Electromagnetic Probes in Heavy-Ion Collisions IV

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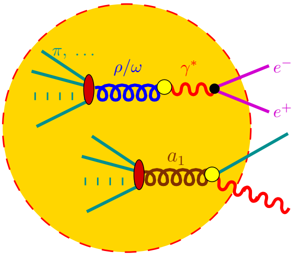
Outline

Em. probes and vector mesons

Why Electromagnetic Probes?

- $\gamma, \ell^{\pm}$: only e. m. interactions
- whole matter evolution



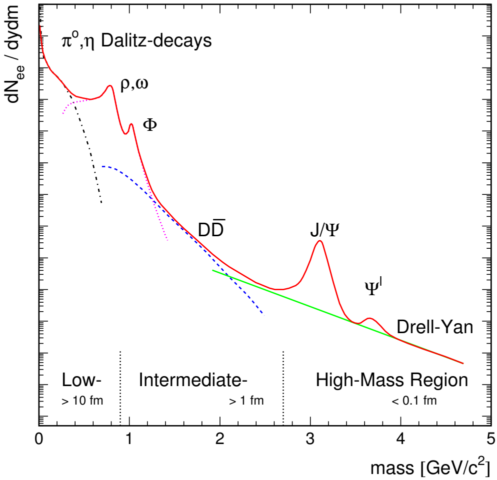


Fig. by A. Drees (from [RW00])

Vector Mesons and electromagnetic Probes

- photon and dilepton thermal emission rates given by same electromagnetic-current-correlation function ($J_\mu = \sum_f Q_f \overline{\psi_f} \gamma_\mu \psi_f$)
- McLerran-Toimela formula (cf. Lecture II)

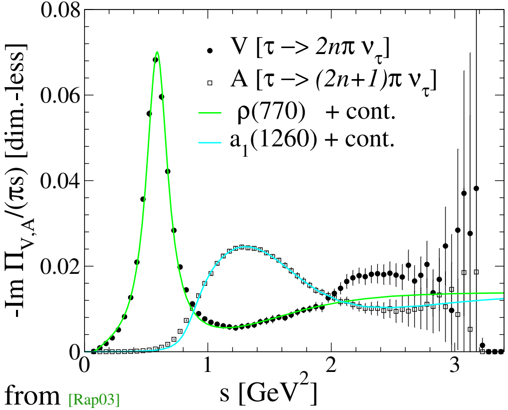
$$\Pi^{<}_{\mu\nu}(q) = \int \mathrm{d}^4 x \exp(\mathrm{i} q \cdot x) \left\langle J_\mu(0) J_\nu(x) \right\rangle_T = -2 n_B(q_0) \, \mathrm{Im} \, \Pi^{(\text{ret})}_{\mu\nu}(q)$$

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

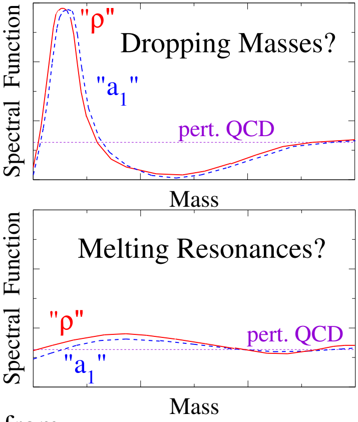
$$\frac{\mathrm{d}N_{e^+e^-}}{\mathrm{d}^4 x \mathrm{d}^4 k} = -g^{\mu\nu} \frac{\alpha^2}{3 q^2 \pi^3} \, \mathrm{Im} \, \Pi^{(\text{ret})}_{\mu\nu}(q,u) \Big|_{q^2 = M^2_{e^+e^-}} f_B(p \cdot u)$$

- manifestly Lorentz covariant (dependent on four-velocity of fluid cell, u)
- to lowest order in α: $4\pi\alpha \Pi_{\mu\nu} \simeq \Sigma^{(\gamma)}_{\mu\nu}$
- derivable from underlying thermodynamic potential, Ω!

Vector Mesons and chiral symmetry



from [Rap03]



from [Rap05]

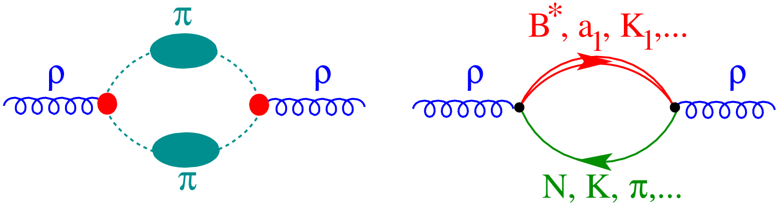
Hadronic models for light vector mesons

Realistic hadronic models for light vector mesons

- many approaches
  - gauged linear σ-model + vector-meson dominance [Pis95, UBW02]
    gauge-symmetry breaking $\Rightarrow$ pions still in physical spectrum!
  - massive Yang-Mills model; gauged non-linear chiral model with explicitly broken gauge symmetry [Mei88, LSY95]
  - hidden local symmetry: Higgs-like chiral model [BK84, HY03, HY03]
    allows for vector manifestation or usual manifestation (with a_1)
- here we concentrate on the phenomenological model by Rapp, Wambach, et al [RW99, RG99, RW00]

Hadronic many-body theory

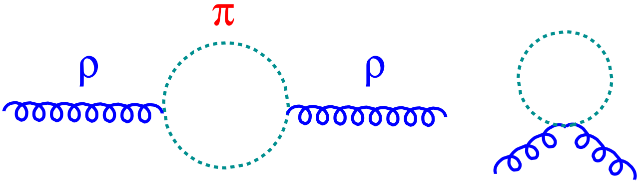
- Phenomenological HMBT [RW99, RG99] for vector mesons
- $\pi\pi$ interactions and baryonic excitations

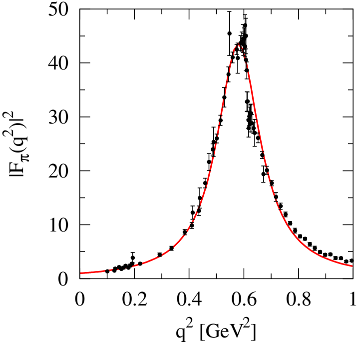


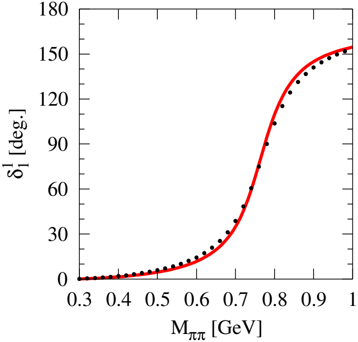
- Baryon (resonances) important, even at RHIC with low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

The meson sector (vacuum)

- most important for ρ-meson: pions

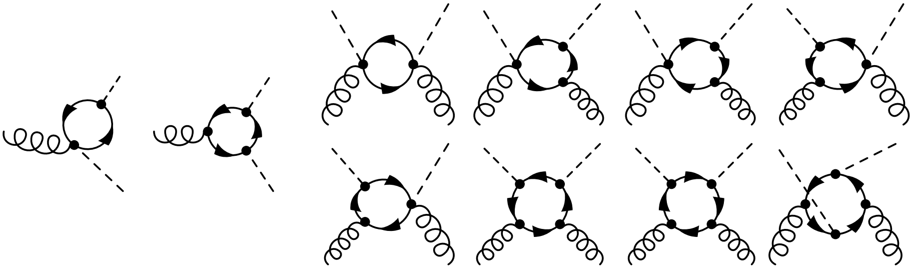




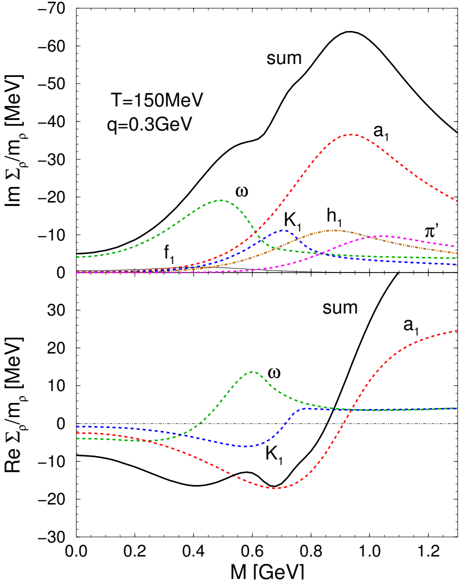


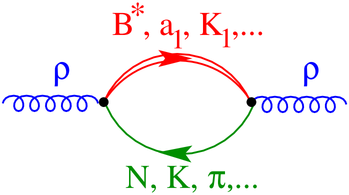
The meson sector (matter)

- Pions dressed with N-hole-, Δ-hole bubbles
- Ward-Takahashi ⇒ vertex corrections mandatory!



