Electromagnetic Probes in Ultrarelativistic Heavy-Ion Collisions

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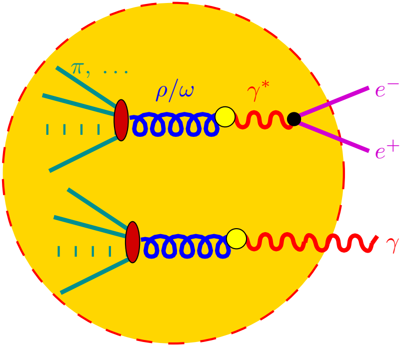
Outline

1. Electromagnetic probes in heavy-ion collisions
   - Vector mesons and electromagnetic probes
   - Sources of dileptons
2. Comparison data (SPS+RHIC)
   - Invariant-mass spectra
   - m_T spectra and slope analysis
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



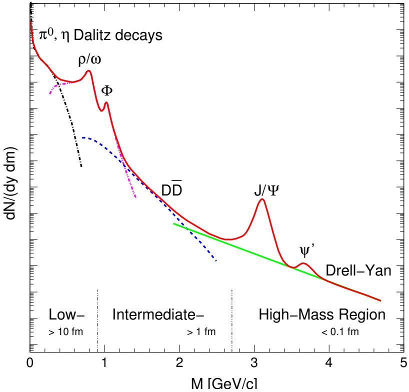


Fig. by A. Drees

Vector Mesons and electromagnetic Probes

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

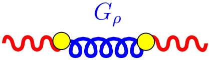
  [L. McLerran, T. Toimela 85, H. A. Weldon 90, C. Gale, J.I. Kapusta 91]

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

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

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

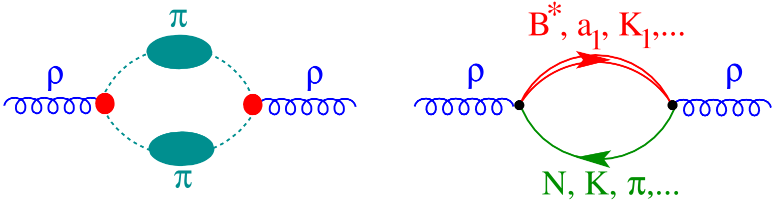
- to lowest order in α: $e^2 \Pi_{\mu\nu} \simeq \Sigma^{(\gamma)}_{\mu\nu}$
- vector-meson dominance model:

$\Sigma^{\gamma}_{\mu\nu} =$ 

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

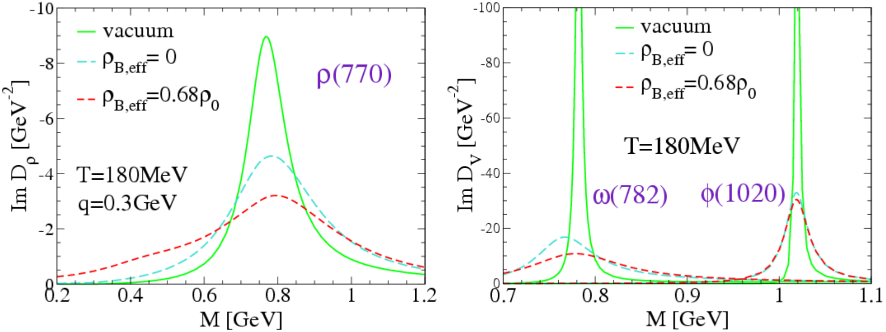
Hadronic many-body theory

- 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 ⇔ 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)

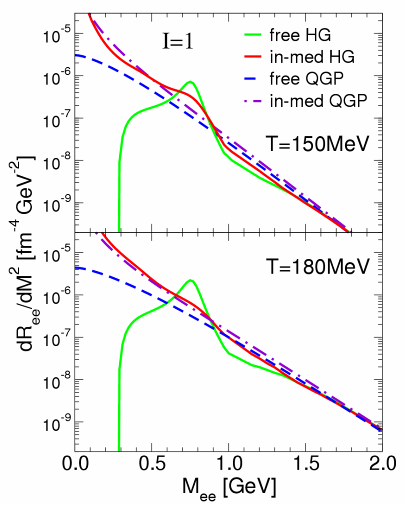
In-medium spectral functions and baryon effects



[R. Rapp, J. Wambach 99]

