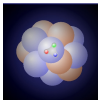


Hadronic Matter and Electromagnetic Probes

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- 1 Electromagnetic probes in heavy-ion collisions
 - Vector mesons and electromagnetic probes
 - Sources of dileptons
- 2 Comparison to NA60 data
 - Invariant-mass spectra
 - m_T spectra and slope analysis
- 3 Conclusions and Outlook

Electromagnetic probes in heavy-ion collisions

- γ, ℓ^\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

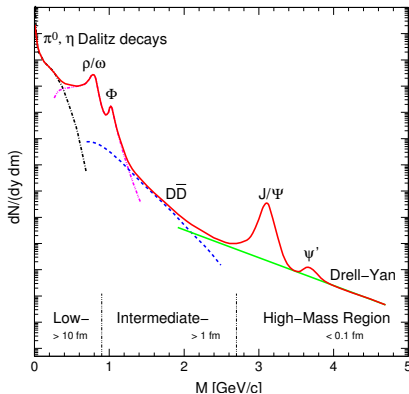
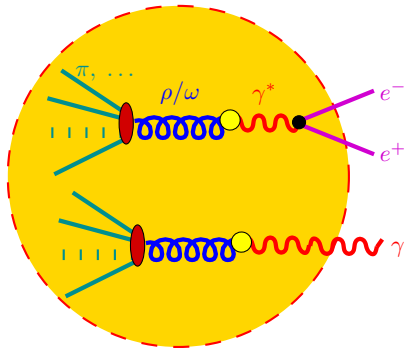


Fig. by A. Drees

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]

$$\Pi_{\mu\nu}^<(q) = \int d^4x \exp(iq \cdot x) \langle J_\mu(0) J_\nu(x) \rangle_T = -2f_B(q_0) \text{Im} \Pi_{\mu\nu}^{(\text{ret})}(q)$$

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

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

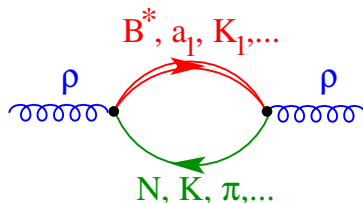
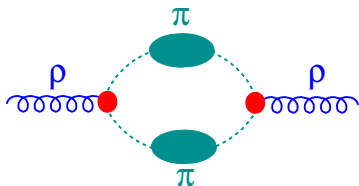
- to lowest order in α : $e^2 \Pi_{\mu\nu} \simeq \Sigma_{\mu\nu}^{(\gamma)}$
- **vector-meson dominance** model:

$$\Sigma_{\mu\nu}^{(\gamma)} = \text{---} G_\rho \text{---}$$

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

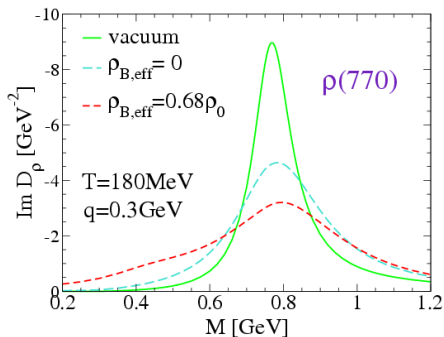
Hadronic many-body theory

- HMBT for vector mesons [Ko et al, Chanfray et al, Herrmann et al, Rapp et al, . . .]
- $\pi\pi$ interactions and **baryonic excitations**

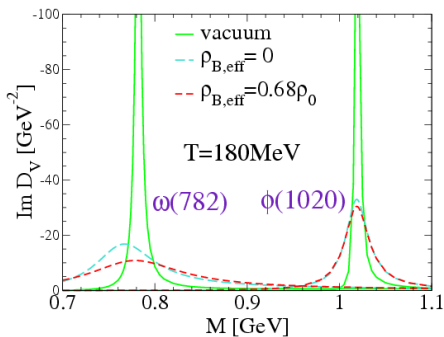


- +corresponding vertex corrections \Leftrightarrow gauge invariance
- **Baryon (resonances)** important, even at RHIC with low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