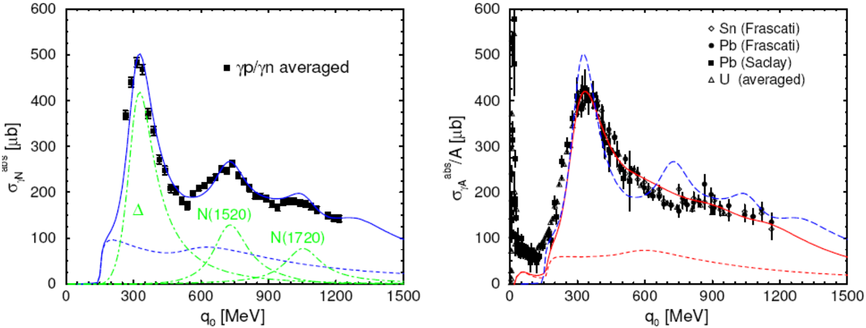
The meson sector (contributions from higher resonances)



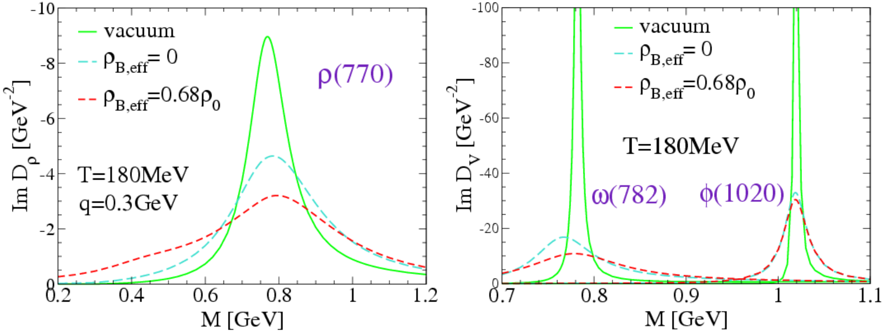


- $P = 1$-baryons: p-wave coupling to ρ:
  N(939), Δ(1232), N(1720), Δ(1905)
- $P = -1$-baryons: s-wave coupling to ρ:
  N(1520), Δ(1620), Δ(1700)

Photoabsorption on nucleons and nuclei



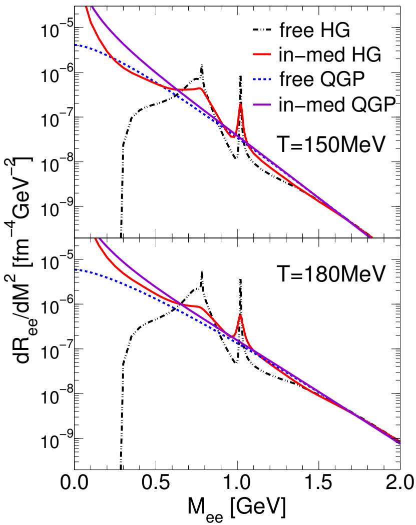
In-medium spectral functions and baryon effects



[RW99]

- baryon effects important
  - large contribution to broadening of the peak
  - responsible for most of the strength at small M
  - important even at RHIC and LHC although $n_{\text{net B}} = n_{\text{B}} - n_{\bar{\text{B}}} \simeq 0$ ($\mu_{\text{B}} \simeq 0$)
  - reason: C-invariance of strong interactions $\Rightarrow n_{\text{B}} + n_{\bar{\text{B}}}$ relevant!

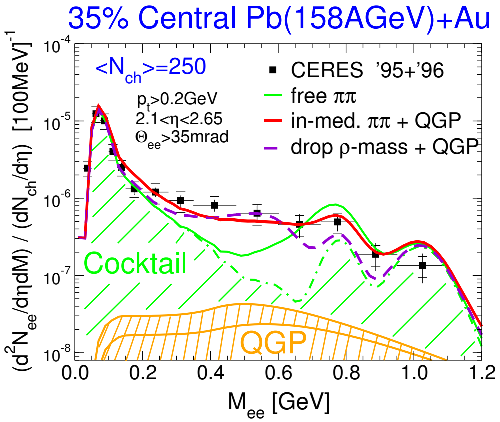
Dilepton rates: Hadron gas ↔ QGP

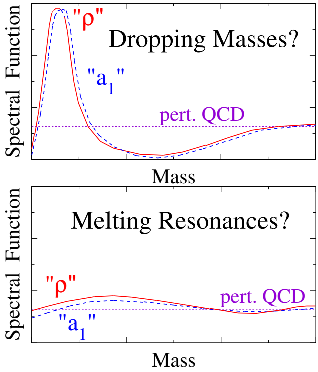


- in-medium hadron gas matches with QGP
- similar results also for γ rates
- "quark-hadron duality"?
- does it work with chiral model?
- hidden local symm.+baryons? [Harada, Yamawaki et al.]

Dileptons in AA collisions

Dilepton rates at SpS

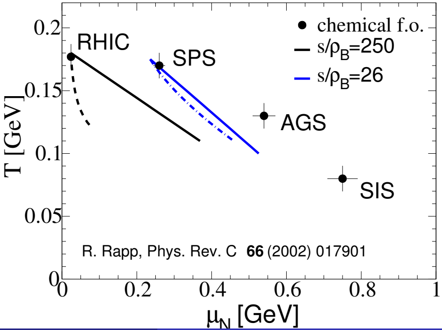




- how to decide about scenario experimentally?
- need to compare (more) precise data to detailed models!

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
  - $T > T_c$: massless gas for QGP with $N_f^{\text{eff}} = 2.3$
  - mixed phase: $f_{\text{HG}}(t) = [s_c^{\text{QGP}} - s(t)]/[s_c^{\text{QGP}} - s_c^{\text{HG}}]$
  - $T < T_c$: 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 $s/\rho_B = 27$
- thermal freezeout: $(T_{\text{fo}}, \mu_\pi^{\text{fo}}) \simeq (120, 80)$ MeV



Flow and particle/resonance distributions

- assume local thermal equilibrium: $T(t)$
- collective radial flow: $u(t,\vec{x}) = 1/\sqrt{1-\vec{v}^2}(1,\vec{v})$
- $\vec{v}(t,\vec{x}) = a_\perp t\, \vec{x}_\perp / R(t)$
- phase-space distribution for hadrons [F. Cooper, G. Frye 74]

$$\frac{\mathrm{d}N_i}{\mathrm{d}^3\vec{p}\,\mathrm{d}^3\vec{x}} = \frac{g_i}{(2\pi)^3} f_{B/F}\left(\frac{p\cdot u(t,\vec{x}) - \mu_i(t)}{T(t)}\right)$$

- NB:
  - covariant notation $\mathrm{d}^3\vec{x}\,\mathrm{d}^3\vec{p} = p_\mu \mathrm{d}\sigma^\mu \mathrm{d}^3\vec{p}/\sqrt{\vec{p}^2+m^2}$
  - $pu(t,\vec{x}) = \overline{p_0}$: energy of particle in rest frame of fluid cell
  - leads to "Doppler shifts" of hadron and dilepton spectra; for radial flow in HICs: blue shift $\Rightarrow$ hardening of p_T spectra
- phase-space distribution for bosonic resonances:

$$\frac{\mathrm{d}N_i}{\mathrm{d}^4p\,\mathrm{d}^3\vec{x}} = \frac{g_i}{(2\pi)^4} f_B\left(\frac{p\cdot u(t,\vec{x}) - \mu_i}{T(t)}\right)[-2p_0 \operatorname{Im} D_i(p)]$$