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

Dilepton rates: Hadron gas $\leftrightarrow$ QGP



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

Sources of dilepton emission in heavy-ion collisions

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

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

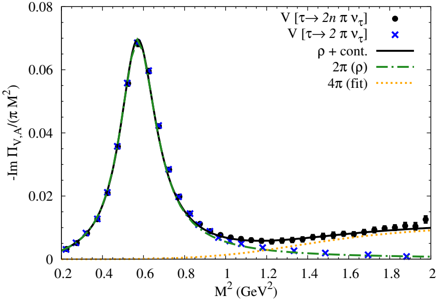
3. "corona" ⇔ emission from "primordial" mesons (jet-quenching)
4. after thermal freeze-out ⇔ emission from "freeze-out" mesons [Cooper, Frye 1975]

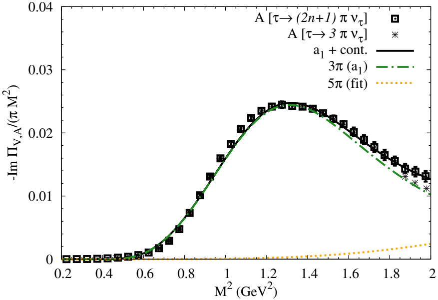
$$N^{(\text{fo})} = \int \frac{\mathrm{d}^3q}{q_0} \int q_\mu \mathrm{d}\sigma^\mu f_B(u_\mu q^\mu/T) \frac{\Gamma_{\text{meson}\to\ell^+\ell^-}}{\Gamma_{\text{meson}}} \mathsf{Acc}$$

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

Intermediate masses: hadronic "4π contributions"

- e.m. current-current correlator $\Leftrightarrow$ $\tau \rightarrow 2n\pi$

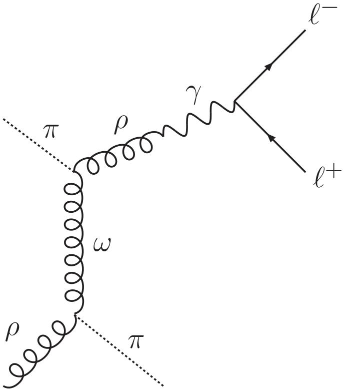




- "4π contributions": $\pi + \omega, a_1 \rightarrow \mu^+ + \mu^-$
- leading-order virial expansion for "four-pion piece"
- additional strength through "chiral mixing"

Radiation from thermal sources: Meson t-channel exchange

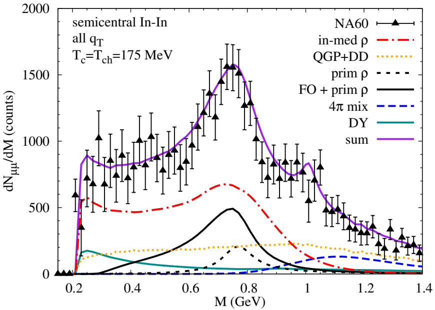
- motivation: q_T spectra too soft compared to NA60 data
- thermal contributions not included in models so far

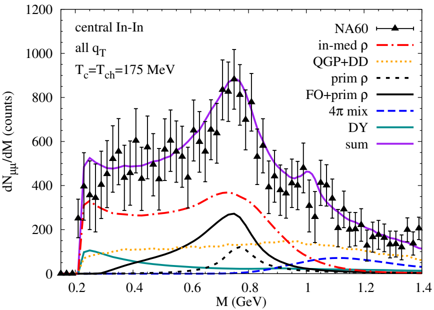


- also for π, a_1

Excess spectra

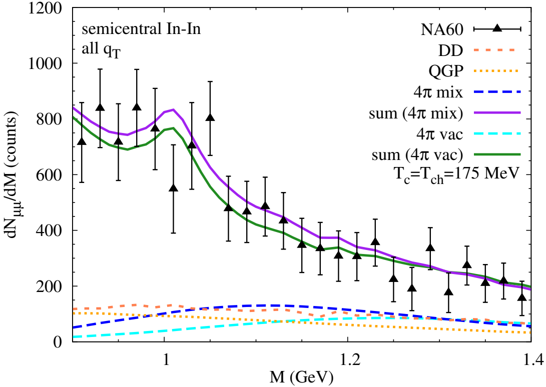
- Fireball with "standard" EoS-A ($T_c = T_{\text{chem}} = 175$ MeV)
- overall normalization ⇔ total fireball lifetime
- relative normalization of thermal radiation fixed by rates
- rates integrated over time, volume, $\vec{q}$ including NA60 acceptance