In-medium spectral functions and baryon effects



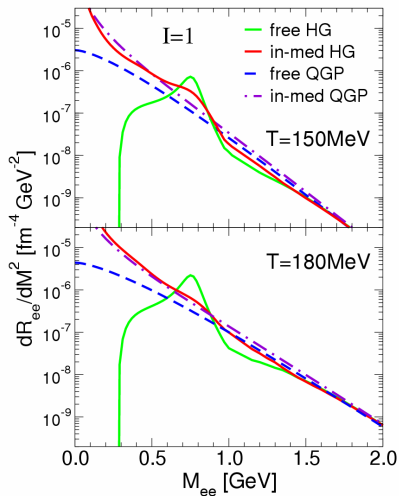
[R. Rapp, J. Wambach 99]



- **baryon effects** important

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

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” \Leftrightarrow emission from thermal source [McLerran, Toimela 1985]

$$\frac{1}{q_T} \frac{dN^{(\text{thermal})}}{dM dq_T} = \int d^4x \int dy \int M d\varphi \frac{dN^{(\text{thermal})}}{d^4x d^4q} \text{Acc}(M, q_T, y)$$

- 3 “corona” \Leftrightarrow emission from “primordial” mesons (jet-quenching)
- 4 after thermal freeze-out \Leftrightarrow emission from “freeze-out” mesons

[Cooper, Frye 1975]

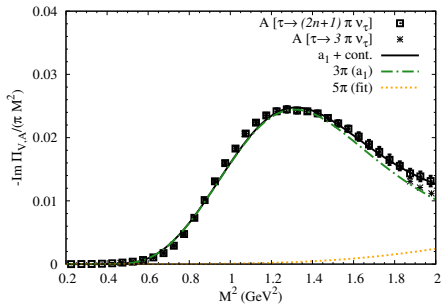
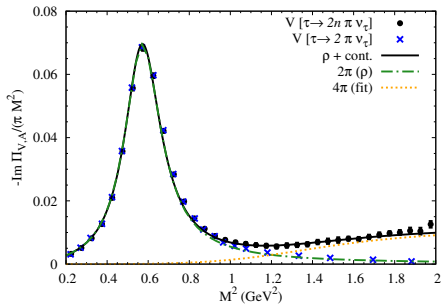
$$N^{(\text{fo})} = \int \frac{d^3q}{q_0} \int q_\mu d\sigma^\mu f_B(u_\mu q^\mu / T) \frac{\Gamma_{\text{meson} \rightarrow \ell^+ \ell^-}}{\Gamma_{\text{meson}}} \text{Acc}$$

- additional factor $\gamma = q_0/M$ compared to thermal emission
- physical reason

- thermal source rate $\propto \tau_{\text{med}} \frac{\Gamma_{\text{meson} \rightarrow \ell^+ \ell^-}}{\gamma}$
- decay of mesons after fo: rate $\propto \frac{\Gamma_{\text{meson} \rightarrow \ell^+ \ell^-}}{\Gamma_{\text{meson}}}$

Intermediate masses: hadronic “ 4π contributions”

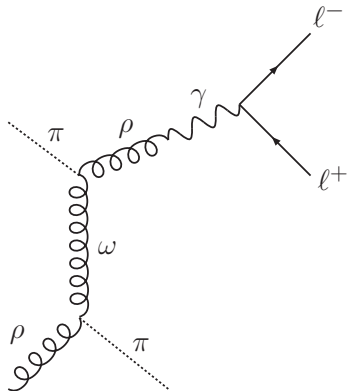
- e.m. current-current correlator $\Leftrightarrow \tau \rightarrow 2n\pi$



- “ 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

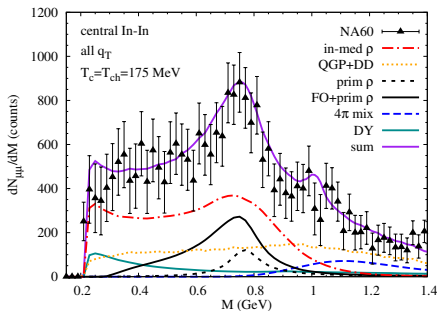
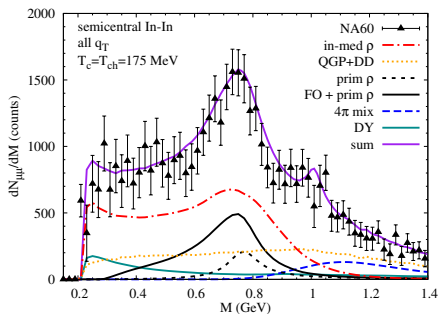
- motivation: q_T spectra too soft compared to NA60 data
- **thermal contributions** not included in models so far