- $D_i(p)$: propagator of resonance, $A_i(p) = -2\operatorname{Im} D_i(p)$: spectral function

Sources of dilepton emission in heavy-ion collisions

Rest of lecture based on [HR06, HR08]

1. "core" ⇔ emission from thermal source [MT85, GK91]

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

2. "corona" ⇔ emission from "primordial" mesons (jet-quenching)
3. after thermal freeze-out ⇔ emission from "freeze-out" mesons

[Cooper, Frye 1975]

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

- 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 $\propto \frac{\Gamma_{\text{meson}\to\ell^+\ell^-}}{\Gamma_{\text{meson}}}$
- initial hard processes: Drell Yan

Radiation from thermal sources: $q\bar{q}$ annihilation

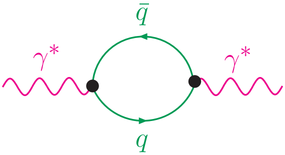
- General: McLerran-Toimela formula

$$\frac{\mathrm{d}N^{(\mathrm{MT})}_{l^+l^-}}{\mathrm{d}^4x\mathrm{d}^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M^2)}{M^2} g_{\mu\nu} \mathrm{Im} \sum_i \Pi^{\mu\nu}_{\mathrm{em},i}(M,\vec{q}) f_B\left(\frac{q\cdot u - \mu_i(t)}{T(t)}\right)$$

- i enumerates partonic/hadronic sources of em. currents
- in-medium em. current-current correlation function

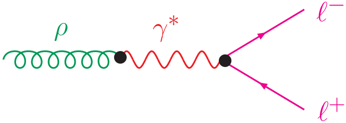
$$\Pi^{\mu\nu}_{\mathrm{em},i} = \mathrm{i}\int \mathrm{d}^4x \exp(\mathrm{i}qx)\Theta(x^0)\left\langle\left[j^{\mu}_{\mathrm{em},i}(x), j^{\nu}_{\mathrm{em},i}(x)\right]\right\rangle$$

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

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

Radiation from thermal sources: ρ decays

- model assumption: vector-meson dominance



$$\frac{\mathrm{d}N^{(\mathrm{MT})}_{\rho\to l^+l^-}}{\mathrm{d}^4x\mathrm{d}^4q} = \frac{M}{q^0}\Gamma_{\rho\to l^+l^-}(M)\frac{\mathrm{d}N_\rho}{\mathrm{d}^3\vec{x}\mathrm{d}^4q}$$

$$= -\frac{\alpha^2}{3\pi^3}\frac{L(M^2)}{M^2}\frac{m_\rho^4}{g_\rho^2}g_{\mu\nu}\,\mathrm{Im}\,D_\rho^{\mu\nu}(M,\vec{q})f_B\left(\frac{q\cdot u-2\mu_\pi(t)}{T(t)}\right)$$

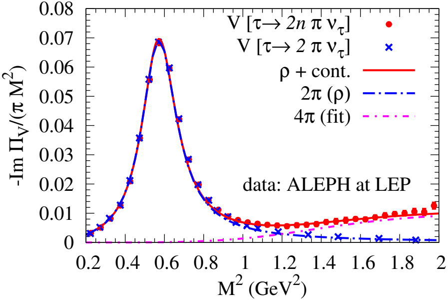
- special case of McLerran-Toimela (MT) formula
- $M^2=q^2$: invariant mass, M, of dilepton pair
- $L(M^2)=(1+2m_l^2/M^2)\sqrt{1-4m_l^2/M^2}$: dilepton phase-space factor
- $D_\rho^{\mu\nu}(M,\vec{q})$: (four-transverse part of) in-medium ρ propagator at given $T(t)$, $\mu_{\text{meson/baryon}}(t)$
- analogous for ω and ϕ

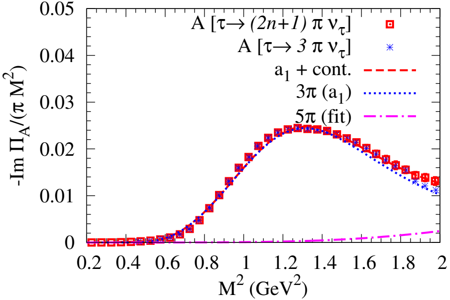
Radiation from thermal sources: multi-π processes

- use vector/axial-vector correlators from τ-decay data
- Dey-Eletsky-Ioffe mixing: $\hat{\varepsilon} = 1/2\varepsilon(T,\mu_\pi)/\varepsilon(T_c,0)$

$$\Pi_V = (1-\hat{\varepsilon}) z_\pi^4 \Pi_{V,4\pi}^{\text{vac}} + \frac{\hat{\varepsilon}}{2} z_\pi^3 \Pi_{A,3\pi}^{\text{vac}} + \frac{\hat{\varepsilon}}{2} (z_\pi^4 + z_\pi^5) \Pi_{A,5\pi}^{\text{vac}}$$

- avoid double counting: leave out two-pion piece and $a_1 \rightarrow \rho + \pi$ (already contained in ρ spectral function)

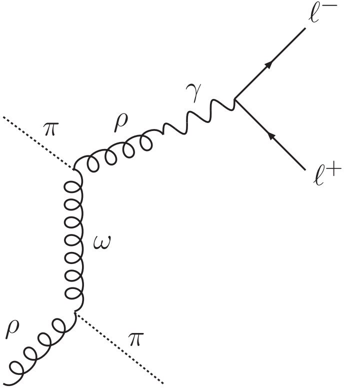




Data: [R. Barate et al (ALEPH Collaboration) 98]

Radiation from thermal sources: Meson t-channel exchange

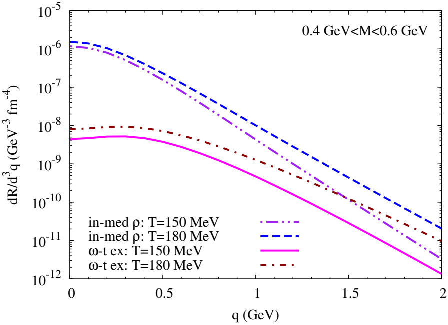
- motivation: q_T spectra too soft compared to NA60 data
- thermal contributions not included in models so far

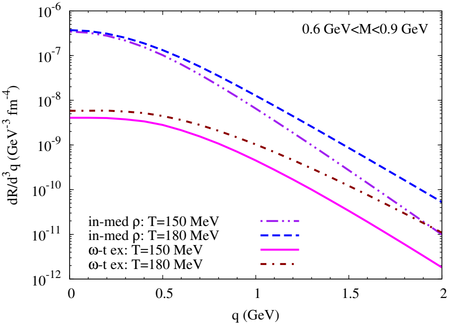


- also for π, a_1

Radiation from thermal sources: Meson t-channel exchange

- t-channel exchange contributions become significant at high momenta
- Mass integrated rates:





ρ decay after thermal freezeout

- assume "sudden freezeout" at constant "lab time": $t = t_{\text{fo}}$
- then Cooper-Frye formula with $\mathrm{d}\sigma^\mu = (\mathrm{d}^3\vec{x}, 0, 0, 0)$

$$\frac{\mathrm{d}N^{(\text{fo})}_{\rho \to l^+ l^-}}{\mathrm{d}^3\vec{x}\,\mathrm{d}^4\vec{q}} = \frac{\Gamma_{l^+ l^-}}{\Gamma^{\text{tot}}_\rho} \frac{\mathrm{d}N_i}{\mathrm{d}^3\vec{x}\,\mathrm{d}^4 q}$$

$$= \frac{q_0}{M} \frac{1}{\Gamma^{\text{tot}}_\rho} \left[\frac{\mathrm{d}N^{(\text{MT})}_{\rho \to l^+ l^-}}{\mathrm{d}^4 x\,\mathrm{d}^4 q} \right]_{t = t_{\text{fo}}}$$

- use vacuum ρ shape with in-medium width $\Gamma^{\text{tot}}_\rho \simeq 260$ MeV
- NB: Momentum dependence for dilepton spectra from ρ decays after thermal freezeout:

  like hadron spectra!

