Electromagnetic Spectra at the CERN-SPS
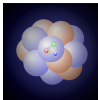
Hendrik van Hees

Justus-Liebig Universität Gießen

September 15, 2010

Institut für Theoretische Physik

JUSTUS-LIEBIG-
UNIVERSITÄT
GIESSEN

Outline

1. Electromagnetic probes in heavy-ion collisions
   - Vector mesons and electromagnetic probes
   - Model approaches to dileptons in heavy-ion collisions
   - Sources of dilepton emission in heavy-ion collisions

2. Comparison to data
   - Invariant-mass spectra
   - m_T spectra

3. 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
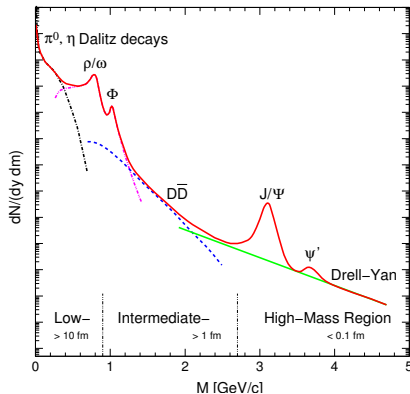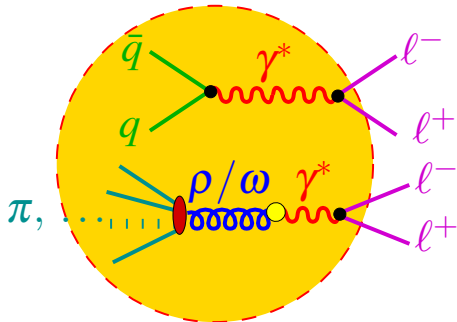 - from VM decays after thermal freezeout

Fig. by A. Drees

Vector Mesons and electromagnetic Probes

- photon and dilepton thermal emission rates given by same electromagnetic-current-correlation function ($J_\mu = \sum_f Q_f \bar{\psi}_f \gamma_\mu \psi_f$)

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

$$\Pi^<_{\mu\nu}(q) = \int \mathrm{d}^4x \exp(\mathrm{i}q \cdot x) \langle J_\mu(0) J_\nu(x) \rangle_T = -2 f_B(q_0) \operatorname{Im} \Pi^{(\mathrm{ret})}_{\mu\nu}(q)$$

$$q_0 \frac{\mathrm{d}N_\gamma}{\mathrm{d}^4x \mathrm{d}^3\vec{q}} = \frac{\alpha}{2\pi^2} g^{\mu\nu} \operatorname{Im} \Pi^{(\mathrm{ret})}_{\mu\nu}(q) \Big|_{q_0=|\vec{q}|} f_B(q_0)$$

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

- to lowest order in α: $e^2 \Pi_{\mu\nu} \simeq \Sigma^{(\gamma)}_{\mu\nu}$
- vector-meson dominance model:

$$\Sigma^\gamma_{\mu\nu} = \overset{G_\rho}{\text{〰〰●⦿⦿⦿⦿⦿●〰〰}}$$

- derivable from partition sum $Z(V, T, \mu, \Phi)$!

Hadronic many-body theory

- HMBT for vector mesons [Ko et al, Chanfray et al, Herrmann et al, Rapp et al, . . .]
- $\pi\pi$ interactions and baryonic excitations
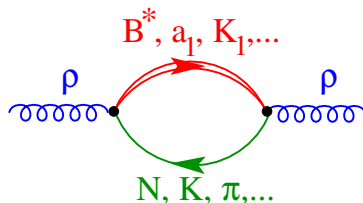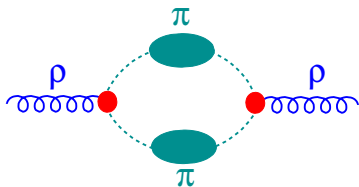
- +corresponding vertex corrections $\Leftrightarrow$ gauge invariance
- Baryon (resonances) important, even at RHIC with low **net** baryon density $n_B - n_{\bar{B}}$
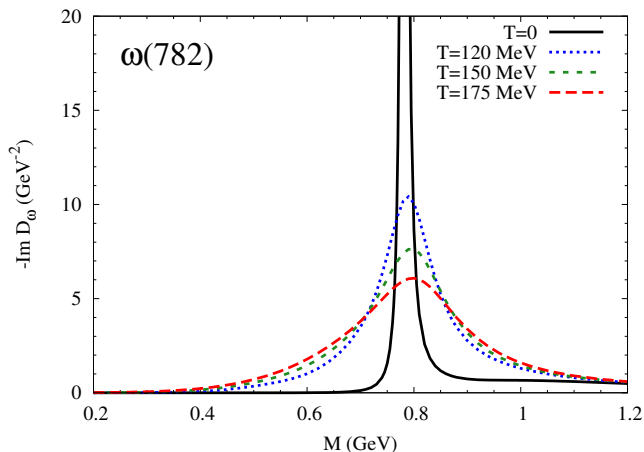- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

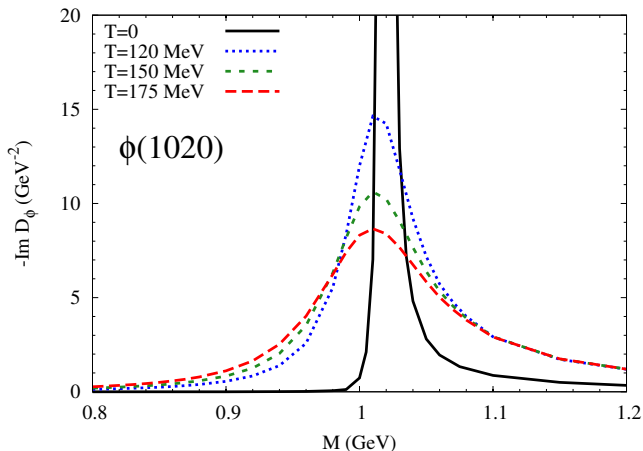# In-medium spectral functions and baryon effects
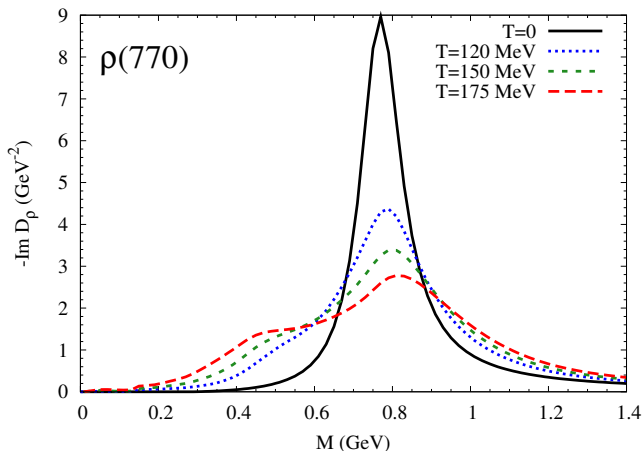
[R. Rapp, J. Wambach 99]

