Electromagnetic spectra at the CERN-SPS

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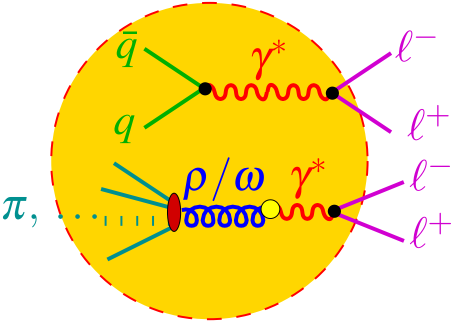
Outline

1. Electromagnetic probes in heavy-ion collisions
   - Vector mesons and electromagnetic probes
   - Sources of dilepton emission in heavy-ion collisions
2. Comparison to NA 60 data
   - Invariant-mass spectra
   - m_T spectra
3. Conclusions and Outlook

Electromagnetic probes in heavy-ion collisions

- γ, $\ell^{\pm}$: 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



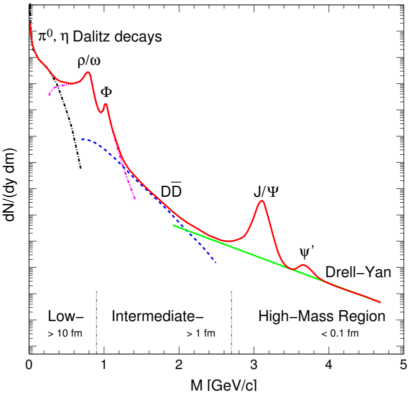


Fig. by A. Drees

Vector Mesons and electromagnetic Probes

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

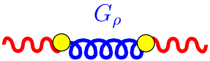
  [L. McLerran, T. Toimela 85, H. A. Weldon 90, C. Gale, J.I. Kapusta 91]

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

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

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

- u: four-velocity of the fluid cell; $p \cdot u = p_0^{\mathrm{hb}}$ energy in "heat-bath frame"
- to lowest order in α: $e^2 \Pi_{\mu\nu} \simeq \Sigma^{(\gamma)}_{\mu\nu}$
- vector-meson dominance model:

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

Sources of dilepton emission in heavy-ion collisions

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

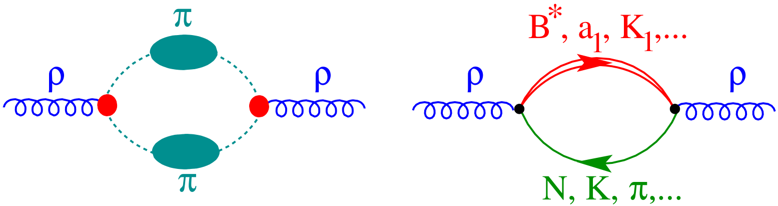
$$\frac{1}{q_T}\frac{\mathrm{d}N^{(\text{thermal})}}{\mathrm{d}M\mathrm{d}q_T} = \int \mathrm{d}^4 x \int \mathrm{d}y \int M\mathrm{d}\varphi \frac{\mathrm{d}N^{(\text{thermal})}}{\mathrm{d}^4 x \mathrm{d}^4 q}$$

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

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

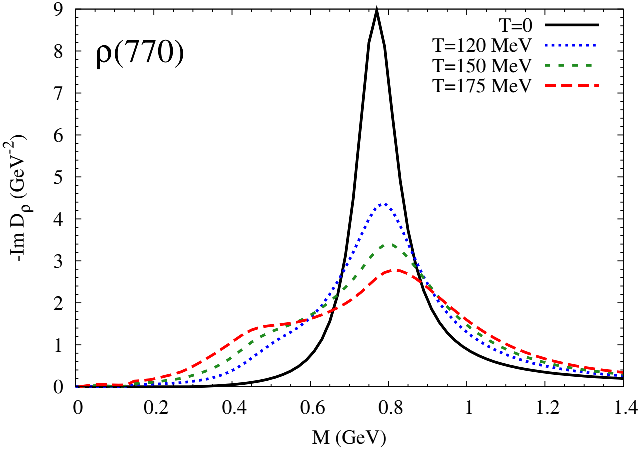
Hadronic many-body theory

- 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)