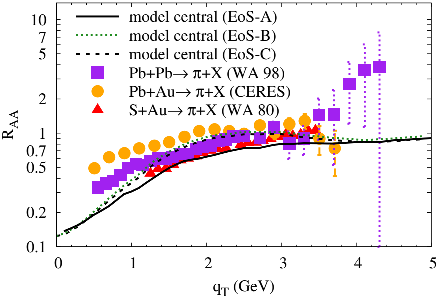
- $\Leftrightarrow$ $l^+ l^-$ from thermal sources softer by Lorentz factor M/q^0 compared to $l^+ l^-$ from decay of freeze-out ρ's

Decay of “primordial” ρ mesons

- ρ mesons, escaping from the fireball without thermalization
- *pp* data for initial ρ spectra; Cronin effect via “Gaussian smearing”
- Schematic jet-quenching model

$$P_{\text{esc}} = \exp\left(-\int \mathrm{d}t \; \sigma_\rho^{\text{abs}}(t) \, \rho(t)\right),$$

$$\sigma_\rho^{\text{abs}}(t) = \begin{cases} \sigma_{\text{ph}} = 0.4 \text{ mb} & \text{for} \quad t < q_0/m_\rho \, \tau_{\text{f}} \\ \sigma_{\text{had}} = 5 \text{ mb} & \text{for} \quad t > q_0/m_\rho \, \tau_{\text{f}} \end{cases}$$



- check with pion R_{AA} data
- “primordial ρ’s” + freezeout ρ’s
- hard q_T spectra including jet quenching

Drell-Yan Annihilation and correlated charm decays

- invariant-mass spectrum for DY pairs

$$\left.\frac{\mathrm{d}N_{\mathrm{DY}}^{AA}}{\mathrm{d}M\mathrm{d}y}\right|_{b=0} = \frac{3}{4\pi R_0^2} A^{4/3} \frac{\mathrm{d}\sigma_{\mathrm{DY}}^{NN}}{\mathrm{d}M\mathrm{d}y}$$

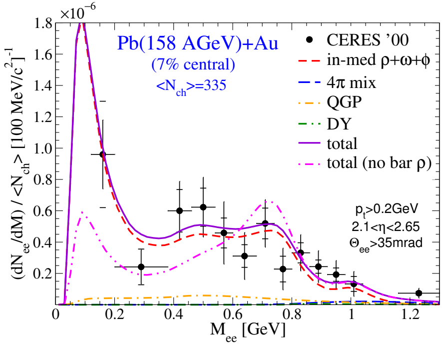
$$\frac{\mathrm{d}\sigma_{\mathrm{DY}}^{NN}}{\mathrm{d}M\mathrm{d}y} = K \frac{8\pi\alpha}{9sM} \sum_{q=u,d,s} e_q^2 \left[q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)\right]$$

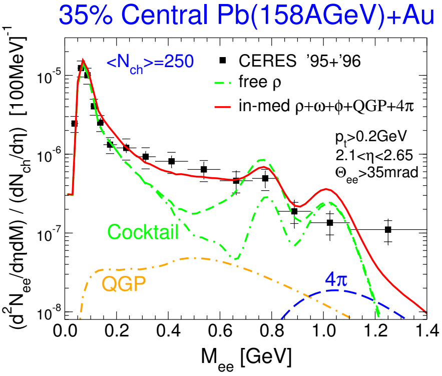
- parton distribution functions: GRV94LO
- higher-order effects
  - K factor
  - non-zero pair q_T: for IMR and HMR fitted by Gaussian spectrum (NA50 procedure)
- extrapolation to LMR: constrained by photon point $M \to 0$
- Correlated decays of D and $\overline{\mathrm{D}}$ mesons
  - use data (provided by NA60 collaboration)

Dileptons at the SPS

CERES/NA45 dielectron spectra

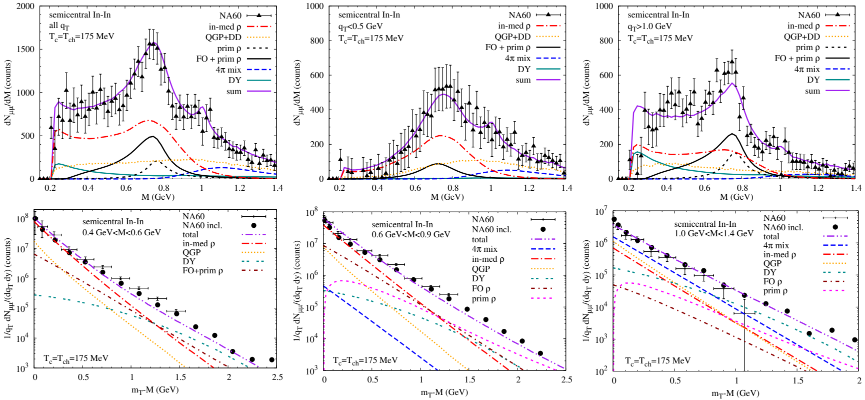
- good agreement also for dielectron spectra in 158 GeV Pb-Au
- further check of low-mass tail from baryon effects down to $M \to 2m_e$





NA60 vs. Hadronic many-body theory

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

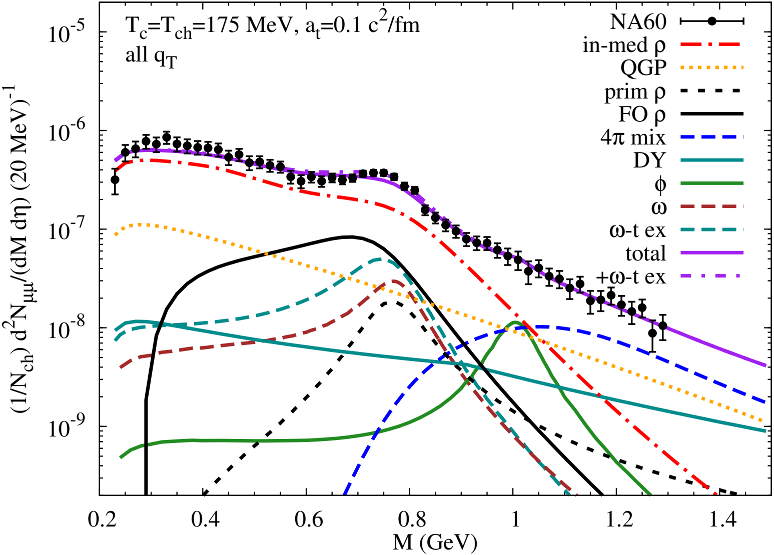


- M spectra

[HvH, Rapp 07]

  - consistent with predicted broadening of ρ meson
  - $M <$ 1GeV: 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

M spectra (in p_T slices)



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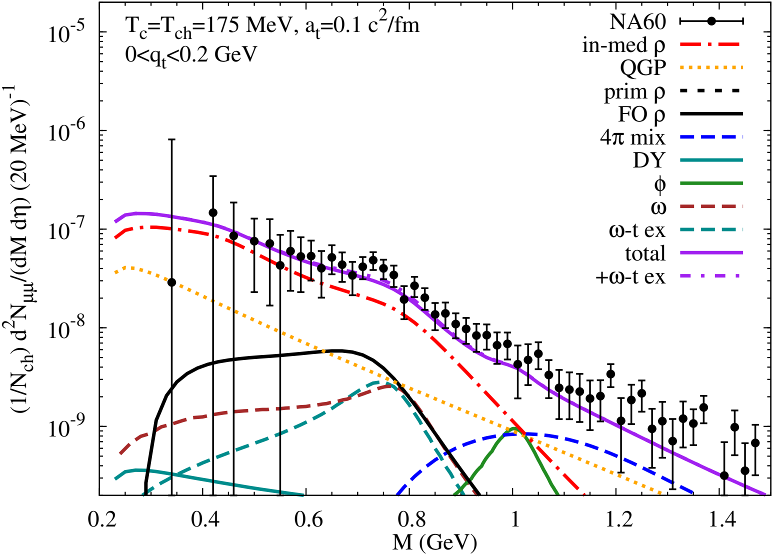