- good description of data

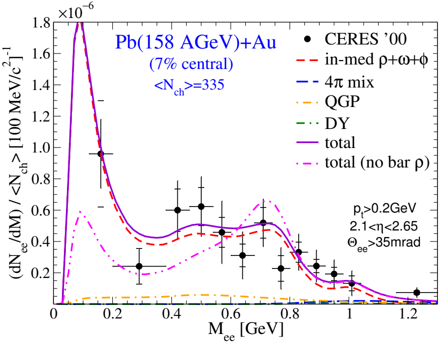
Excess spectra: IMR and multi-pion contributions

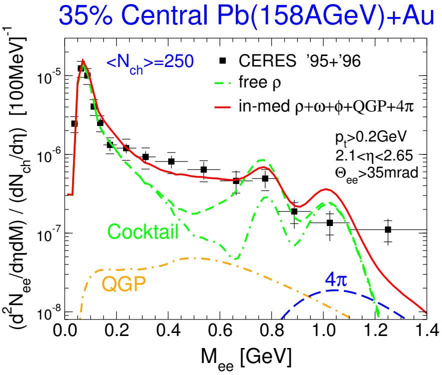


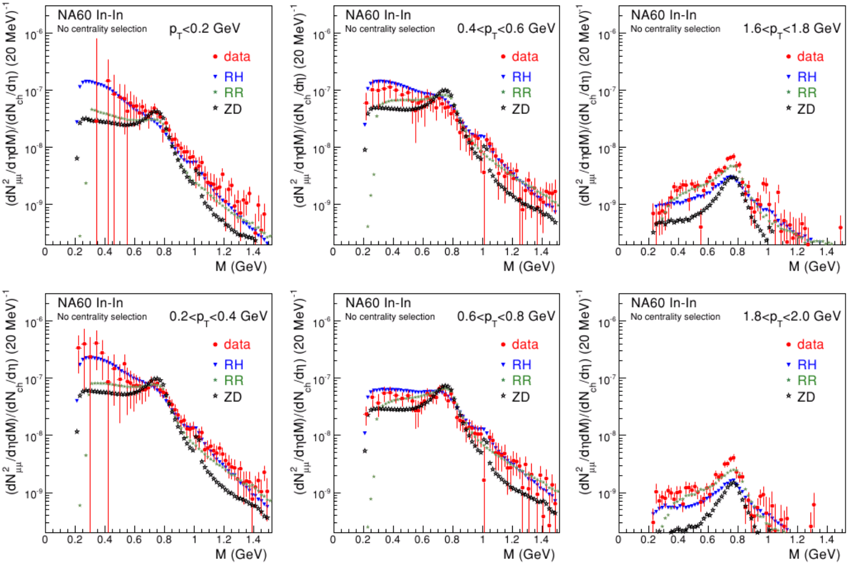
- "4π contributions" ($\pi + \omega, a_1 \to \mu^+ + \mu^-$)
- slightly enhanced by VA mixing

CERES/NA45 dielectron spectra

- good agreement also for dielectron spectra in $158\ \mathrm{GeV}$ Pb-Au
- allows further check of low-mass tail from baryon effects down to $M \to 2m_e$



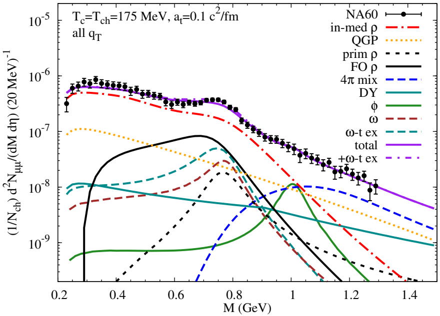


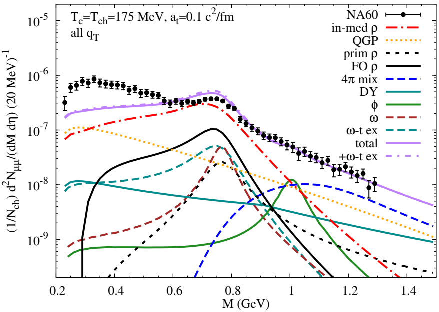


ZD: [K. Dusling, D. Teaney, I. Zahed 2007], RR: [J. Ruppert, T. Renk et al 2008], RH: [HvH, R. Rapp 2008]

Importance of baryon effects

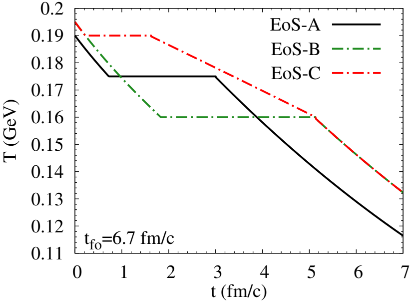
- Baryonic interactions important!
- in-medium broadening
- low-mass tail!