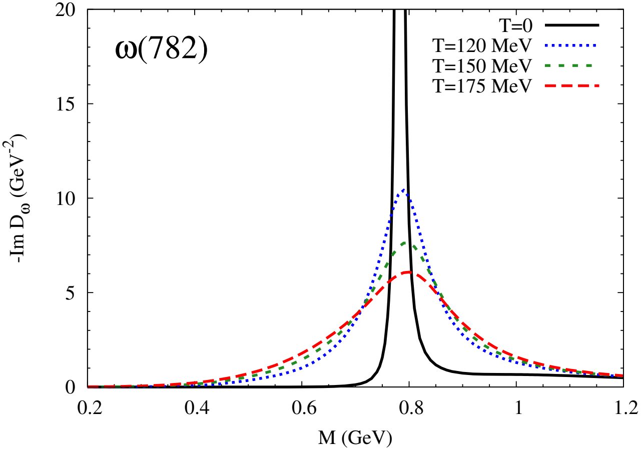
In-medium spectral functions and baryon effects



[R. Rapp, J. Wambach 99]

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

In-medium spectral functions and baryon effects



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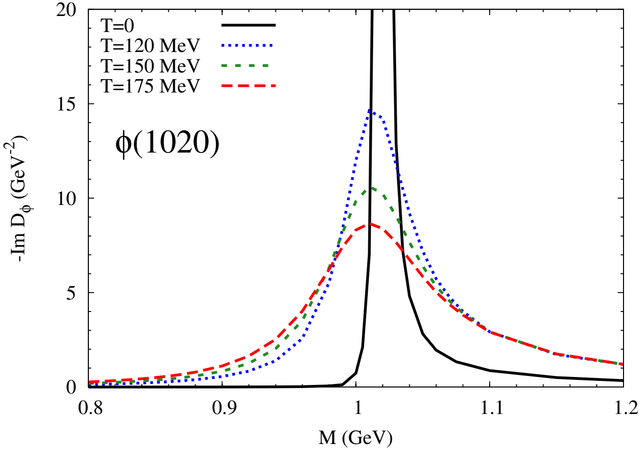

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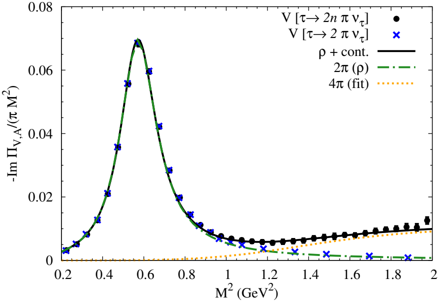
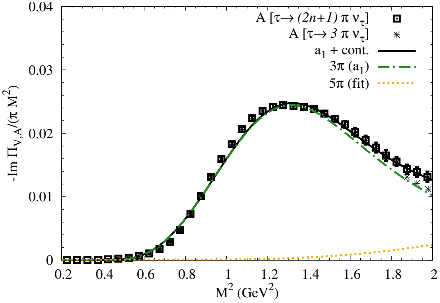
Intermediate masses: hadronic "4π contributions"

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

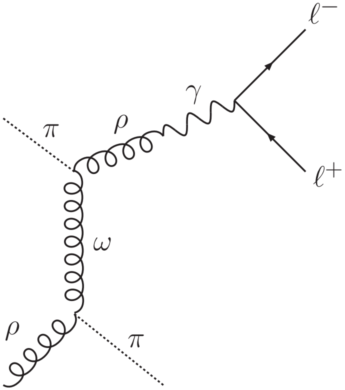




- "4π contributions": $\pi + \omega, a_1 \rightarrow \mu^+ + \mu^-$
- leading-order virial expansion for "four-pion piece"
- additional strength through "chiral mixing"