- also for π , a_1

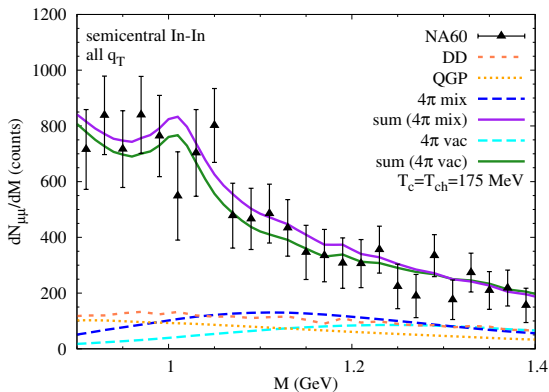
Excess spectra

- Fireball with “standard” EoS-A ($T_c = T_{\text{chem}} = 175$ MeV)
- overall normalization \Leftrightarrow 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

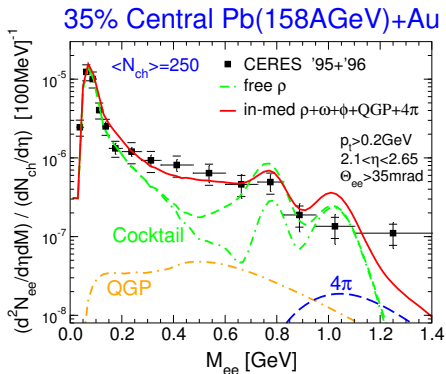
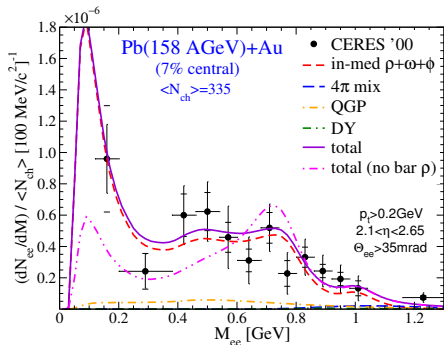
Excess spectra: IMR and multi-pion contributions



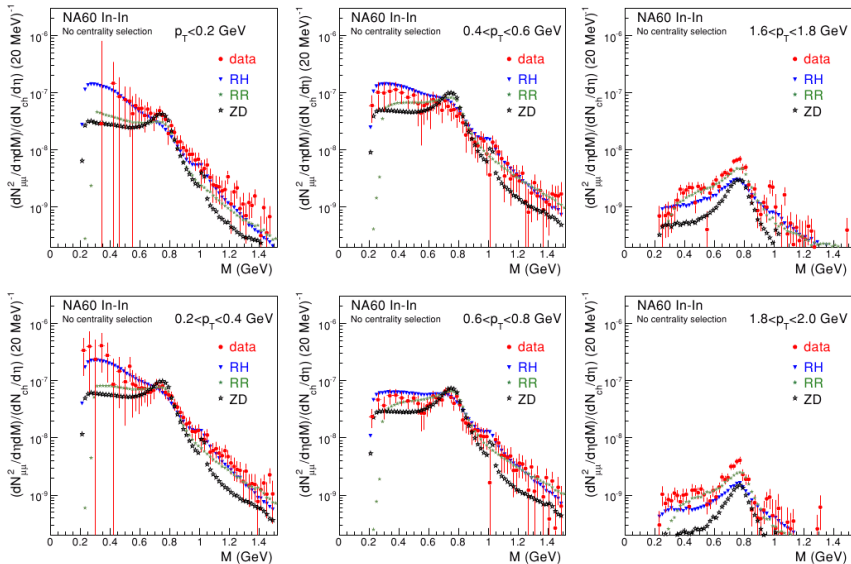
- “ 4π contributions” ($\pi + \omega, a_1 \rightarrow \mu^+ + \mu^-$)
- slightly enhanced by VA mixing