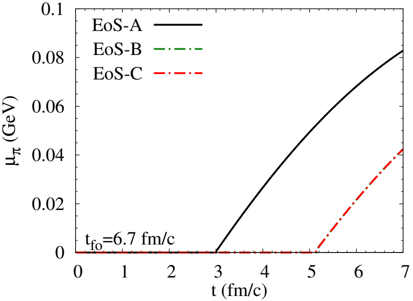




Sensitivity to T_c and hadro-chemistry

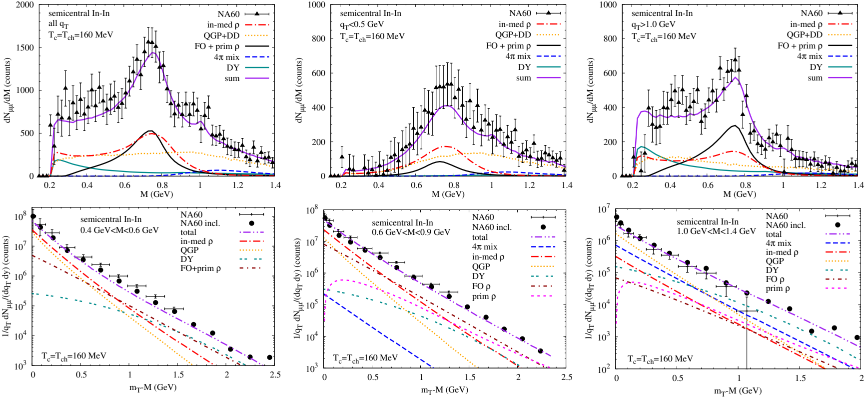
- recent lattice QCD: $T_c \simeq 190\text{-}200$ MeV or $T_c \simeq 150\text{-}160$ MeV?
- thermal-model fits to hadron ratios: $T_{\text{chem}} \simeq 150\text{-}160$ MeV





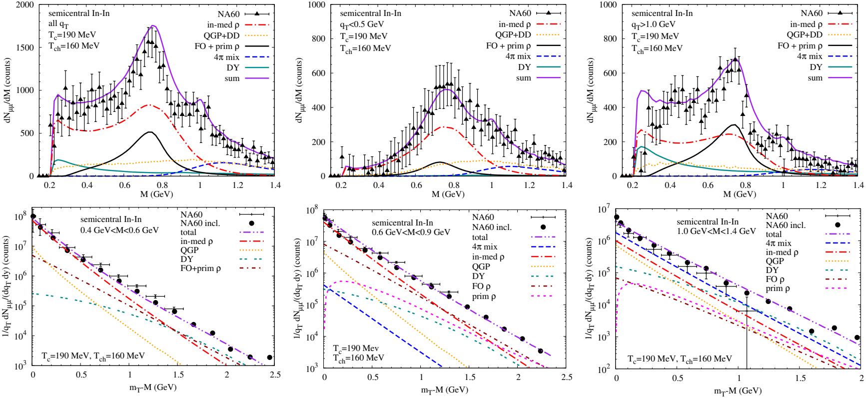
- EoS-A: $T_c = T_{\text{chem}} = 175$ MeV
- EoS-B: $T_c = T_{\text{chem}} = 160$ MeV
- EoS-C: $T_c = 190$ MeV, $T_{\text{chem}} = 160$ MeV
  - $T_c \geq T \geq T_{\text{chem}}$: hadron gas in chemical equilibrium
- keep fireball parameters the same (including life time)