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

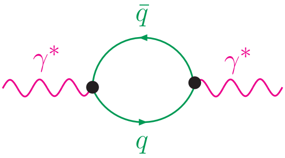


- also for π, a_1

Dileptons from thermal QGP

- in QGP phase: $q\bar{q}$ annihilation
- HTL improved electromagnetic current correlator

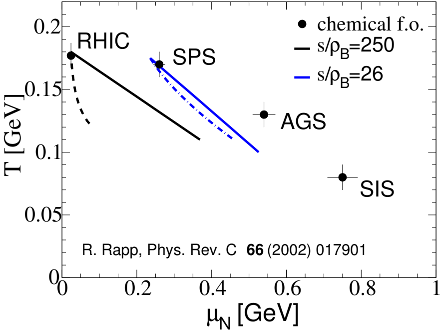
$$-\mathrm{i}\Pi_{\mathrm{em,QGP}} =$$



- or electromagnetic current correlator from the lattice [H.-T. Ding, A. Francis et al (Bielefeld) 2011] (extrapolated to finite q)
- "quark-hadron duality" around T_c

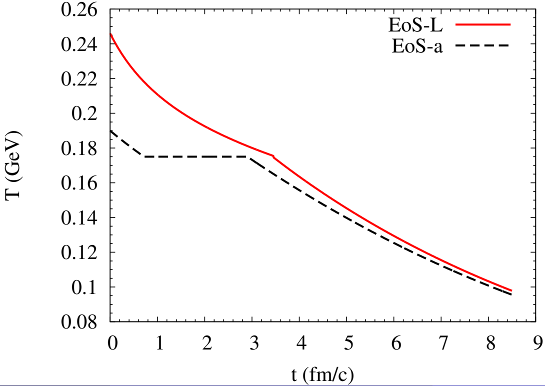
Fireball and Thermodynamics

- cylindrical fireball model: $V_{\text{FB}} = \pi(z_0 + v_{z0}t + \frac{a_z}{2}t^2)\left(\frac{a_\perp}{2}t^2 + r_0\right)^2$
- thermodynamics:
  - isentropic expansion; S_{tot} fixed by N_{ch}; $T_c = T_{\text{chem}} = 175$ MeV
  - $T > T_c$: QGP; lattice equation of state
  - continuous cross-over (no 1st-order mixed state!)
  - $T < T_c$: hadron-resonance gas
- $\Rightarrow T(t), \mu_{\text{baryon,meson}}(t)$
- chemical freezeout:
  - $\mu_N^{\text{chem}} = 232$ MeV
  - hadron ratios fixed
    $\Rightarrow \mu_N, \mu_\pi, \mu_K, \mu_\eta$ at fixed $s/\varrho_B = 27$
- thermal freezeout:
  $(T_{\text{fo}}, \mu_\pi^{\text{fo}}) \simeq (120, 80)$ MeV

