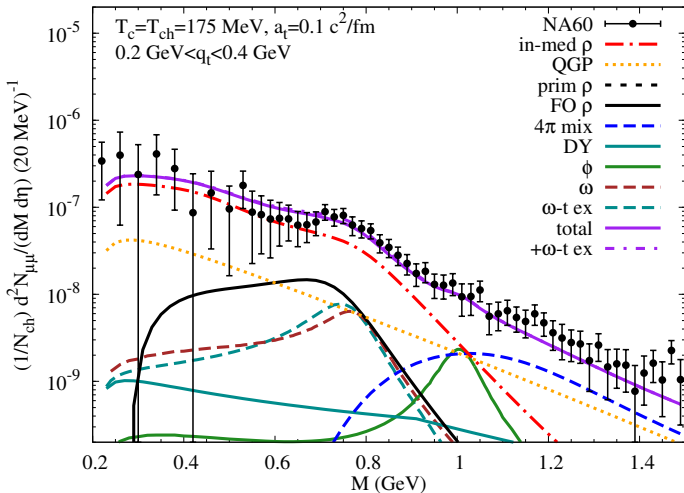 (min-bias data: $\langle N_{ch} \rangle = 120$, calculation $N_{ch} = 140$)

M spectra (in p_T slices)

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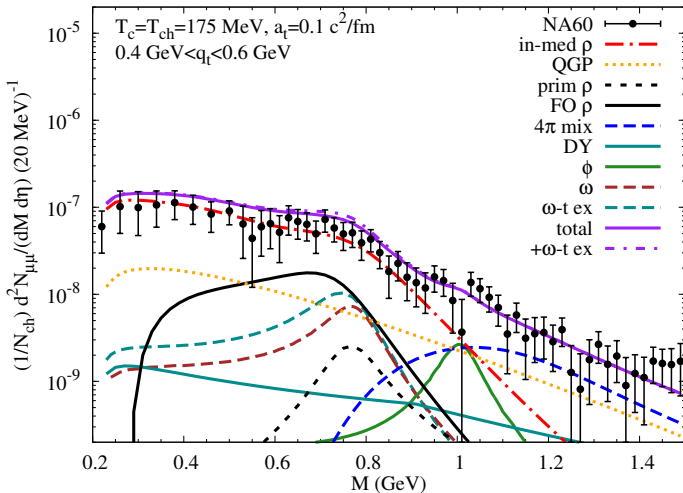 (min-bias data: $\langle N_{ch} \rangle = 120$, calculation $N_{ch} = 140$)

M spectra (in p_T slices)

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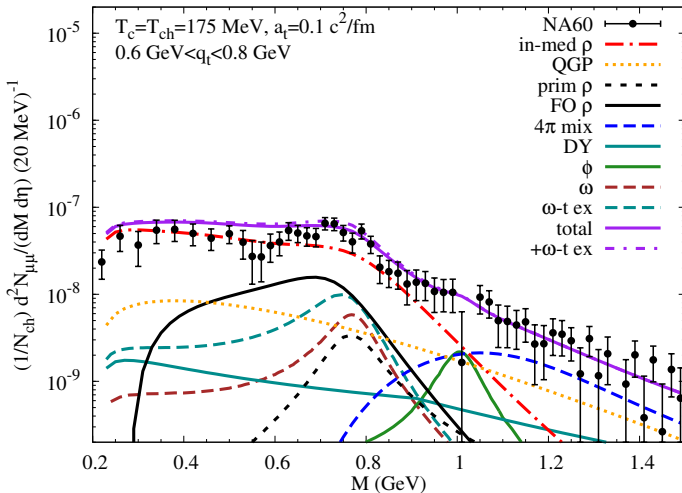 (min-bias data: $\langle N_{ch} \rangle = 120$, calculation $N_{ch} = 140$)

M spectra (in p_T slices)

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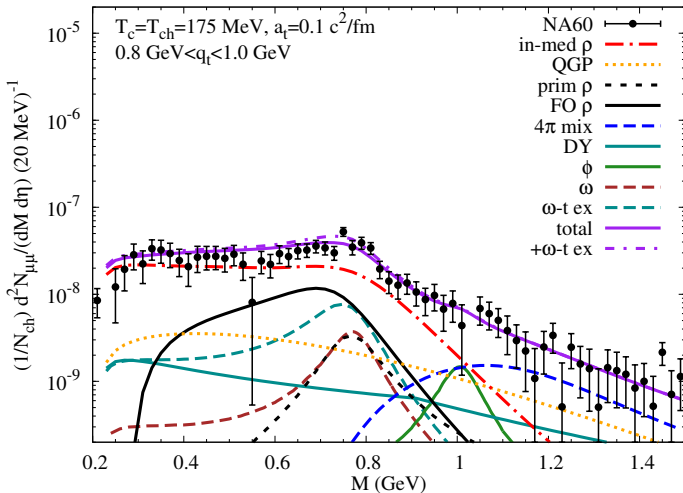 (min-bias data: $\langle N_{ch} \rangle = 120$, calculation $N_{ch} = 140$)