EoS-B



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

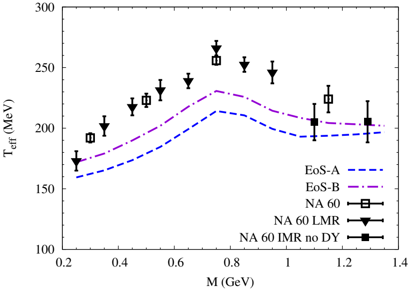
EoS-C

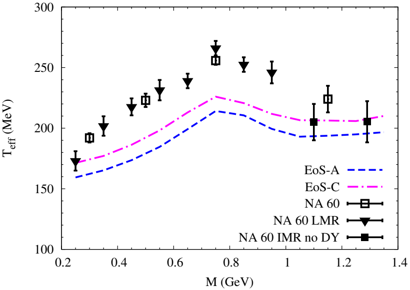


- mass spectra comparable to EoS-A ↔ slight reduction of fireball lifetime
- in IMR multi-pion ≫ QGP contribution
- higher hadronic temperatures + high-density hadronic phase ⇒ harder q_T spectra
- better agreement with data

Inverse-slope analysis

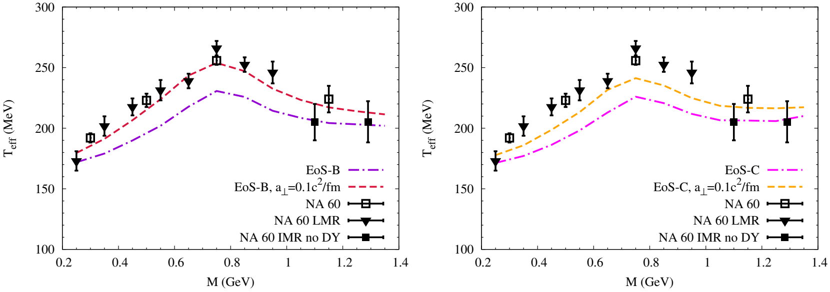
- to extract T_{eff} fit to
$$\frac{1}{q_T}\frac{\mathrm{d}N}{\mathrm{d}q_T} = \frac{1}{m_T}\frac{\mathrm{d}N}{\mathrm{d}m_T} = C\exp\left(-\frac{m_T}{T_{\text{eff}}}\right)$$
- fit of theoretical q_T spectra: 1 GeV $< q_T < 1.8$ GeV





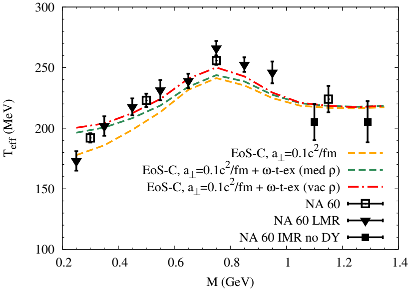
- standard fireball acceleration: too soft q_T spectra
- lower T_c in EoS-B and EoS-C helps (higher hadronic temperatures)
- NB: here, Drell Yan contribution taken out

Inverse-slope analysis



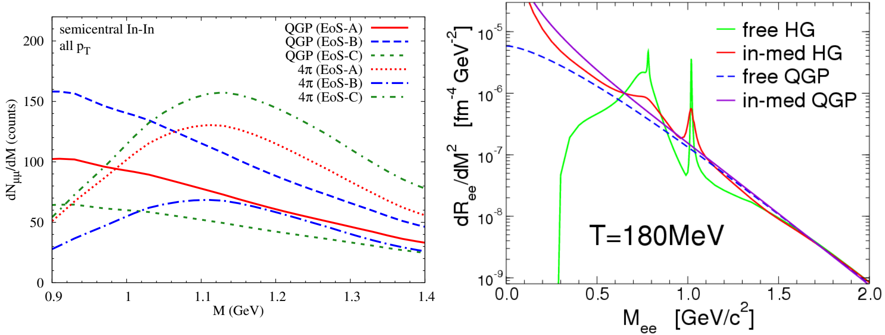
- enhance fireball acceleration to $a_\perp = 0.1c^2/\text{fm}$
- effective at all stages of fireball evolution
- agreement in IMR not spoiled $\Leftrightarrow$ dominated from earlier stages
- EoS-B harder $\Leftrightarrow$ relative contribution of harder freezeout ρ decays vs. thermal ρ's larger

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 ⇔ 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

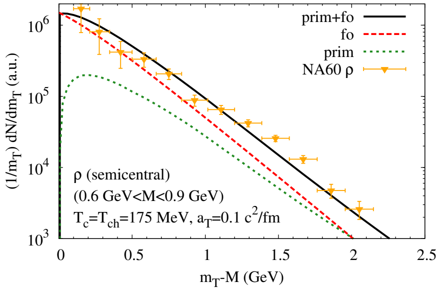
$$\text{reason}: \mathrm{d}N_{ll}/\mathrm{d}M\mathrm{d}T \propto \mathrm{Im}\,\Pi_{\mathrm{em}}(M,T)\ \exp(-M/T)\ T^{-5.5}$$