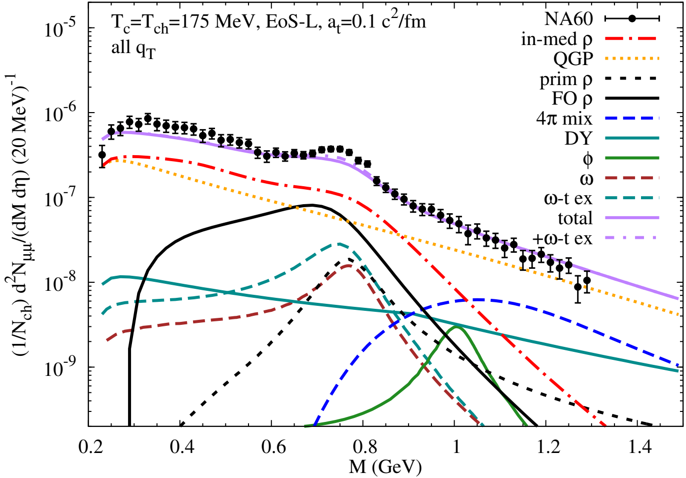


Fireball evolution

- comparison 1st-order EoS (EoS-A) vs. lattice EoS (EoS-L)
- in both $T_c = T_{\text{ch}} = 175$ MeV
- EoS-A: $t_{\text{form}} = 1\ \text{fm}/c$, $r_0 = 4.6$ fm, $z_0 = 1.8$ fm $\Rightarrow$
  $T_{\text{initial}} = 195$ MeV
- EoS-L: $t_{\text{form}} = 0.67\ \text{fm}/c$, $r_0 = 4.0$ fm, $z_0 = 1.2$ $\Rightarrow$
  $T_{\text{initial}} = 245$ MeV

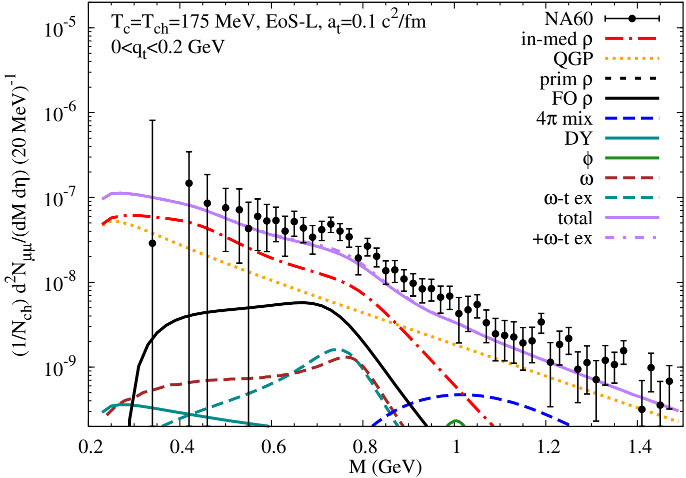


- norm corrected by $\sim$3% due to centrality correction (min-bias data: $\langle N_{\rm ch} \rangle = 120$, calculation $N_{\rm ch} = 140$)



M spectra (in p_T slices)

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



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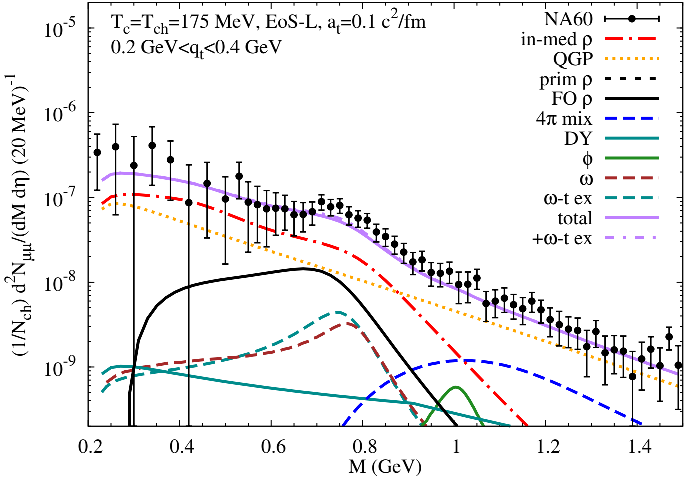