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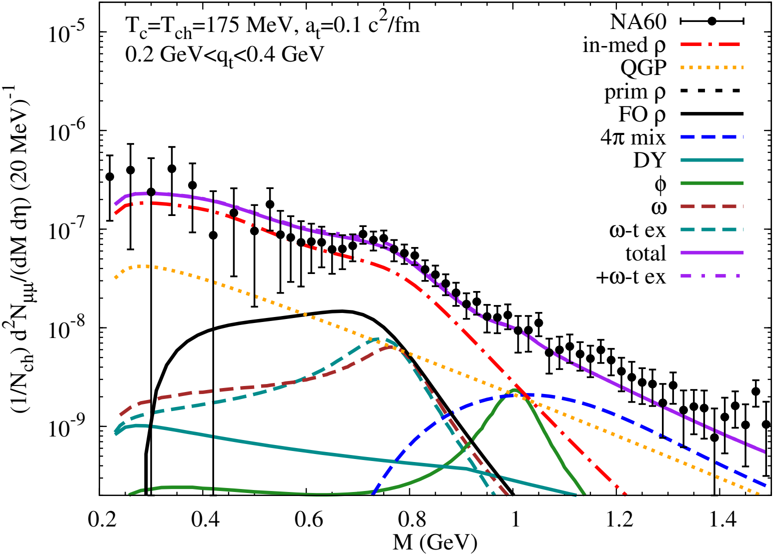

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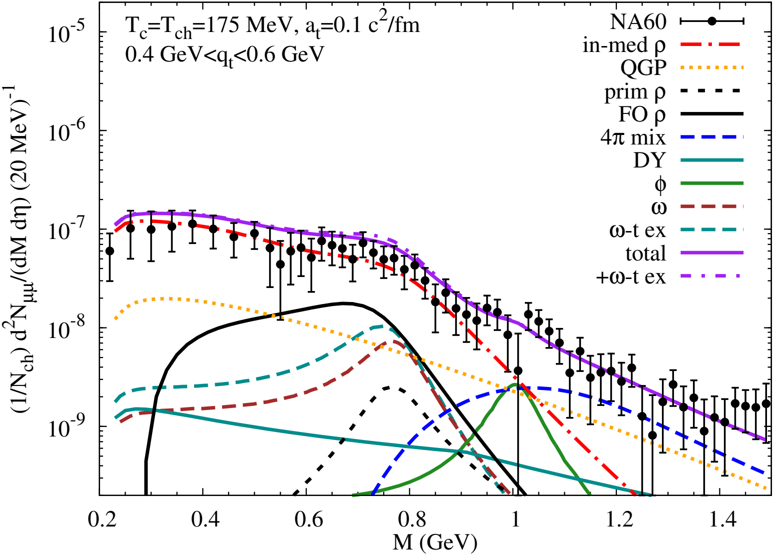

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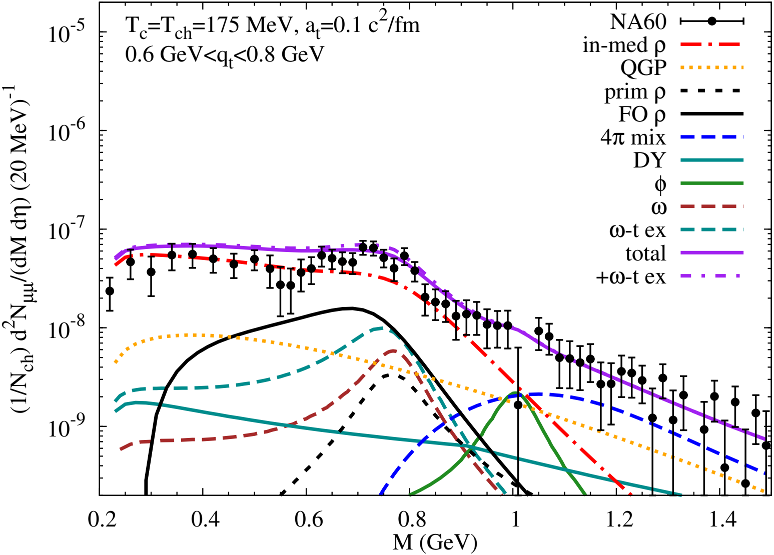

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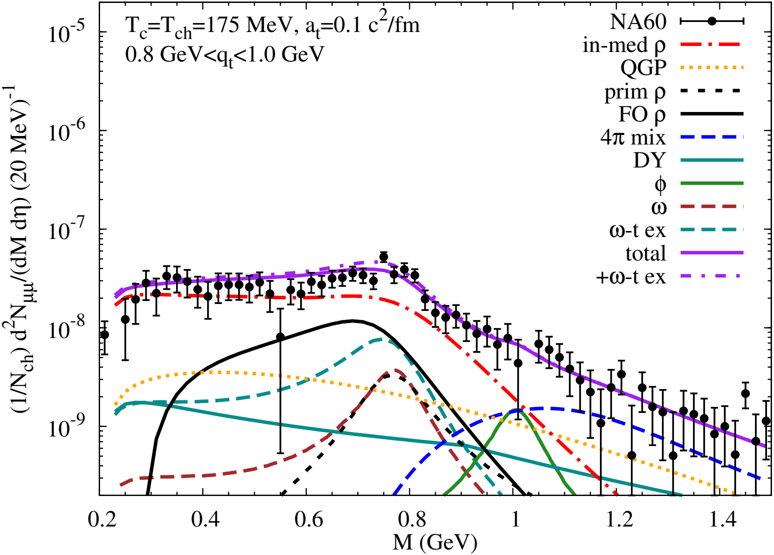
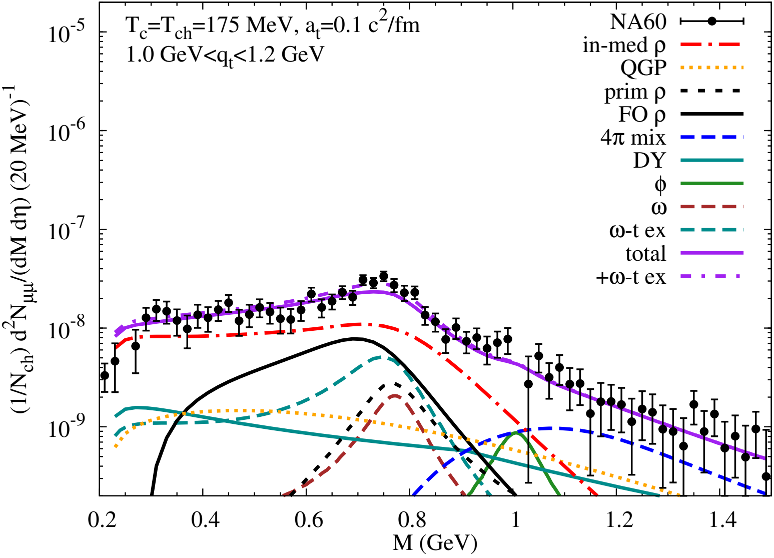
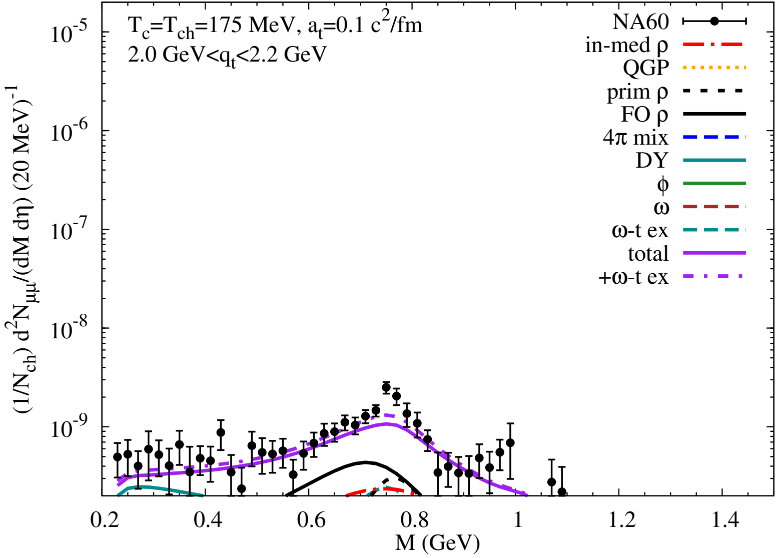