- baryon effects important
  - large contribution to broadening of the peak
  - responsible for most of the strength at small M

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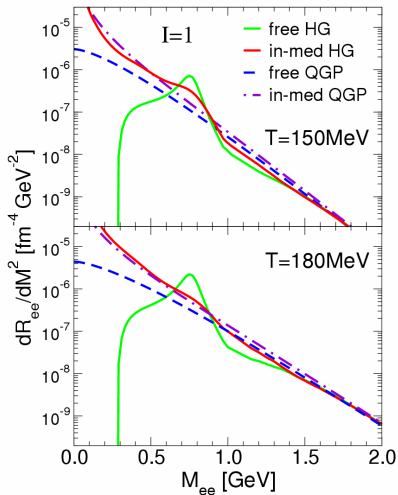 - responsible for most of the strength at small M

In-medium spectral functions and baryon effects
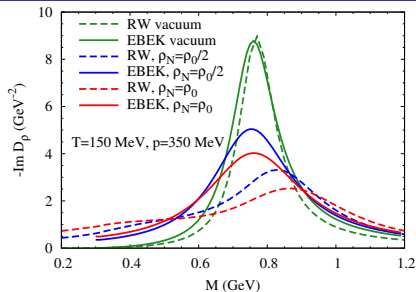
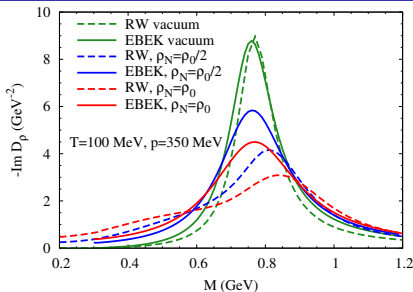

[R. Rapp, J. Wambach 99]

- baryon effects important
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  - responsible for most of the strength at small M

Dilepton rates: Hadron gas ↔ QGP

- in-medium hadron gas matches with QGP
- similar results also for γ rates
- "quark-hadron duality"!?
- indirect evidence for chiral-symmetry restoration

ρ meson in hot hadronic matter

- **EBEK:** [Eletsky, Belkacem, Ellis, Kapusta 01]
  - empirical $\rho + B/M$ scattering amplitudes
    $+$ Pomeron/Regge background
  - $T\rho$ approximation for finite-T effects
- **RW:** Hadronic many-body theory [Rapp, Wambach 99]
- **Somewhat different results**
  - more broadening and level repulsion:
    in-med modifications of pion-cloud $+ \rho BN$ interactions

Chiral approaches

- Chiral reduction formalism [Steele et al 96]
  - leading order in π and N density + chiral reduction formulas
  - $\Rightarrow$ in-medium current correlators in terms of vacuum correlators
  - no Dyson resummation!
- Hidden local symmetry [Bando et al 85; Harada, Yamawaki 01,...]
  - Vector manifestation of chiral symmetry: ρ_{long} chiral partner of π
  - $\Rightarrow$ dropping ρ mass + violation of vector dominance ($T > T_{\text{flash}} = 0.7 T_c$)
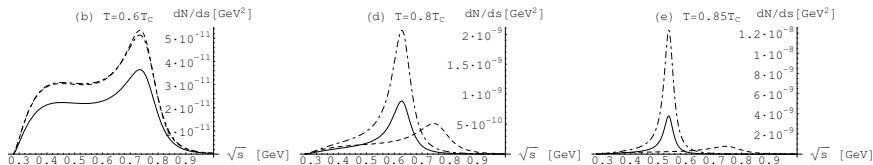
[Harada, Sasaki 07]

- dilepton rates similar to more simple dropping mass models

Sources of dilepton emission in heavy-ion collisions

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

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

3. **"corona"** $\Leftrightarrow$ **emission from "primordial" mesons** (jet-quenching)
4. **after thermal freeze-out** $\Leftrightarrow$ **emission from "freeze-out" mesons**
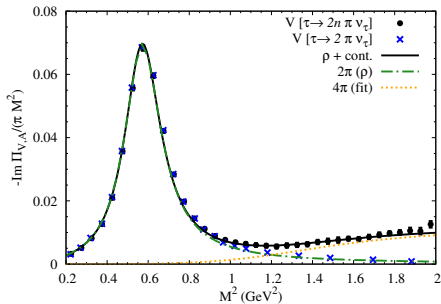   [Cooper, Frye 1975]

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

- additional factor $\gamma = q_0/M$ compared to thermal emission
- physical reason
  - thermal source rate $\propto \tau_{\mathsf{med}}\frac{\Gamma_{\mathsf{meson}\to\ell^+\ell^-}}{\gamma}$
  - decay of mesons after fo: rate $\propto \frac{\Gamma_{\mathsf{meson}\to\ell^+\ell^-}}{\Gamma_{\mathsf{meson}}}$

Intermediate masses: hadronic "4π contributions"

- e.m. current-current correlator $\Leftrightarrow \tau \to 2n\pi$
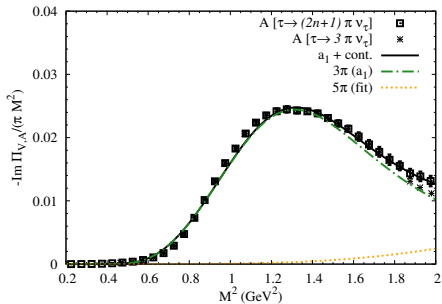
- "4π contributions": $\pi + \omega, a_1 \to \mu^+ + \mu^-$
- leading-order virial expansion for "four-pion piece"
- additional strength through "chiral mixing"