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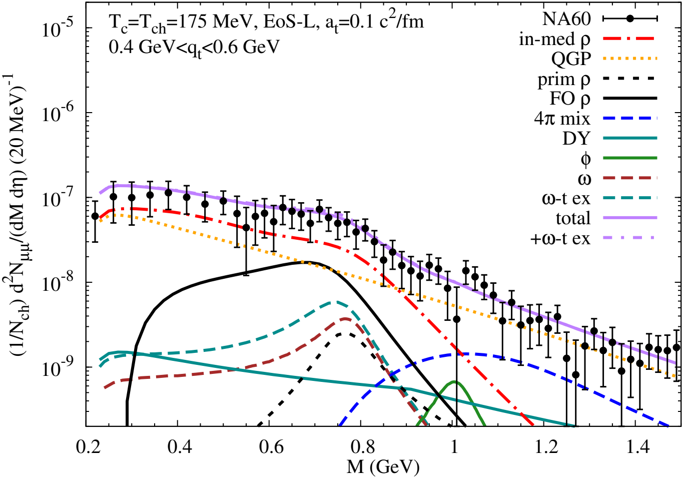
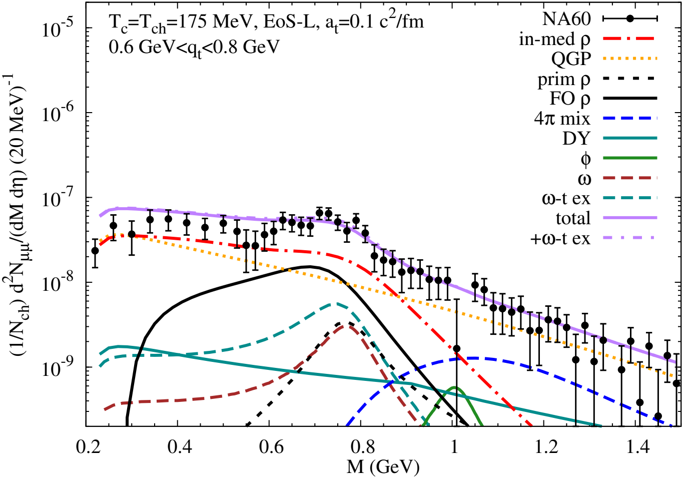


M spectra (in p_T slices)

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



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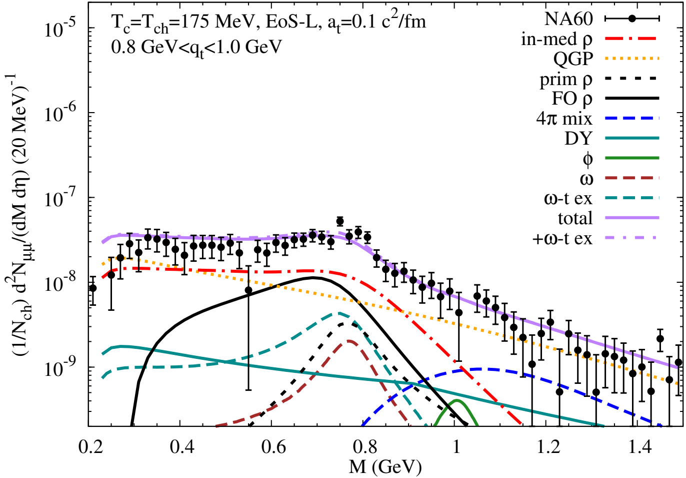

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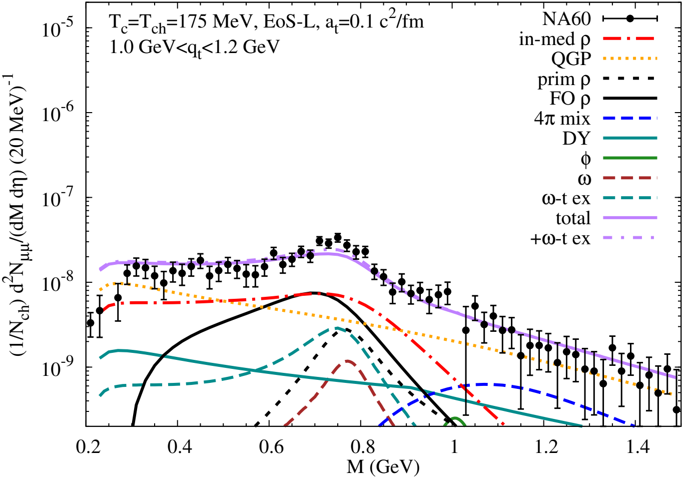