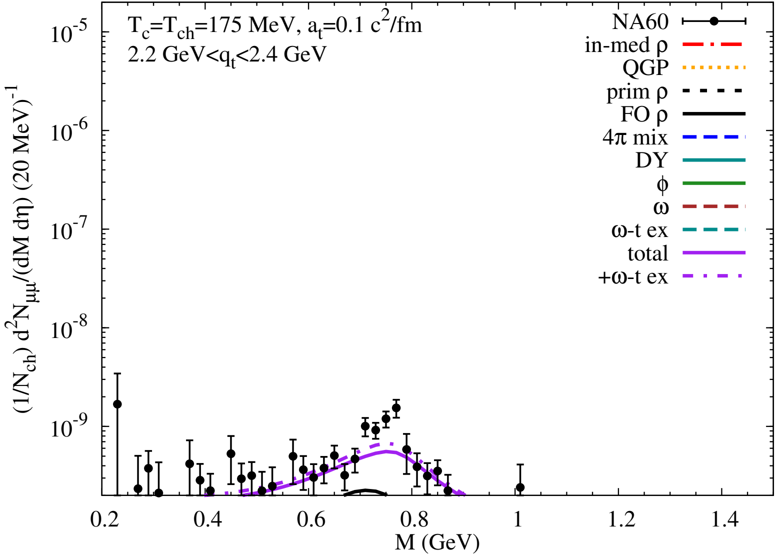
M spectra (in p_T slices)



M spectra (in p_T slices)

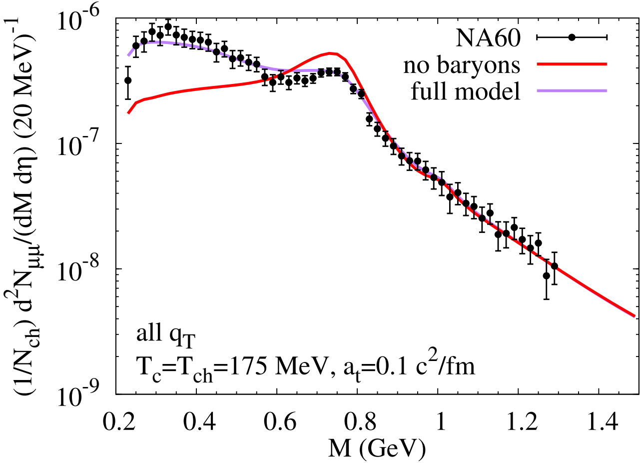


M spectra (in p_T slices)



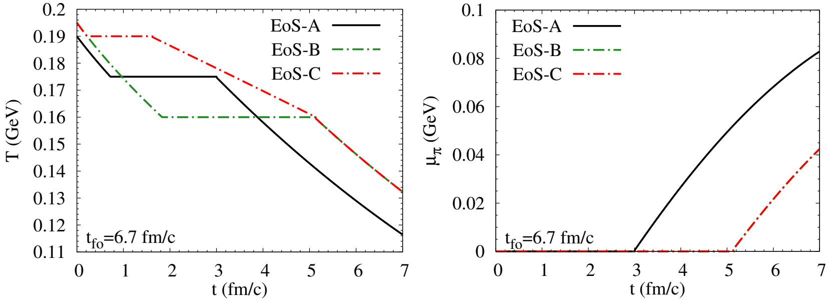
Importance of baryon effects

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



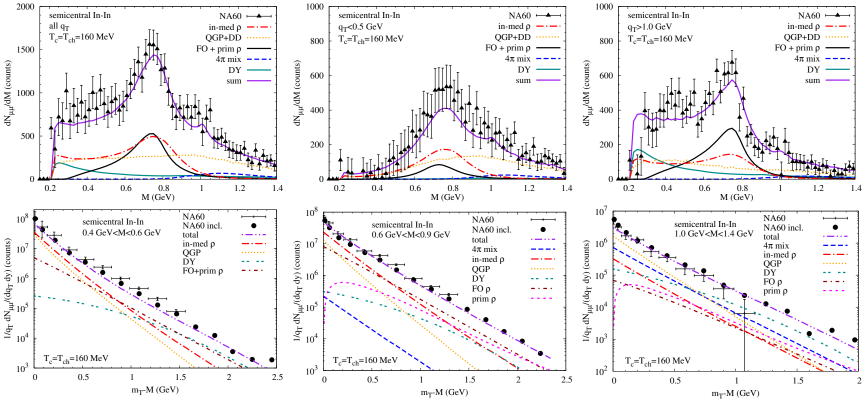
Sensitivity to T_c and hadro-chemistry

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



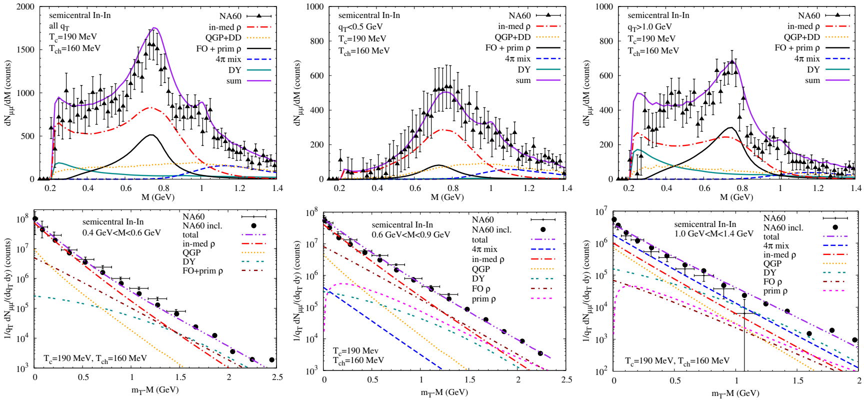
- EoS-A: $T_c = T_{\text{chem}} = 175$ MeV
- EoS-B: $T_c = T_{\text{chem}} = 160$ MeV
- EoS-C: $T_c = 190$ MeV, $T_{\text{chem}} = 160$ MeV
  - $T_c \geq T \geq T_{\text{chem}}$: hadron gas in chemical equilibrium
- keep fireball parameters the same (including life time)

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

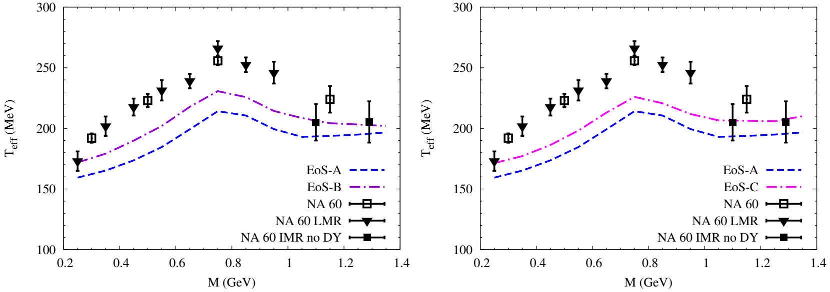


- mass spectra comparable to EoS-A ↔ slight reduction of fireball lifetime
- in IMR multi-pion ≫ QGP contribution
- higher hadronic temperatures + high-density hadronic phase ⇒ harder q_T spectra
- better agreement with data

- to extract T_{eff} fit to

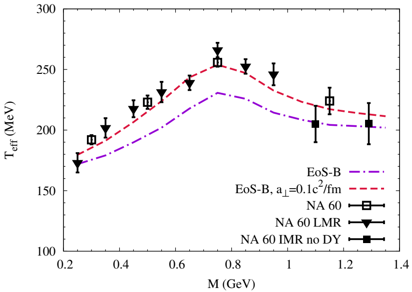
$$\frac{1}{q_T}\frac{\mathrm{d}N}{\mathrm{d}q_T} = \frac{1}{m_T}\frac{\mathrm{d}N}{\mathrm{d}m_T} = C\exp\left(-\frac{m_T}{T_{\text{eff}}}\right)$$

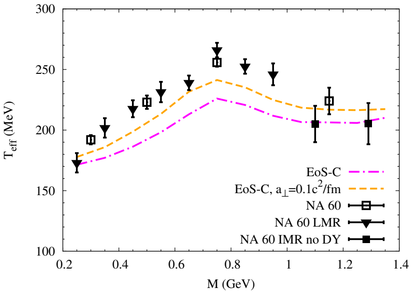
- fit of theoretical q_T spectra: $1\,\text{GeV} < q_T < 1.8\,\text{GeV}$