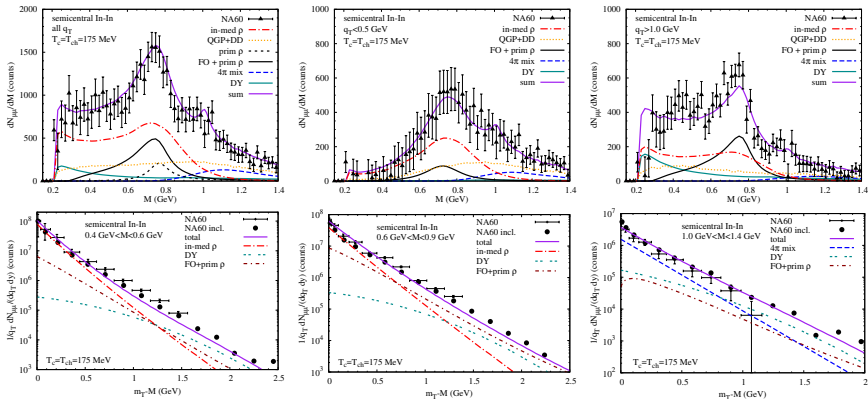# Radiation from thermal sources: Meson t-channel exchange

- motivation: q_T spectra too soft compared to NA60 data
- thermal contributions not included in models so far
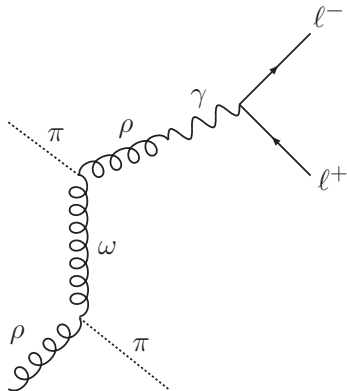
- also for π, a_1

NA60 vs. Hadronic many-body theory + HR fireball

- ρ, ω, ϕ multi-π, QGP, freeze-out+primordial ρ, Drell-Yan

[HvH, Rapp 07]

- M spectra
  - consistent with predicted broadening of ρ meson
  - $M < 1$GeV: thermal ρ; $M > 1$ GeV: thermal multi-pion processes
- m_t spectra
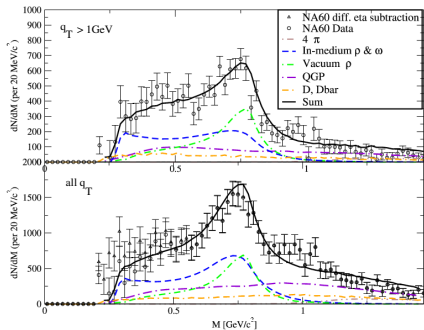 - $q_t < 1$ GeV: thermal radiation
  - $q_t > 1$ GeV: freeze-out + hard primordial ρ, Drell-Yan

[Dusling, Teaney, Zahed 07]

- low-mass + IMR spectrum described
- ρ: lack of broadening (due to low-density approximation)
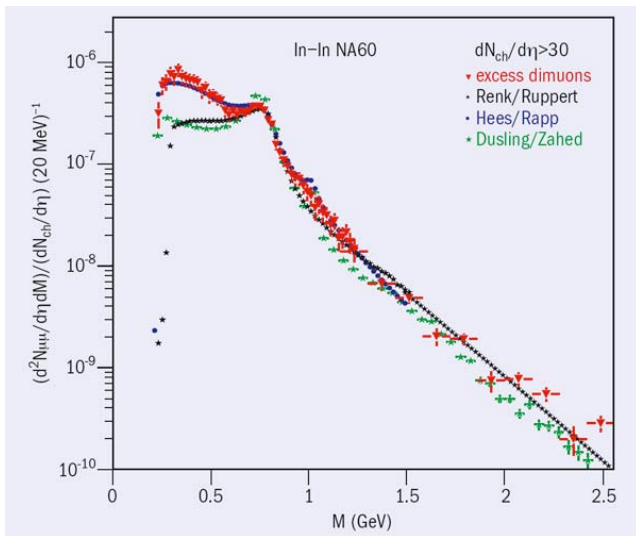- q_T spectra: only thermal + freezeout, no primordial ρ
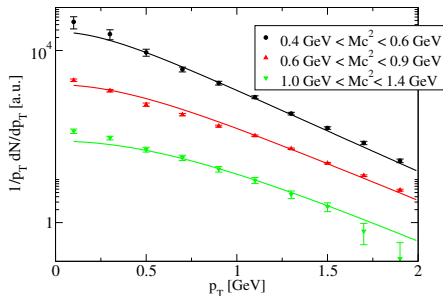
[Ruppert et al 07]

- only thermal + freeze-out

- large QGP contribution
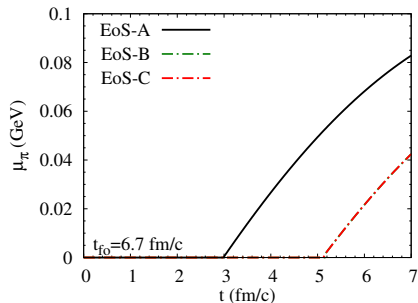
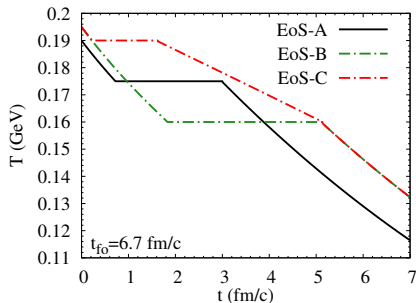- sensitivity of spectral functions to data?!