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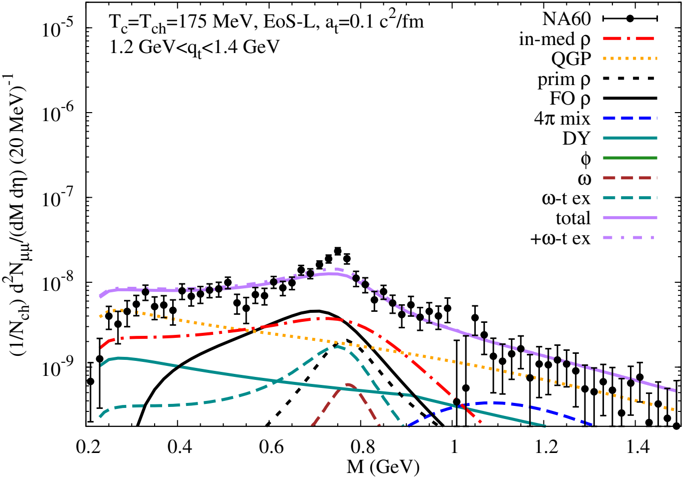

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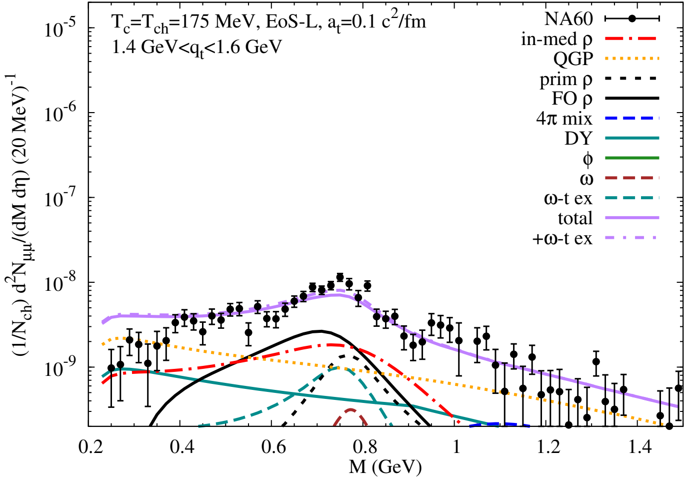

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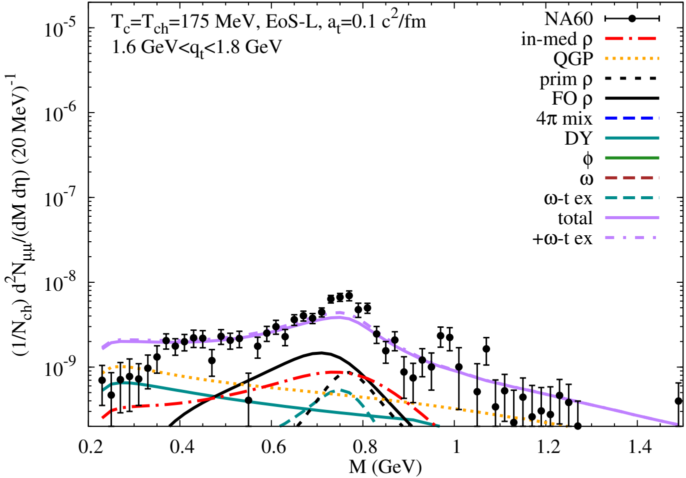