CERES/NA45 dielectron spectra

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



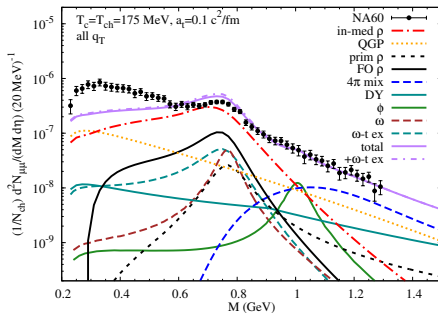
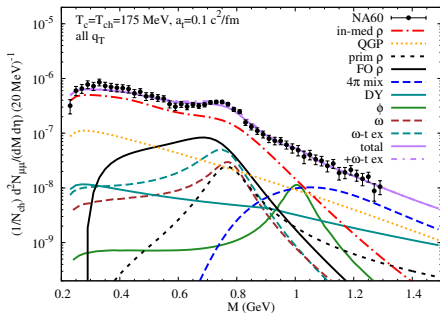
Excess spectra: acceptance-corrected mass spectra



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

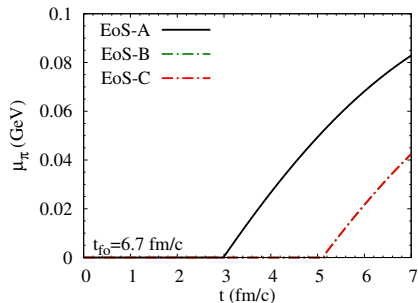
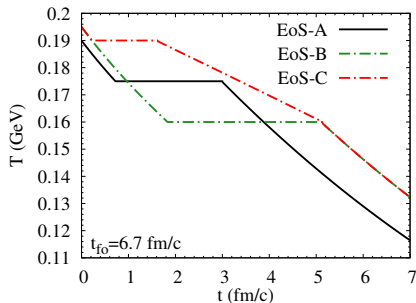
Importance of baryon effects