- radiation maximal for $T = T_{\max} = M/5.5$
- 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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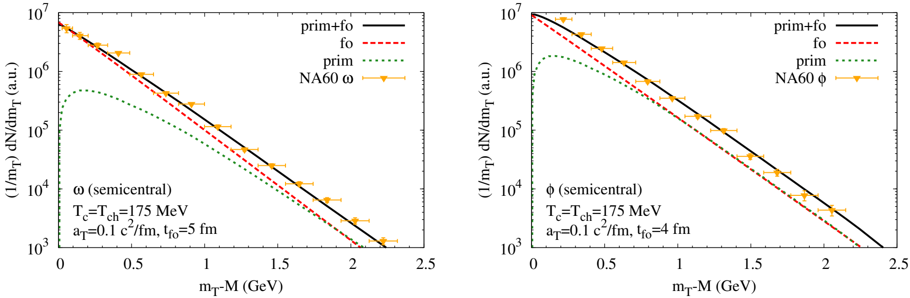
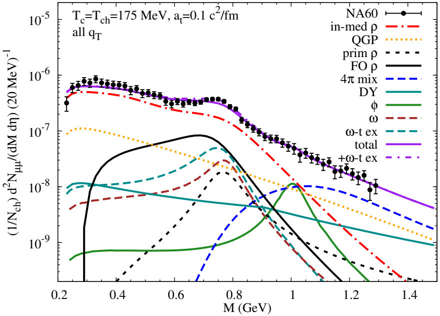
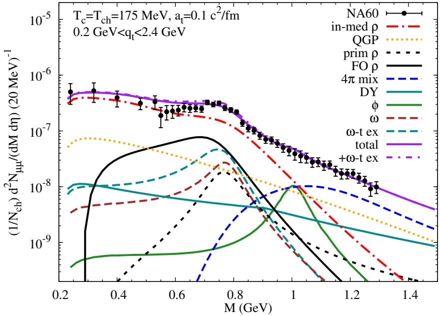


M spectra (in p_T slices)

- EoS-A: $T_c = T_{\text{ch}} = 175$ MeV
- transverse acceleration: $a_\perp = 0.1c^2/\text{fm}$





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

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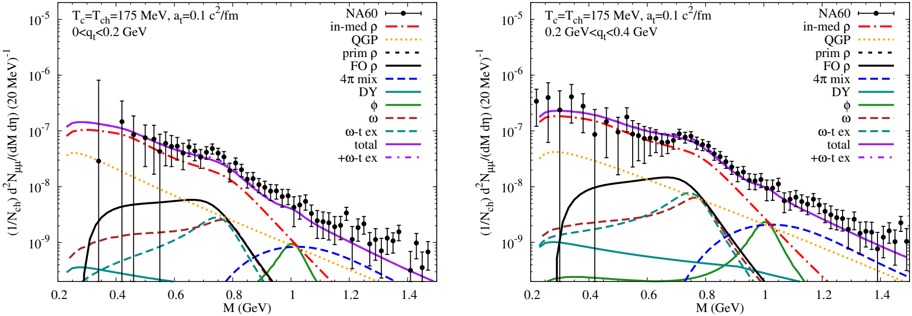

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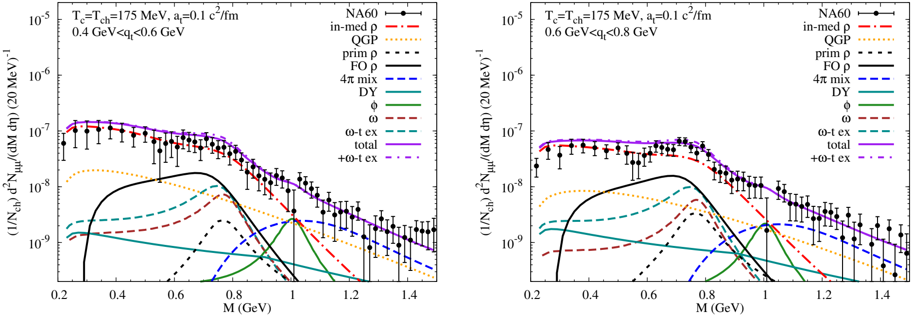