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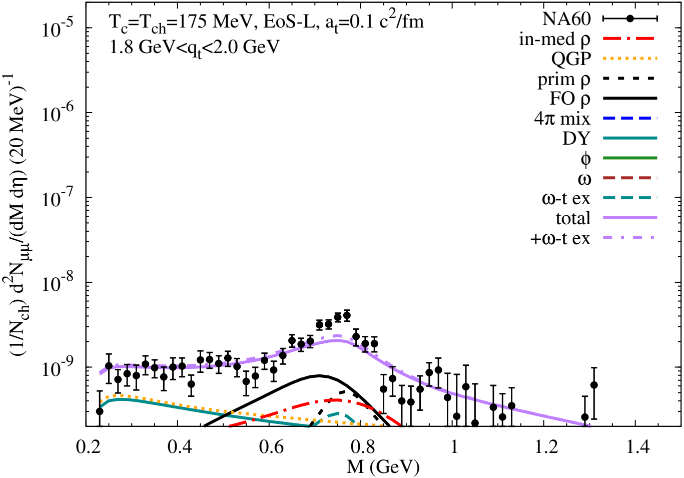

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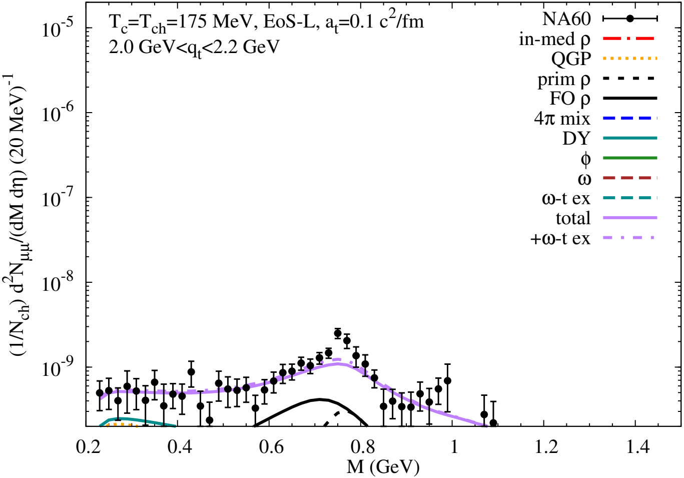

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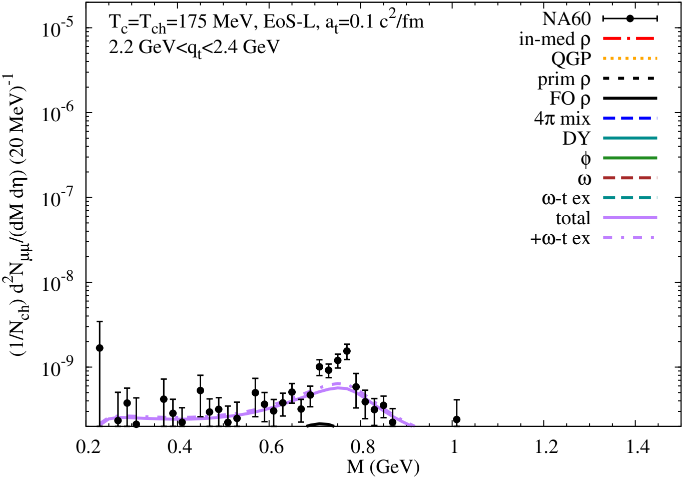
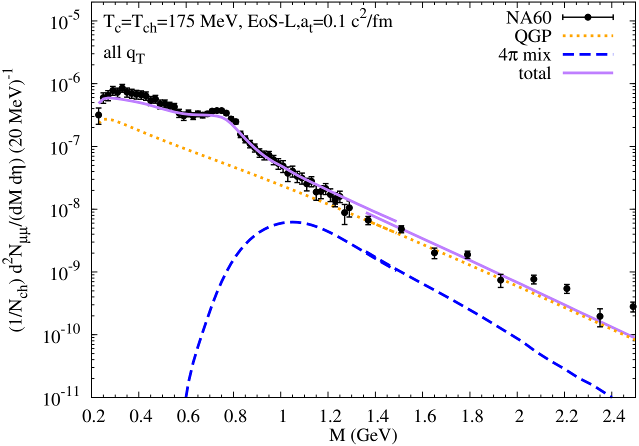