- 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

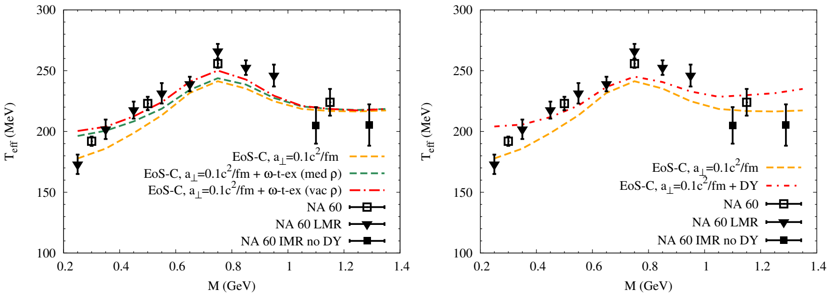
Inverse-slope analysis





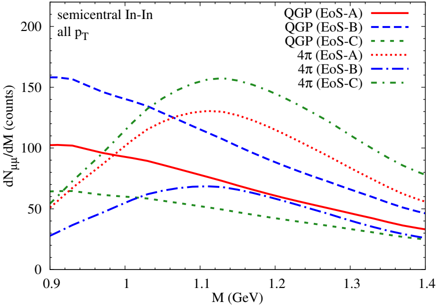
- enhance fireball acceleration to $a_\perp = 0.1c^2/\text{fm}$
- effective at all stages of fireball evolution
- agreement in IMR not spoiled ⇔ dominated from earlier stages
- EoS-B harder ⇔ relative contribution of harder freezeout ρ decays vs. thermal ρ's larger

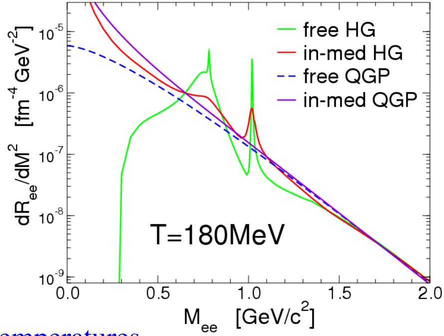
Inverse-slope analysis



- 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

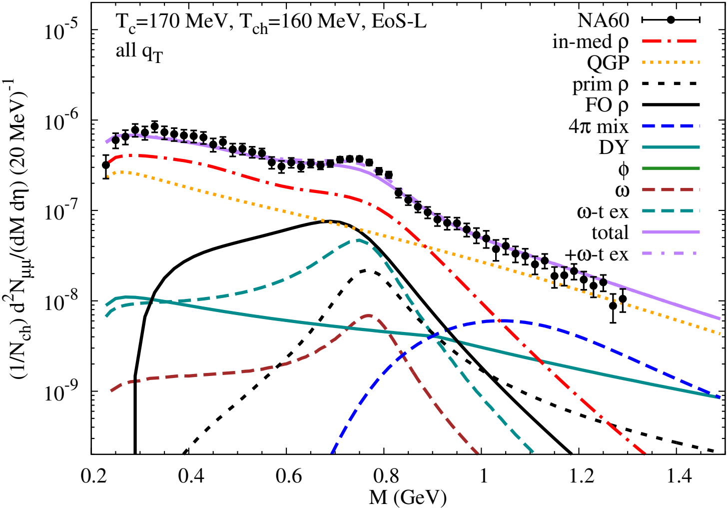




- different critical and freeze-out temperatures
  $T_c = 160 \ldots 190$ MeV, $T_{\text{chem}} = 160 \ldots 175$ MeV
- M- and p_T spectra comparably well described!
- reason: T vs. volume $\Rightarrow$ maximal l^+l^- emission for $T = T_{\text{max}} = M/5.5$
- hadronic and partonic radiation "dual" for $T \sim T_c$
  compatible with chiral-symmetry restoration!
- inconclusive whether hadronic or partonic emission in IMR!

Update: Using lattice equation of state

- use equation of state from lattice calculations (cross over!)
- use QGP rates adapted to recent lattice results



Update: Using lattice equation of state

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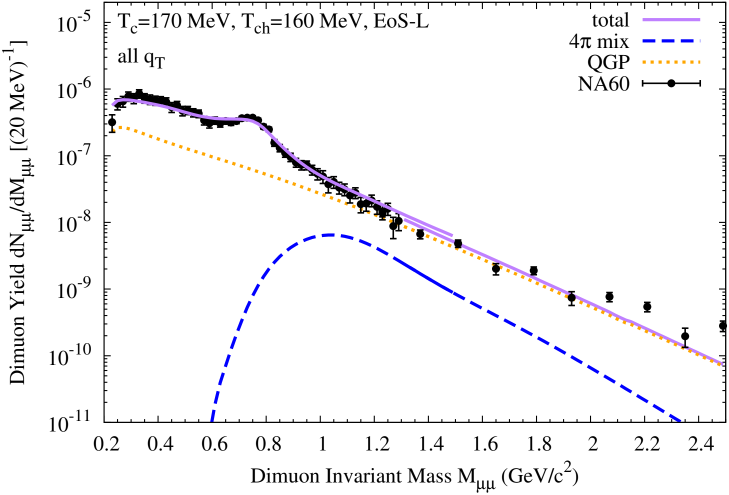
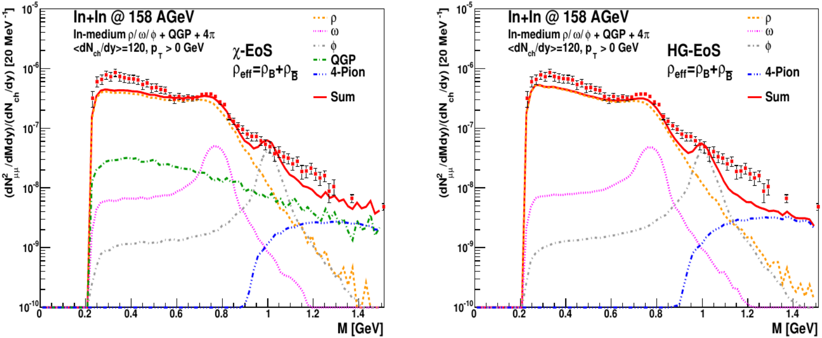
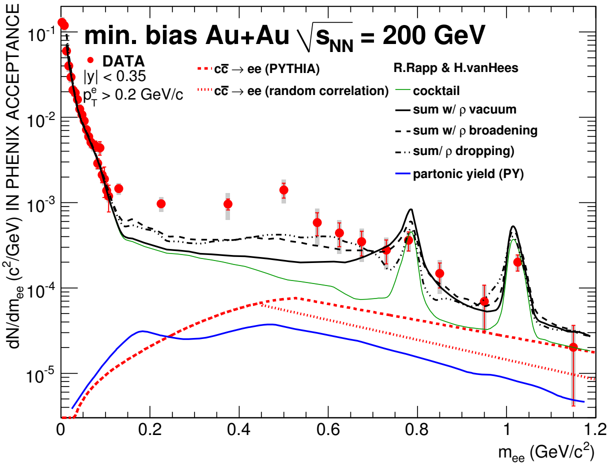


UrQMD: Coarse-grained transport

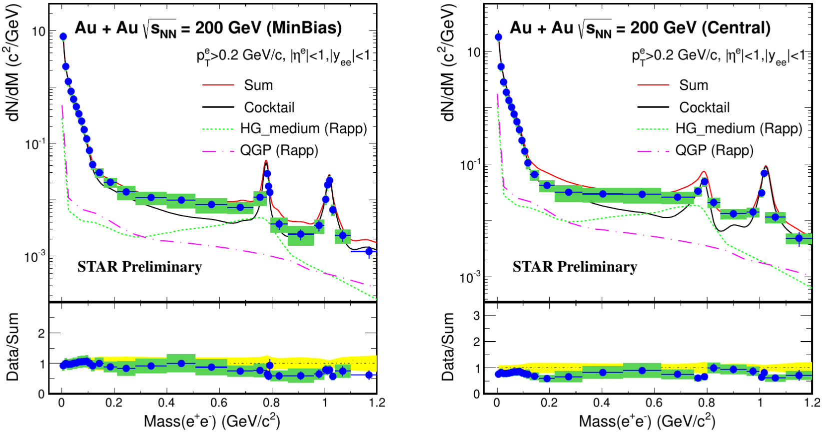
- using the coarse-grained transport approach at SPS energies
- Rapp-Wambach rates
- some sensititivity to equation of state