# Excess spectra: acceptance-corrected mass spectra

[J. Ruppert, T. Renk et al 2008], [HvH, R. Rapp 2008], [K. Dusling, D. Teaney, I. Zahed 2007]

Sensitivity to T_c and hadro-chemistry

- recent lattice QCD: $T_c \simeq 190\text{-}200$ MeV or $T_c \simeq 150\text{-}160$ MeV?
- thermal-model fits to hadron ratios: $T_{\mathrm{chem}} \simeq 150\text{-}160$ MeV

- EoS-A: $T_c = T_{\mathrm{chem}} = 175$ MeV
- EoS-B: $T_c = T_{\mathrm{chem}} = 160$ MeV
- EoS-C: $T_c = 190$ MeV, $T_{\mathrm{chem}} = 160$ MeV
  - $T_c \geq T \geq T_{\mathrm{chem}}$: hadron gas in chemical equilibrium
- keep fireball parameters the same (including life time)

EoS-B
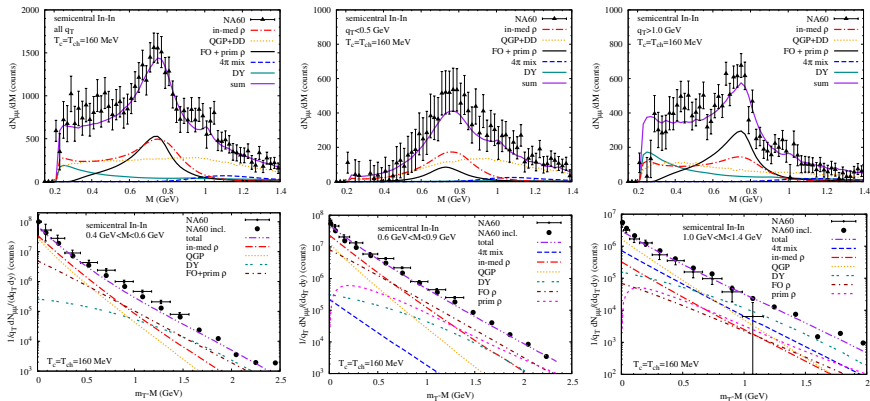
- mass spectra comparable to EoS-A $\leftrightarrow$ slight enhancement of fireball lifetime
- in IMR QGP $>$ multi-pion contribution
- higher hadronic temperatures $\Rightarrow$ slightly harder q_T spectra
- not enough to resolve discrepancy with data

EoS-C
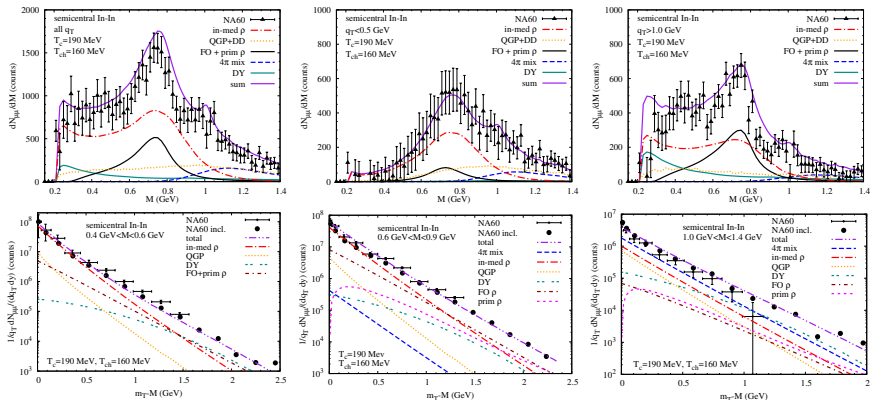
- mass spectra comparable to EoS-A $\leftrightarrow$ slight reduction of fireball lifetime
- in IMR multi-pion $\gg$ QGP contribution
- higher hadronic temperatures + high-density hadronic phase $\Rightarrow$ harder q_T spectra
- better agreement with data

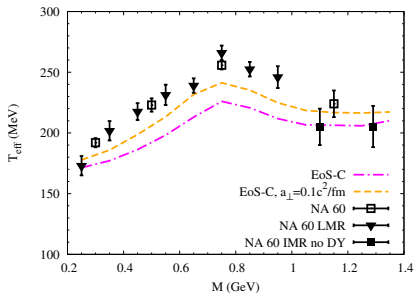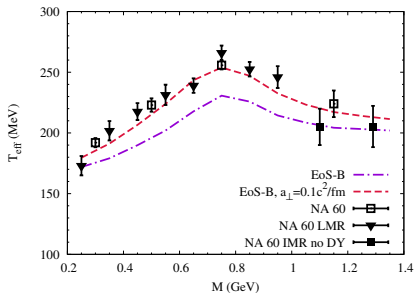# Inverse-slope analysis

- to extract T_{eff} fit to
$$\frac{1}{q_T}\frac{dN}{dq_T} = \frac{1}{m_T}\frac{dN}{dm_T} = C\exp\left(-\frac{m_T}{T_{\text{eff}}}\right)$$

- fit of theoretical q_T spectra: $1\text{ GeV} < q_T < 1.8\text{ GeV}$
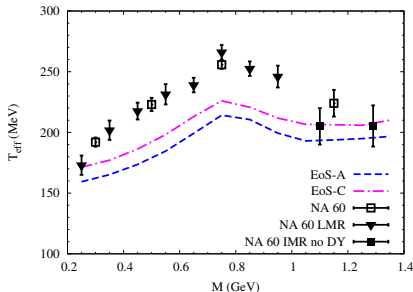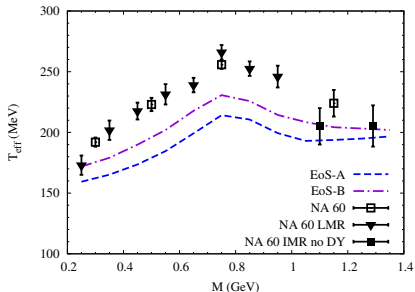
- standard fireball acceleration: too soft q_T spectra
- lower T_c in EoS-B and EoS-C helps (higher hadronic temperatures)
- NB: here, Drell Yan contribution taken out

Inverse-slope analysis

- enhance fireball acceleration to $a_\perp = 0.1c^2/\text{fm}$
- effective at all stages of fireball evolution
- agreement in IMR not spoiled $\Leftrightarrow$ dominated from earlier stages
- EoS-B harder $\Leftrightarrow$ relative contribution of harder freezeout ρ decays vs. thermal ρ's larger

Inverse-slope analysis
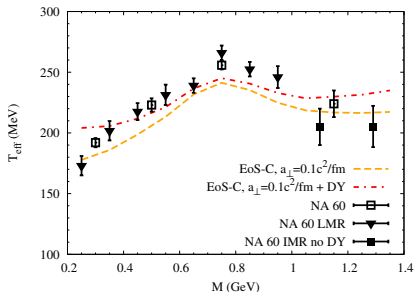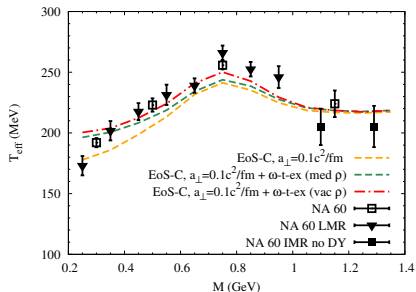
- sensitivity to contributions from meson t-channel exchange
  - hardens low-mass region
  - using vacuum ρ in t-channel contribution: enhances slope in ρ region
- sensitivity to Drell-Yan contribution
  - for IMR: describes effect seen in data (open vs. solid square data point)
  - in LMR: too high around muon threshold $\Leftrightarrow$
    due to uncertainties in extrapolation to low M?!?