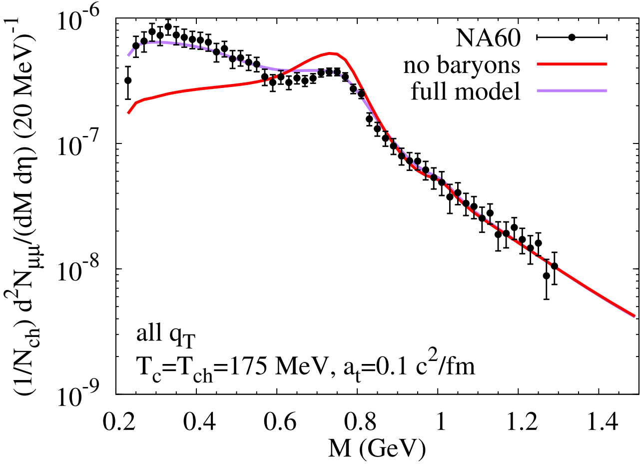
The higher-mass region



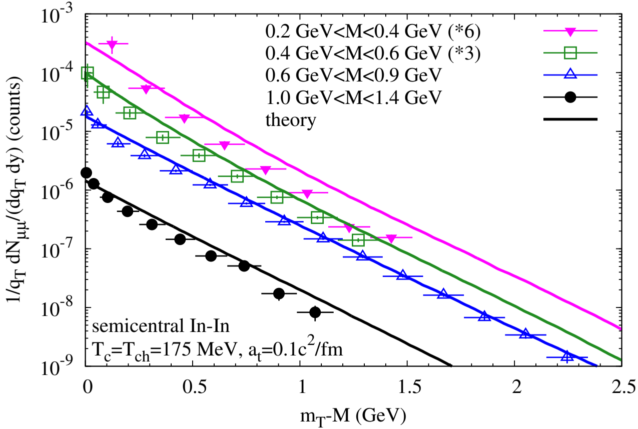
- DY subtracted in data
- theory a bit low ⇒ need longer QGP phase ⇒ somewhat smaller formation time

Importance of baryon effects

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



m_T spectra



0.2 GeV<M<0.4 GeV (*6)
0.4 GeV<M<0.6 GeV (*3)
0.6 GeV<M<0.9 GeV
1.0 GeV<M<1.4 GeV
theory
semicentral In-In
T_c=T_{ch}=175 MeV, a_t=0.1c^2/fm
$1/q_T\, dN_{\mu\mu}/(dq_T\, dy)$ (counts)
m_T-M (GeV)

Conclusions and Outlook

- dilepton spectra ⇔ 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
- 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
  - 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!
  - here: lattice EoS ⇒ QGP dominates over hadronic in the IMR
  - dimuons in In-In (NA60), Pb-Au (CERES/NA45), γ AA at SPS, RHIC, LHC ⇒ Charles Gale's talk on Thursday

Conclusions and Outlook

- More realistic medium evolution
  - use transport model for medium evolution
  - dilemma: consistent implementation of in-medium em. current correlators?
  - pragmatic solutions:
    - use transport-hydro-hybrid approach: for UrQMD+Shasta 3D hydro $\Rightarrow$ [Elvira Santini et al 2010/11]; use thermal rates in hydro; “shining” in UrQMD “afterburner”
    - new approach: “coarse-grained transport” $\Rightarrow$ find energy + baryon density (“Eckhart frame”) $\Rightarrow$ EoS. gives $(T, \mu_B) + \mu_\pi, \mu_K$; use again thermal rates in coarse-grained fluid cells $\Rightarrow$ Stephan Endres’s talk on Thursday!
- Further theoretical developments
  - 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!
    $\Rightarrow$ Paul Hohler’s talk today!