M spectra (in p_T slices)

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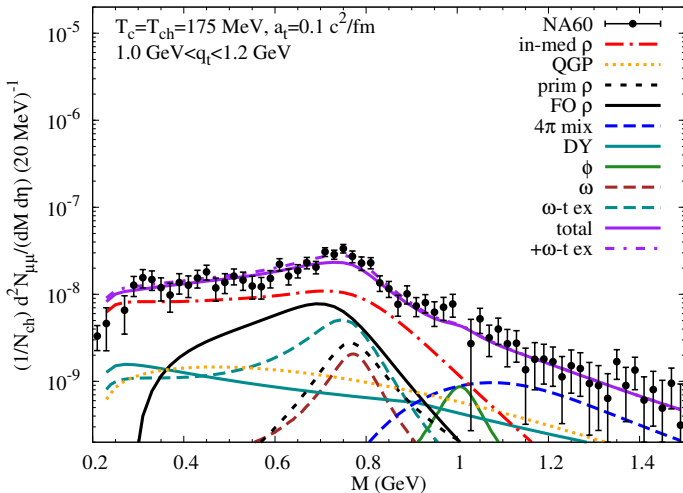 (min-bias data: $\langle N_{ch} \rangle = 120$, calculation $N_{ch} = 140$)

M spectra (in p_T slices)

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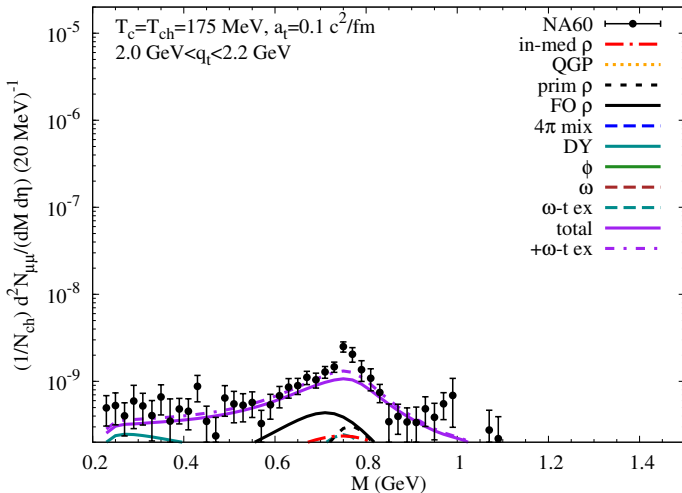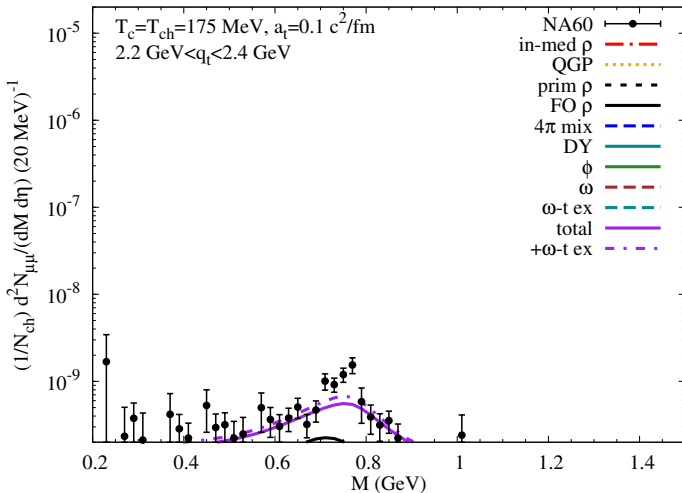 (min-bias data: $\langle N_{ch} \rangle = 120$, calculation $N_{ch} = 140$)

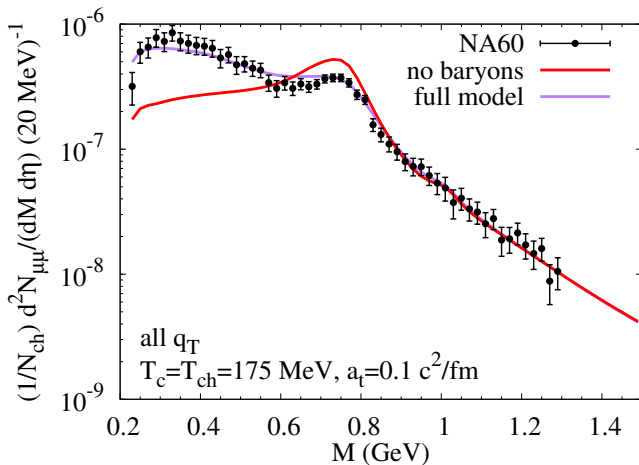# M spectra (in p_T slices)