IMR: QGP vs. multi-pion radiation
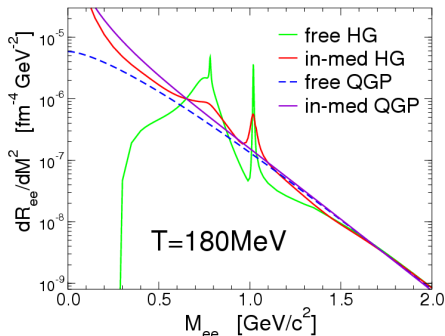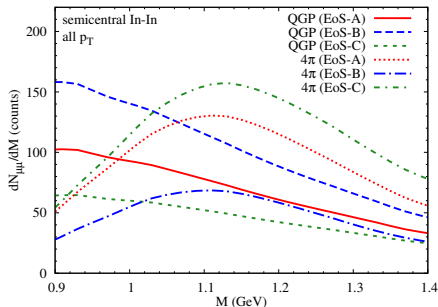
- EoS-B: QGP dominates over multi-pion radiation
- opposite in EoS-A and EoS-C
- multi-pion radiation dominantly from high-density hadronic phase

    reason: $\mathrm{d}N_{ll}/\mathrm{d}M\mathrm{d}T \propto \mathrm{Im}\,\Pi_{\mathrm{em}}(M,T)\ \exp(-M/T)\ T^{-5.5}$

- radiation maximal for $T = T_{\mathrm{max}} = M/5.5$
- hadronic and partonic radiation "dual" for $T \sim T_c$
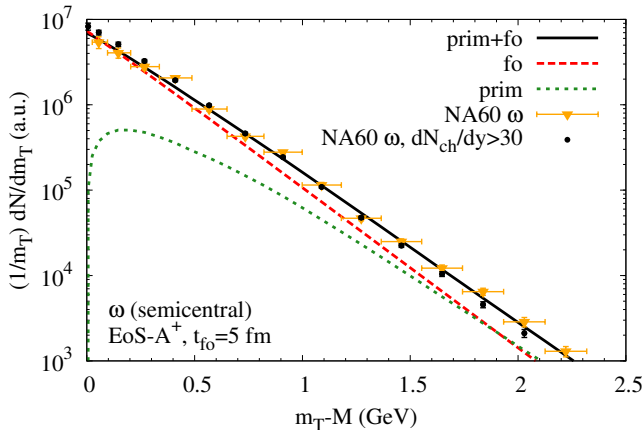 compatible with chiral-symmetry restoration!

Hadron spectra

- analysis of "cocktail": hadron-m_T spectra
- comparison to fireball evolution
- "sequential freeze-out" due to different coupling strength
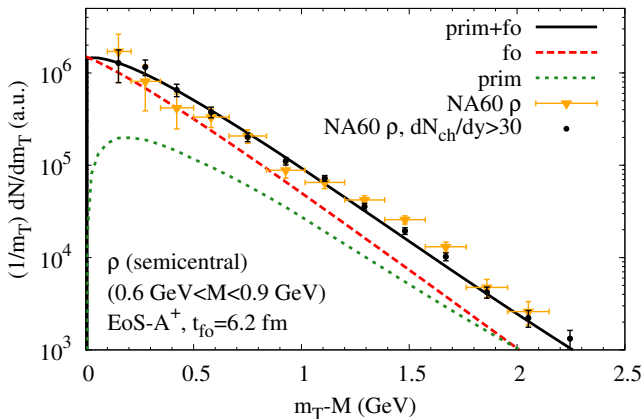
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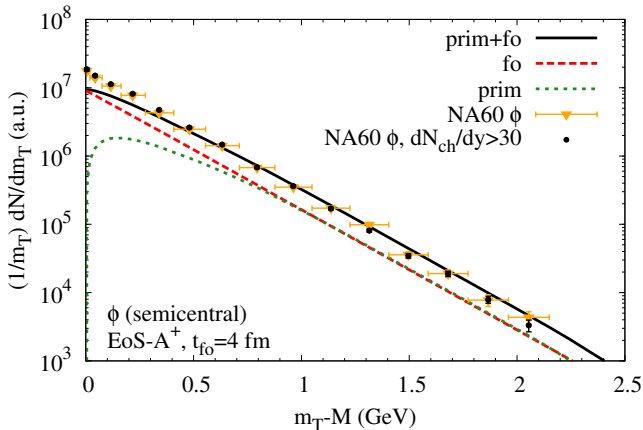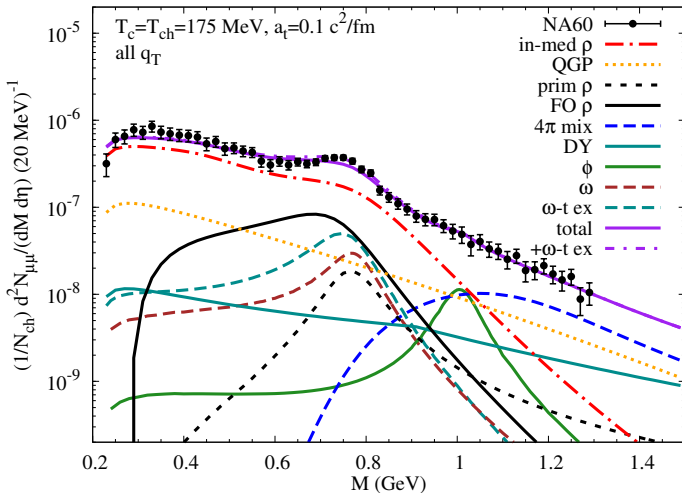- "sequential freeze-out" due to different coupling strength