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

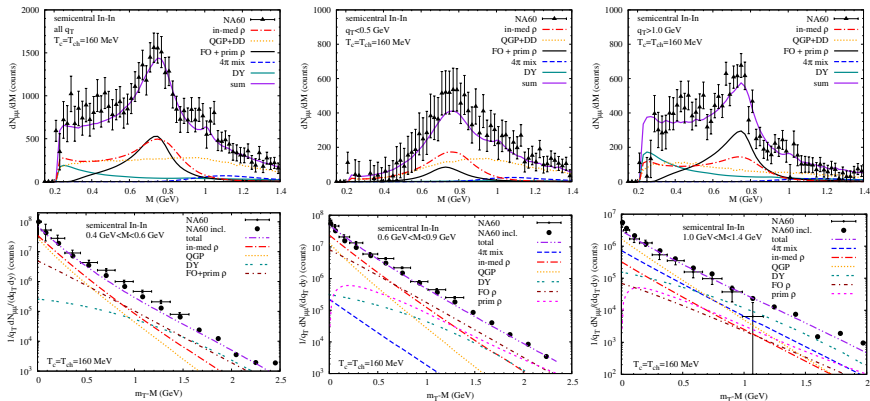


Sensitivity to T_c and hadro-chemistry

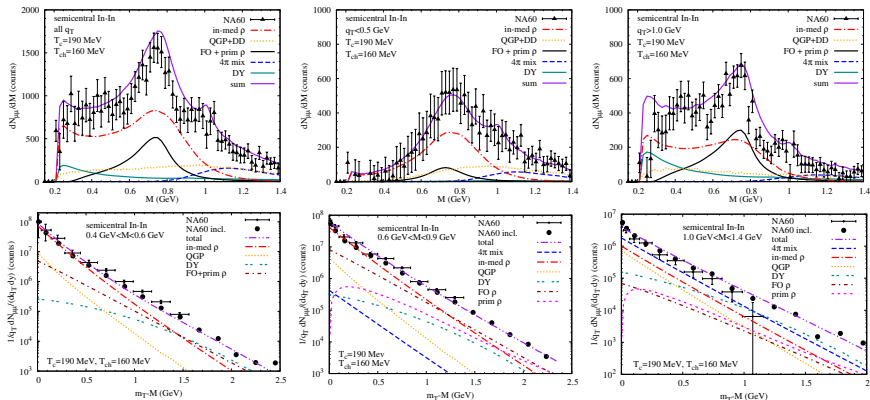
- recent lattice QCD: $T_c \simeq 190\text{-}200$ MeV or $T_c \simeq 150\text{-}160$ MeV?
- thermal-model fits to hadron ratios: $T_{\text{chem}} \simeq 150\text{-}160$ MeV



- 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)



- 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



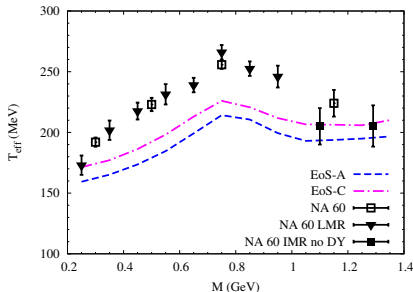
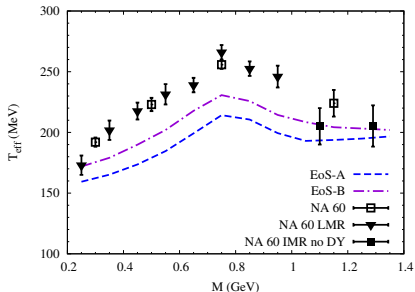
- mass spectra comparable to EoS-A \leftrightarrow slight reduction of fireball lifetime
- in IMR **multi-pion** \gg **QGP** contribution
- higher hadronic temperatures + high-density hadronic phase \Rightarrow harder q_T spectra
- better agreement with data

Inverse-slope analysis

- to extract T_{eff} fit to

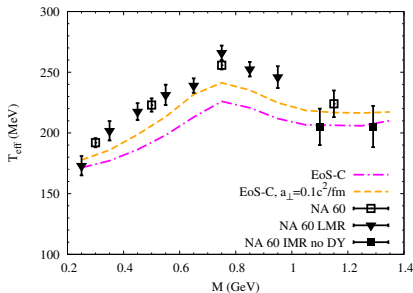
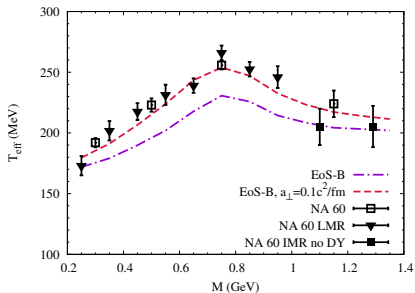
$$\frac{1}{q_T} \frac{dN}{dq_T} = \frac{1}{m_T} \frac{dN}{dm_T} = C \exp\left(-\frac{m_T}{T_{\text{eff}}}\right)$$

- fit of theoretical q_T spectra: $1 \text{ GeV} < q_T < 1.8 \text{ GeV}$



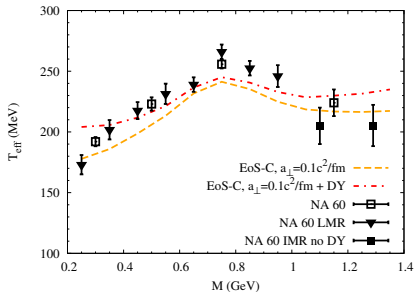
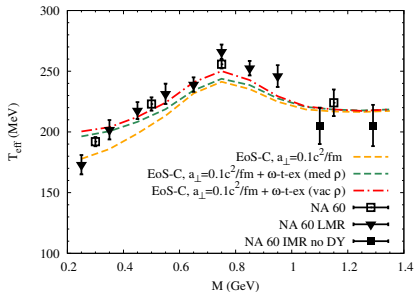
- standard fireball acceleration: **too soft q_T spectra**
- lower T_c in EoS-B and EoS-C helps (higher hadronic temperatures)
- NB: here, Drell Yan contribution taken out