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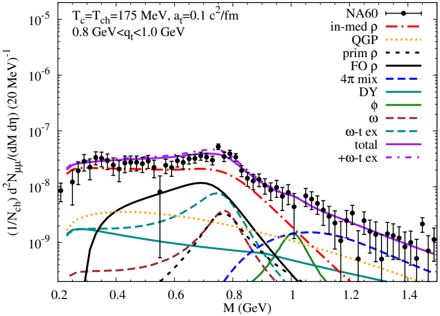

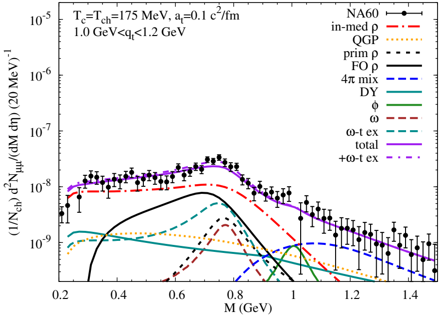

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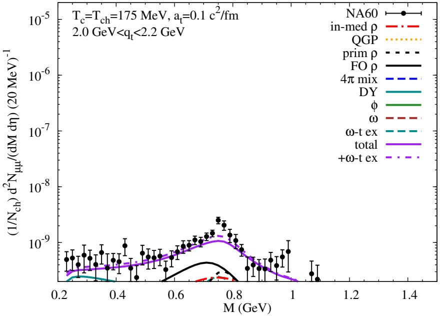

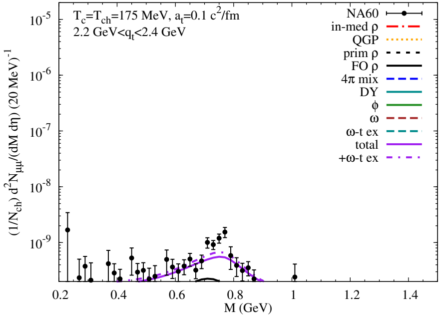

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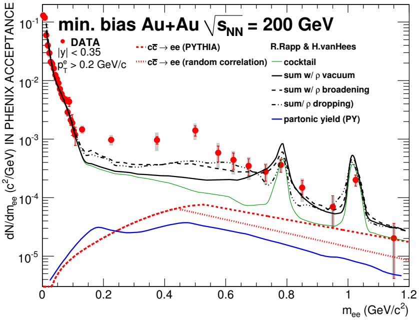
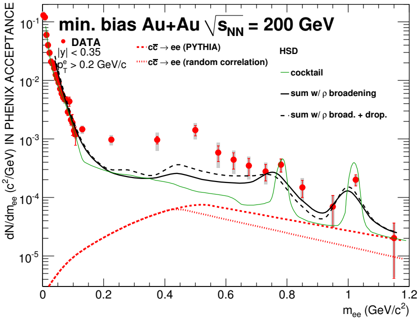
Dileptons@RHIC: New Puzzle?

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



model: Rapp, HvH

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



model: HSD Bratkovskaya, Cassing

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

Conclusions and Outlook

- dilepton spectra ⇔ in-medium em. current correlator
- model 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 $160 \text{ MeV} \leq T \leq 190 \text{ MeV}$
      ⇔ "parton-hadron" duality of rates
      ⇔ compatible with chiral-symmetry restoration!
  - dimuons in In-In (NA60), Pb-Au (CERES/NA45), γ in Pb-Pb (WA98)
- recent review: [R. Rapp, J. Wambach, HvH, Landolt-Brnstein, 1-23A, arXiv: 0901.3289 [hep-ph]]

Conclusions and Outlook

- fireball/freeze-out dynamics ⇔ m_T spectra and effective slopes
  - "non-thermal sources" important for $q_T \gtrsim 1 \text{ GeV}$
  - lower T_c ⇒ higher hadronic temperatures ⇒ harder q_T spectra
  - to describe measured effective slopes $a_\perp = 0.085 c^2/\text{fm} \rightarrow 0.1 c^2/\text{fm}$
  - off-equilibrium effects (viscous hydro)?
- Further developments
  - understand recent PHENIX results (large dilepton excess in LMR)
  - understand "DLS puzzle" (exp. confirmed by HADES)
    NN (np!) bremsstrahlung!
  - 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!