Hadron spectra

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- comparison to fireball evolution
- "sequential freeze-out" due to different coupling strength

M spectra (in p_T slices)

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

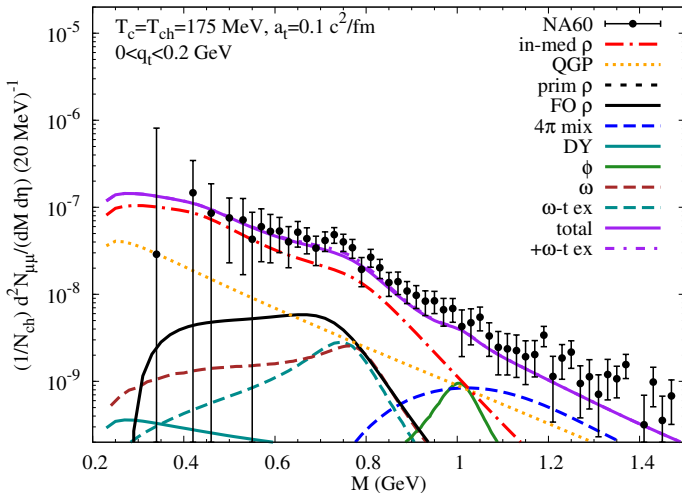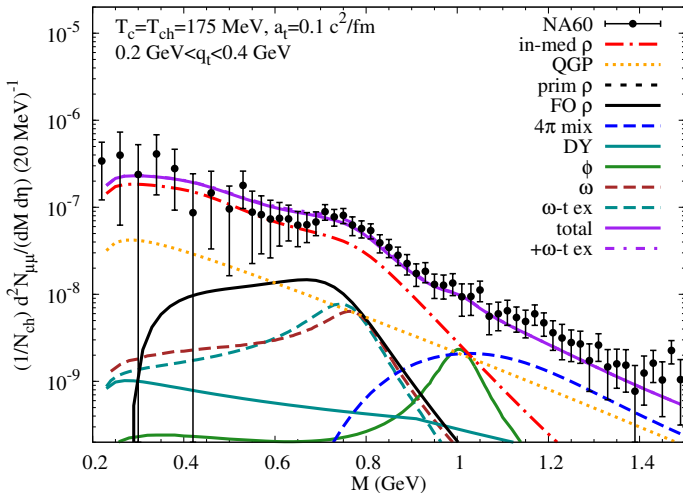# M spectra (in p_T slices)

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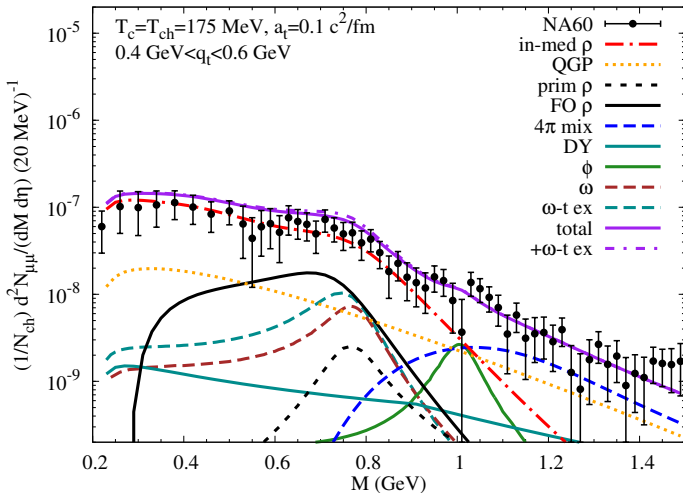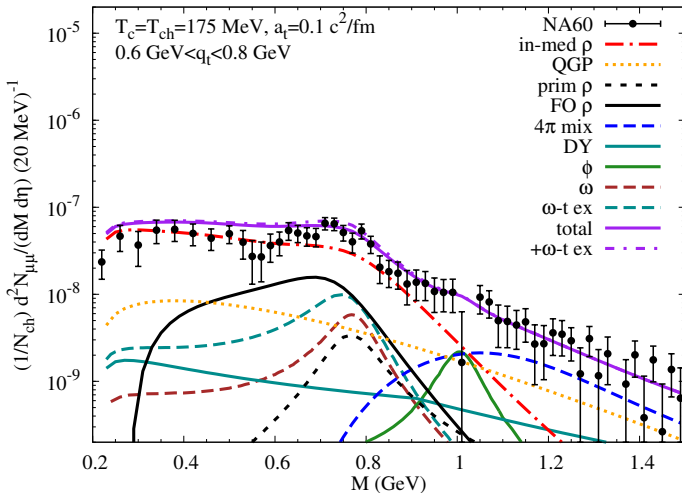
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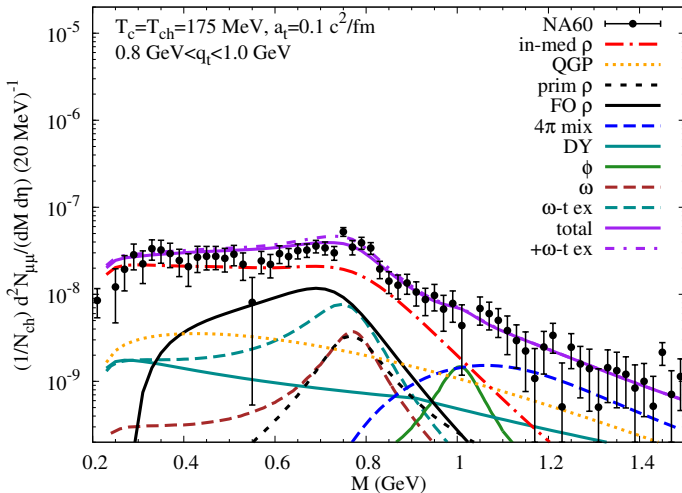
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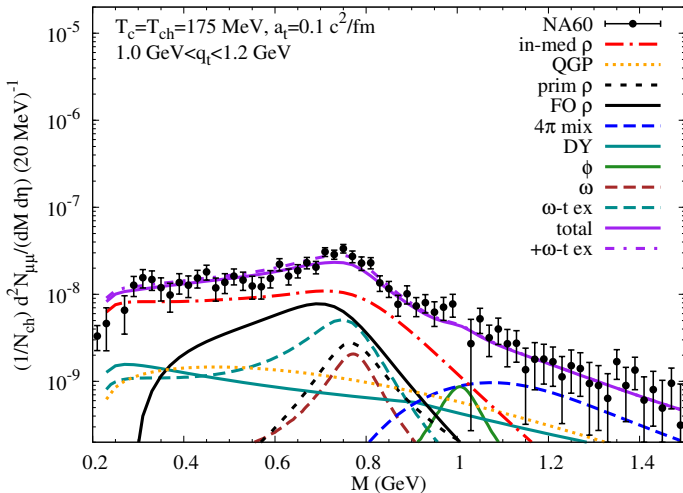# M spectra (in p_T slices)