Inverse-slope analysis



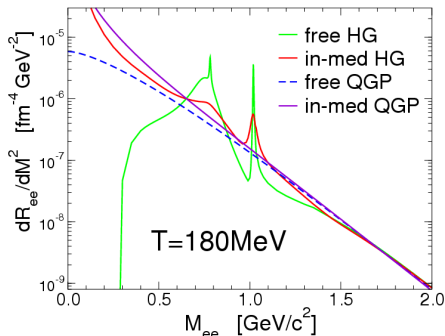
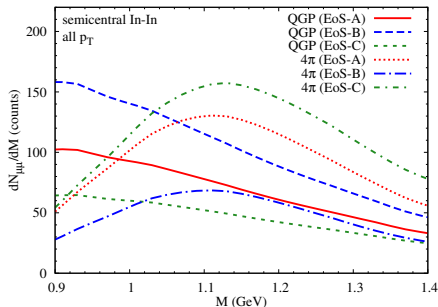
- enhance fireball acceleration to $a_{\perp} = 0.1c^2/\text{fm}$
- effective at all stages of fireball evolution
- agreement in IMR not spoiled \Leftrightarrow dominated from earlier stages
- EoS-B harder \Leftrightarrow relative contribution of harder freezeout ρ decays vs. thermal ρ 's larger

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



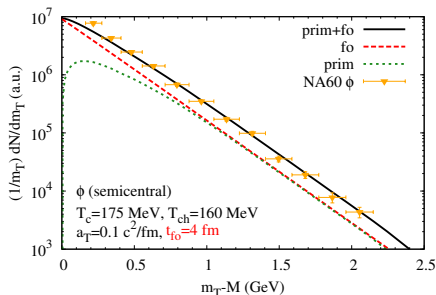
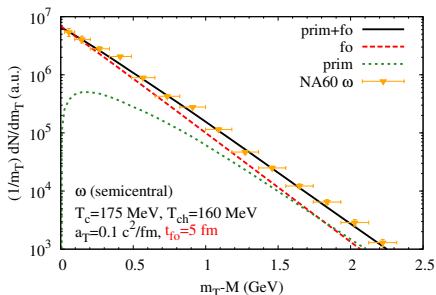
- EoS-B: QGP dominates over multi-pion radiation
- opposite in EoS-A and EoS-C
- multi-pion radiation dominantly from high-density hadronic phase

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

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

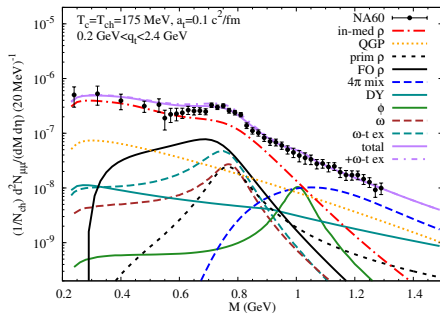
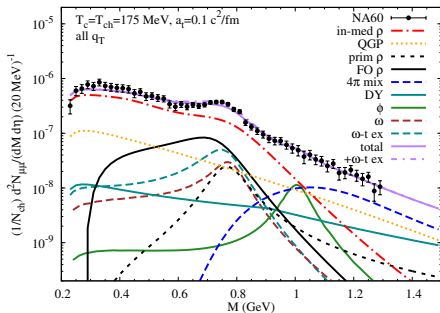
Hadron spectra

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



M spectra (in p_T slices)

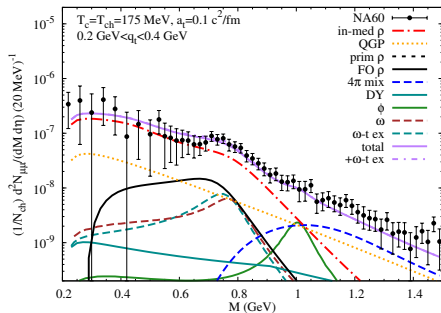
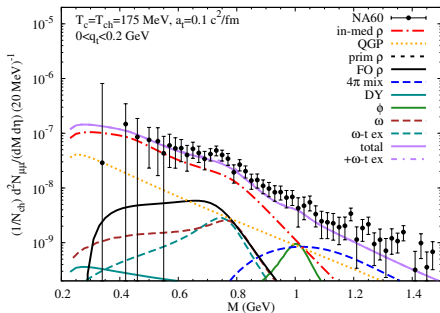
- **EoS-A:** $T_c = T_{ch} = 175$ MeV
- **transverse acceleration:** $a_{\perp} = 0.1 c^2/\text{fm}$