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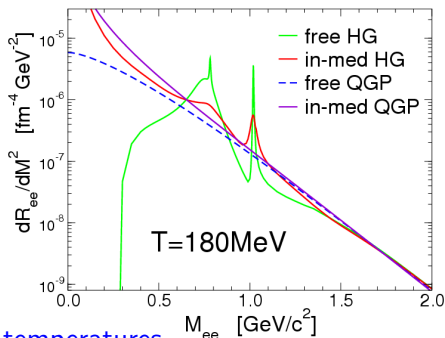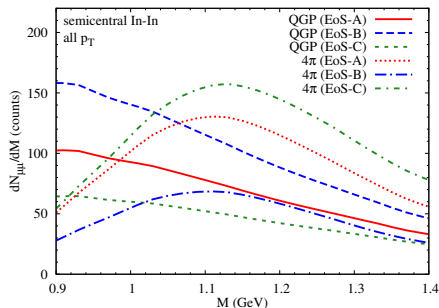 (min-bias data: $\langle N_{ch} \rangle = 120$, calculation $N_{ch} = 140$)

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
  $T_c = 160 \dots 190$ MeV, $T_{\text{chem}} = 160 \dots 175$ MeV
- M- and p_T spectra comparably well described!
- reason: T vs. volume $\Rightarrow$ maximal l^+l^- emission for
  $T = T_{\text{max}} = M/5.5$
- 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?

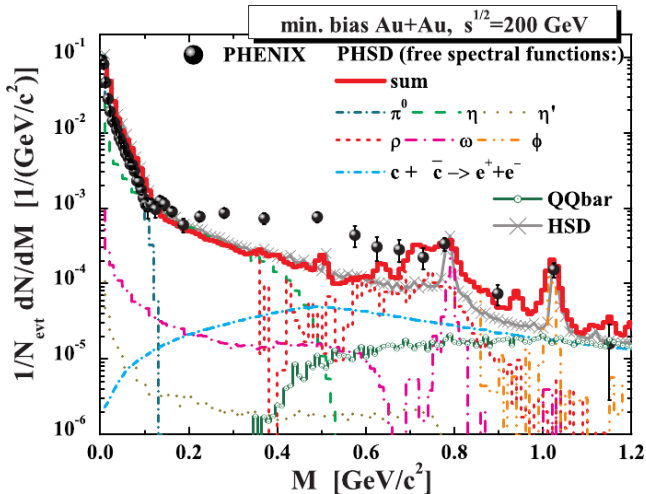- huge enhancement in the LMR unexplained yet!
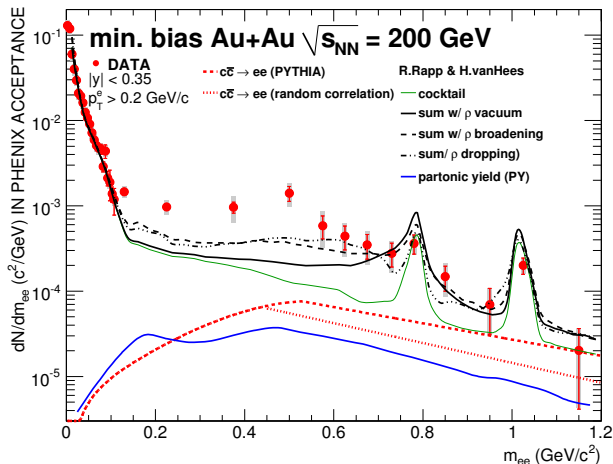
model: Rapp, HvH
[A. Adare et al (PHENIX), PRC **81**, 034911 (2010)]

Dileptons@RHIC: (Another) new Puzzle?

- huge enhancement in the LMR unexplained yet!

model: PHSD
[O. Linnyk, W. Cassing, E.L. Bratkovskaya, J. Manninen, NPA **855**, 273 (2011)]

Conclusions and Outlook

- dilepton spectra ⇔ in-medium em. current correlator
- SIS energies
  - dominated by bremsstrahlung and Dalitz decays
  - puzzle in OBE models (pp vs. pn)?
  - nucleon/π form factors important bremsstrahlung
- 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?!?
  - recent review:
    R. Rapp, J. Wambach, HvH, Landolt-Börnstein, 1-23A
    arXiv: 0901.3289 [hep-ph]