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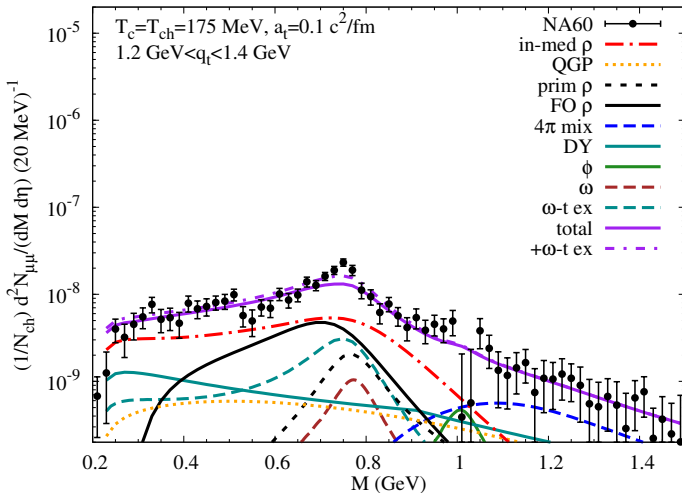 (min-bias data: $\langle N_{ch} \rangle = 120$, calculation $N_{ch} = 140$)

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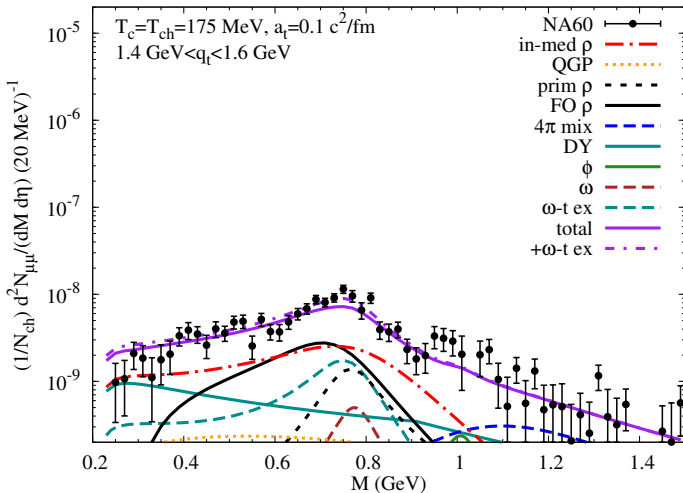 (min-bias data: $\langle N_{ch} \rangle = 120$, calculation $N_{ch} = 140$)

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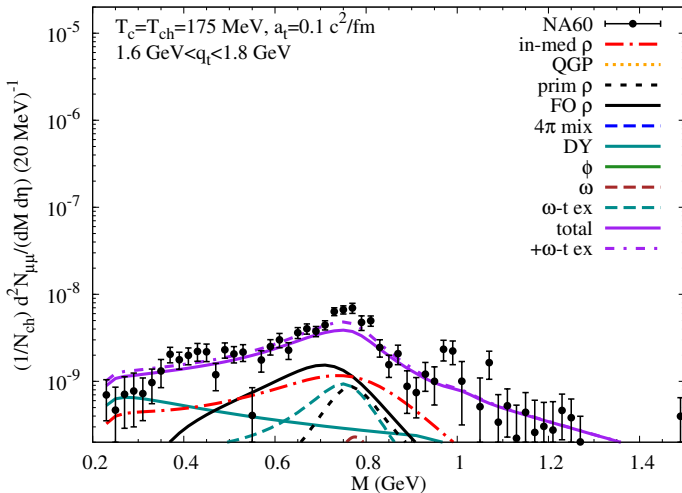 (min-bias data: $\langle N_{ch} \rangle = 120$, calculation $N_{ch} = 140$)

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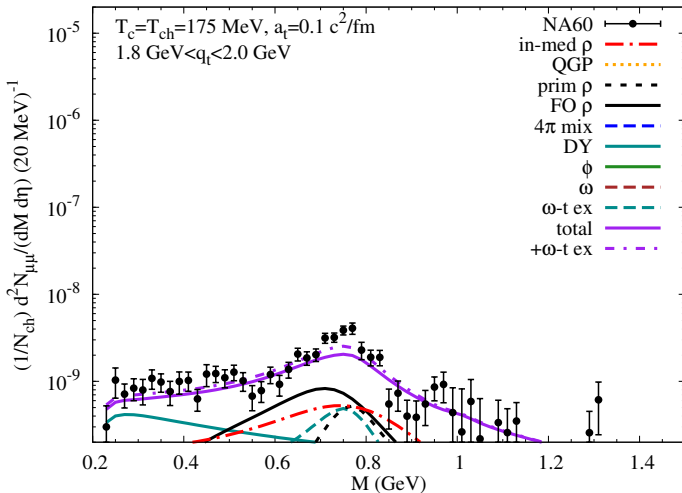 (min-bias data: $\langle N_{ch} \rangle = 120$, calculation $N_{ch} = 140$)