- huge enhancement in the LMR unexplained yet!



model: Rapp, HvH [A+10]



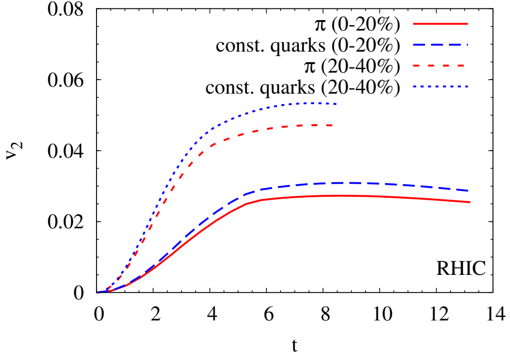
[Rap13], data from [Zha11]

- compatible with medium modifications in model calculation
- a new puzzle at RHIC?
- wait for “hadron blind PHENIX” central-collision data!(?)

Direct photons at RHIC and LHC

Fireball parametrization

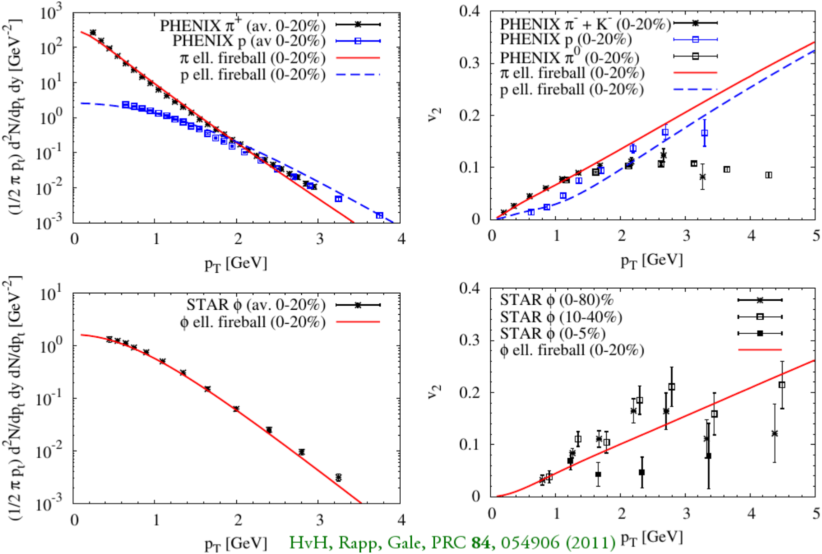
- parameters fit to initial condition + measured p_T spectra and v_2 of multi-strange and other hadrons, respectively
- can be achieved with (ideal) hydro [He, Fries, Rapp, PRC **85**, 044911 (2012)]



- important for "sufficient" photon v_2:
  - rapid buildup of v_2
  - (nearly) full v_2 at end of mixed phase
  - consistent with CQN scaling for multi-strange and other hadrons!

Fireball parametrization

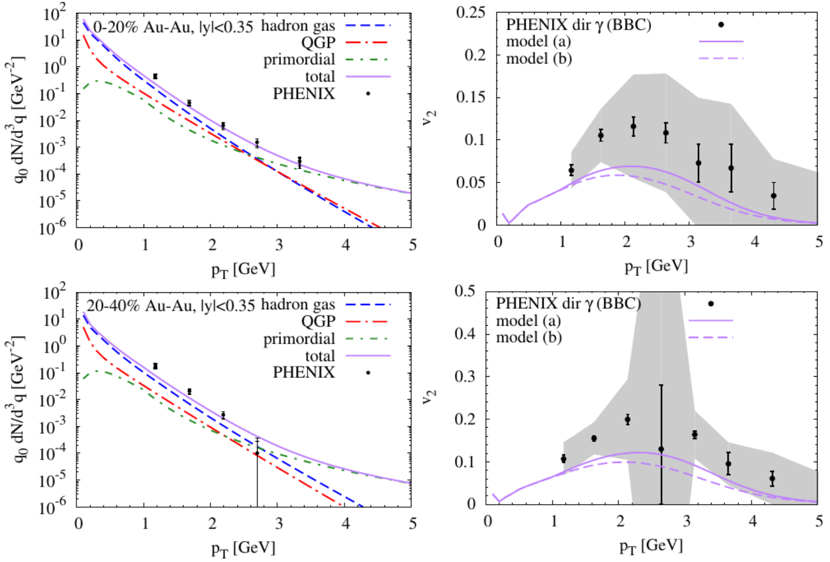
RHIC:



HvH, Rapp, Gale, PRC **84**, 054906 (2011)

Direct Photons at RHIC

RHIC:

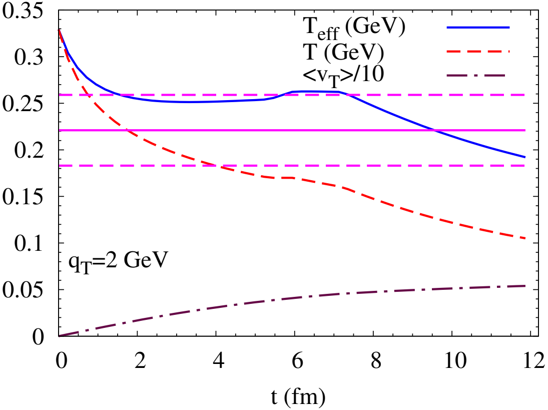


[HGR11]

Effective slopes vs. temperatures

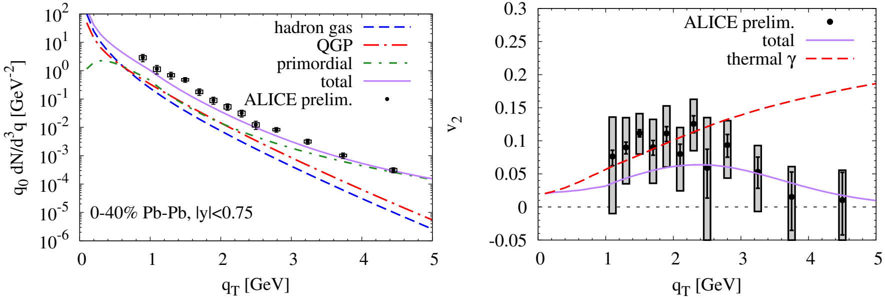
- effective slopes of photon p_T spectra are NOT temperatures!
- emission from a flowing medium ⇒ Doppler effect

$$T_{\text{eff}} \simeq \sqrt{\frac{1+\langle v_T \rangle}{1-\langle v_T \rangle}} T$$



Direct Photons at the LHC

LHC: same model, fireball adapted to hadron data from ALICE



[HvH, Rapp, Gale, unpublished]

- large direct-γ v_2
- early buildup of v_2; here developed already at end of QGP phase
- emission mostly around T_c (dual rates!) $\Rightarrow$
- $\Rightarrow$ source has already developed radial flow and v_2
- large effective slopes include blueshift from radial flow!
- still additional (hadronic?) sources (bremsstrahlung?) missing?!?

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Quiz

1. Why do we need effective hadronic models to theoretically study electromagnetic probes in HICs?
2. How do we constrain effective hadronic models theoretically?
3. How do we determine all the parameters (couplings, masses, form factors) of the models?
4. What is left to be predicted from such models?
5. What are the most important processes leading to medium modifications of the vector mesons' spectral functions?
6. What are the different dilepton sources that are important in UHICs?
7. Which interesting information can be gained from investigating also $\ell^+\ell^-$-p_T spectra in addition to M spectra?
8. What fundamental properties about the hot and dense medium produced in HICs have we inferred from $\ell^+\ell^-$ data so far?
9. What's the "photon-v_2 puzzle" in HICs? How can it (perhaps) be explained?