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

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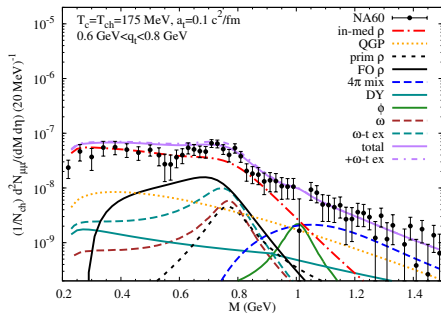
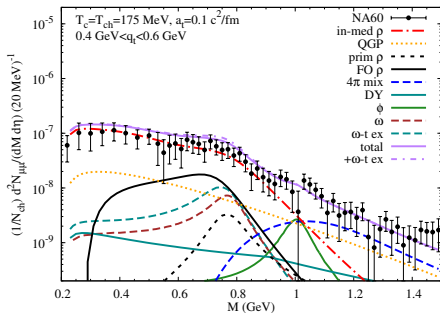
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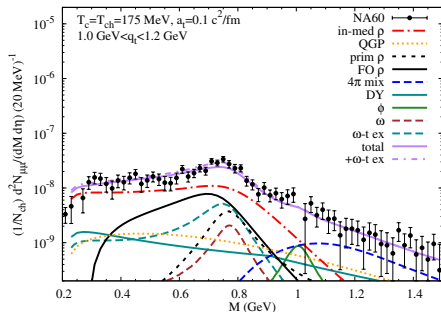
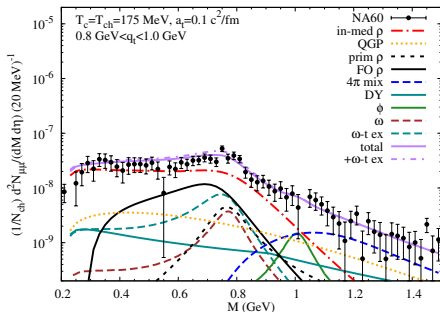
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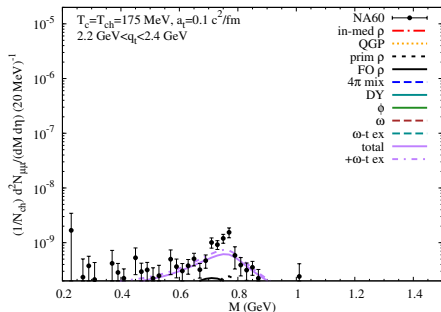
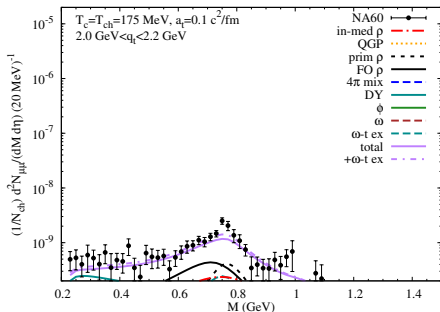
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Conclusions and Outlook

- dilepton spectra \Leftrightarrow 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 $160 \text{ MeV} \leq T \leq 190 \text{ MeV}$
 - \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)

- fireball/freeze-out dynamics $\Leftrightarrow m_T$ spectra and effective slopes
 - “non-thermal sources” important for $q_T \gtrsim 1$ GeV
 - lower $T_c \Rightarrow$ higher hadronic temperatures \Rightarrow harder q_T spectra
 - to describe measured effective slopes $a_{\perp} = 0.085c^2/\text{fm} \rightarrow 0.1c^2/\text{fm}$
 - 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 IQCD via **in-medium Weinberg chiral sum rules**
 - **direct connection to chiral phase transition!**