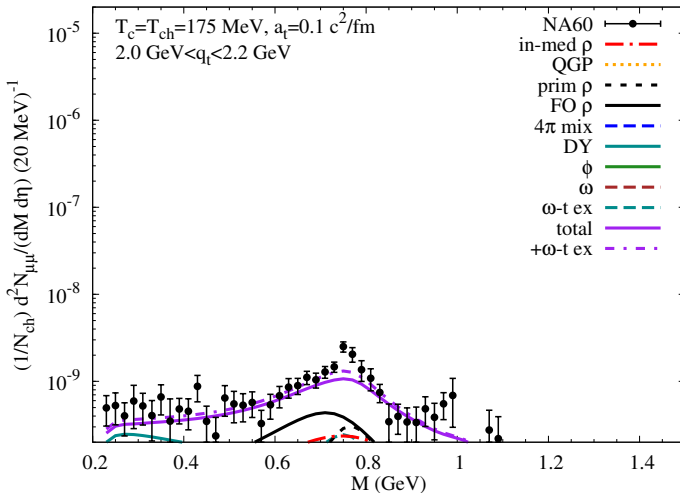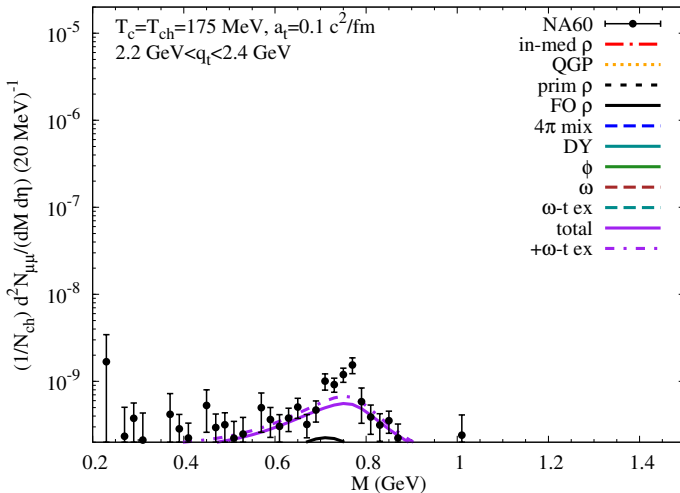# M spectra (in p_T slices)

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Importance of baryon effects

- Baryonic interactions important!
- in-medium broadening
- low-mass tail!
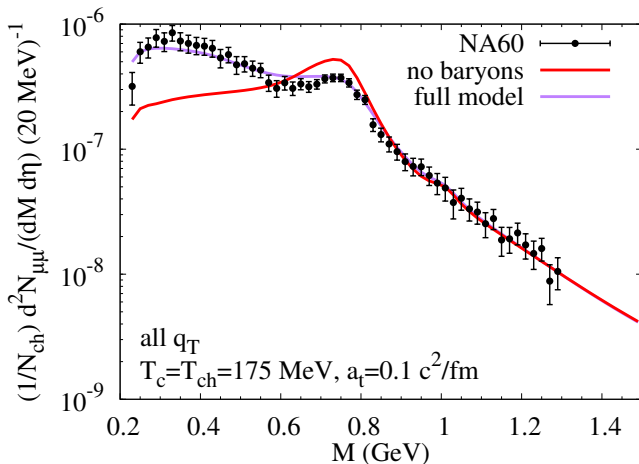
Dileptons@RHIC: New Puzzle?

- huge enhancement in the LMR unexplained yet!
- for details see previous talk!

QGP+HMBT: R. Rapp, HvH

[A. Adare et al (PHENIX), arXiv:0912.0244 [nucl-ex]]

HSD: Linnyk, Bratkovskaya, Cassing

[E. L. Bratkovskaya, O. Linnyk, W. Cassing, J. Phys. Conf.Ser. **230**, 012032 (2010)]

Conclusions and Outlook

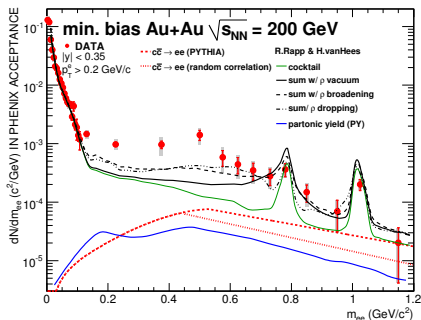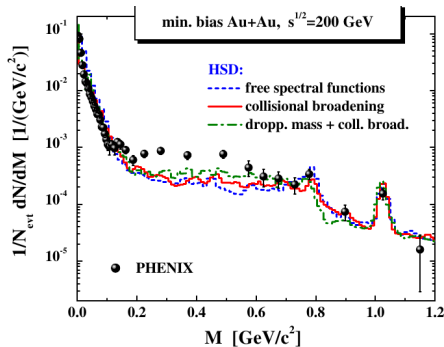- dilepton spectra $\Leftrightarrow$ in-medium em. current correlator
- models for dilepton sources
  - radiation from thermal sources: QGP, ρ, ω, ϕ
  - ρ-decay after thermal freeze-out
  - decays of non-thermalized primordial ρ's
  - Drell-Yan annihilation, correlated $D\bar{D}$ decays
- invariant-mass spectra and medium effects
  - excess yield dominated by radiation from thermal sources
  - baryons essential for in-medium properties of vector mesons
  - melting ρ with little mass shift robust signal! (independent of T_c)
  - IMR well described by scenarios with radiation dominated either by QGP or multi-pion processes (depending on EoS)
    - Reason: mostly from thermal radiation around
      $160 \text{ MeV} \leq T \leq 190 \text{ MeV}$
      $\Leftrightarrow$ "parton-hadron" duality of rates
      $\Leftrightarrow$ compatible with chiral-symmetry restoration!
  - dimuons in In-In (NA60), Pb-Au (CERES/NA45), γ in Pb-Pb (WA98)

Conclusions and Outlook

- fireball/freeze-out dynamics $\Leftrightarrow m_T$ spectra and effective slopes
  - "non-thermal sources" important for $q_T \gtrsim 1 \text{ GeV}$
  - lower $T_c \Rightarrow$ higher hadronic temperatures $\Rightarrow$ harder q_T spectra
  - off-equilibrium effects (viscous hydro)?

- recent review: [R. Rapp, J. Wambach, HvH, Landolt-Brnstein, 1-23A, arXiv: 0901.3289 [hep-ph]]

- Further developments
  - understand recent PHENIX results (large dilepton excess in LMR)
  - vector- should be complemented with axial-vector-spectral functions (a_1 as chiral partner of ρ)
  - constrained with lQCD via in-medium Weinberg chiral sum rules
  - direct connection to chiral phase transition!