

Electromagnetic Probes in Heavy-Ion Collisions III

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 - Vector mesons and chiral symmetry
 - Realistic hadronic models for light vector mesons
 - Hadronic many-body theory (HMBT)
- 2 Dileptons in AA collisions at the SpS
 - Fireball model for evolution of the bulk
 - Sources of dileptons
- 3 Comparison to SPS data
 - Invariant-mass spectra
 - m_T spectra and slope analysis
- 4 The situation at RHIC
- 5 Conclusions and Outlook

Why Electromagnetic Probes?

- γ, l^\pm : only e. m. interactions
- whole matter evolution

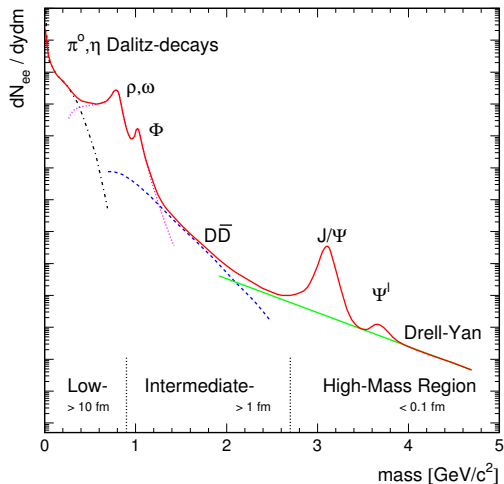
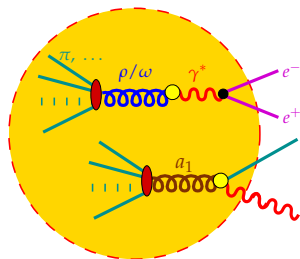


Fig. by A. Drees (from [RW00])

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

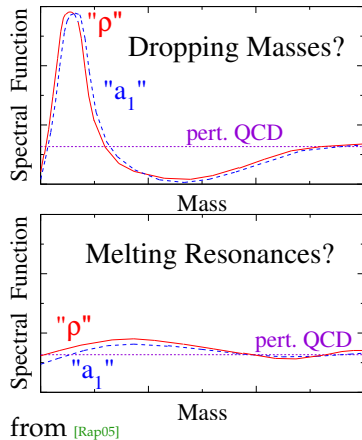
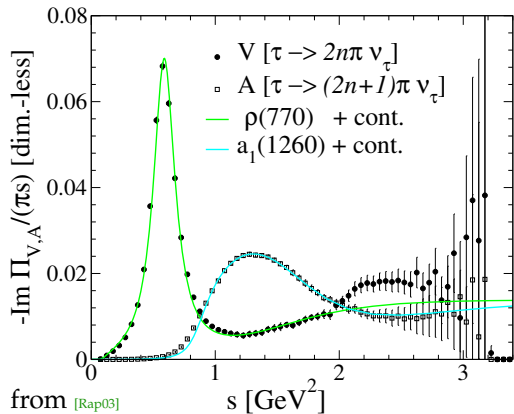
$$\Pi_{\mu\nu}^<(q) = \int d^4x \exp(iq \cdot x) \langle J_\mu(0) J_\nu(x) \rangle_T = -2n_B(q_0) \text{Im} \Pi_{\mu\nu}^{(\text{ret})}(q)$$

$$q_0 \frac{dN_\gamma}{d^4x d^3\vec{q}} = \frac{\alpha_{\text{em}}}{2\pi^2} g^{\mu\nu} \text{Im} \Pi_{\mu\nu}^{(\text{ret})}(q) \Big|_{q_0=|\vec{q}|} f_B(p_0)$$

$$\frac{dN_{e^+e^-}}{d^4x d^4k} = -g_{\mu\nu} \frac{\alpha^2}{3q^2 \pi^3} \text{Im} \Pi_{\mu\nu}^{(\text{ret})}(q) \Big|_{q^2=M_{e^+e^-}^2} f_B(p_0)$$

- **Caveat:** NOT manifestly Lorentz covariant \Leftrightarrow **heat-bath rest frame!**
- to lowest order in α : $4\pi\alpha\Pi_{\mu\nu} \simeq \Sigma_{\mu\nu}^{(\gamma)}$
- derivable from underlying thermodynamic potential, $\Omega!$

Vector mesons and chiral symmetry

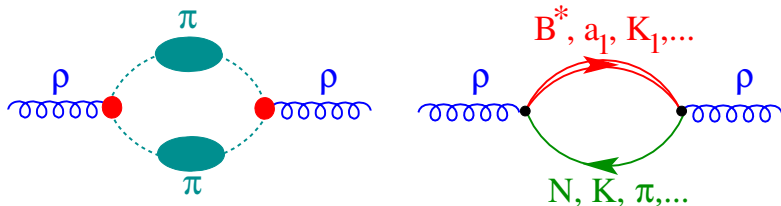


Realistic hadronic models for light vector mesons

- CERES data: pion- ρ model too simplistic
- many approaches to more realistic models
 - 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]

Hadronic many-body theory

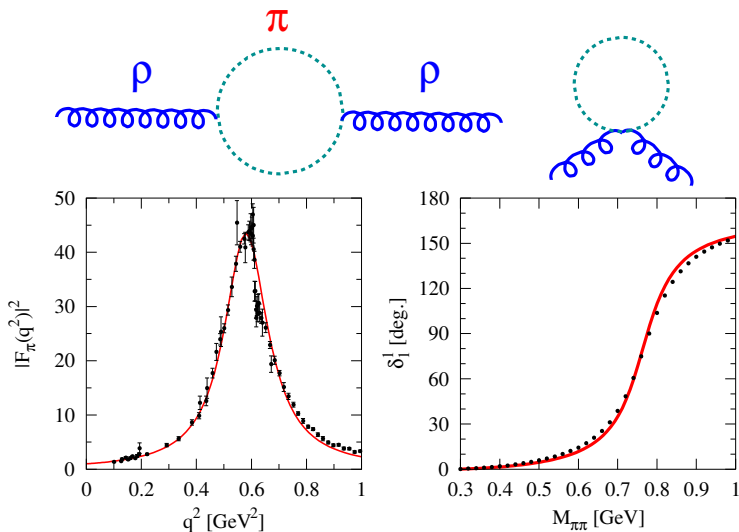
- Phenomenological HMBT [RW99] for vector mesons
- $\pi\pi$ interactions and **baryonic excitations**



- **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)

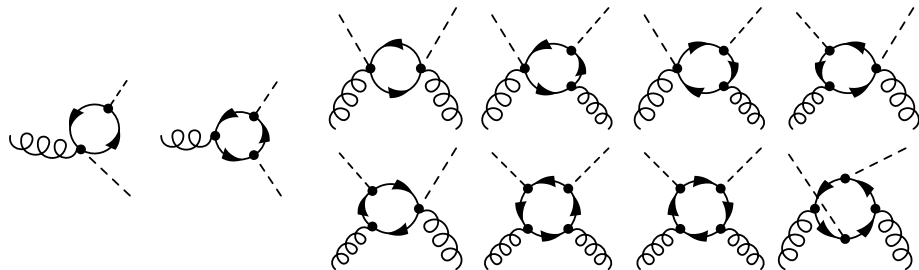
The meson sector (vacuum)

- most important for ρ -meson: pions

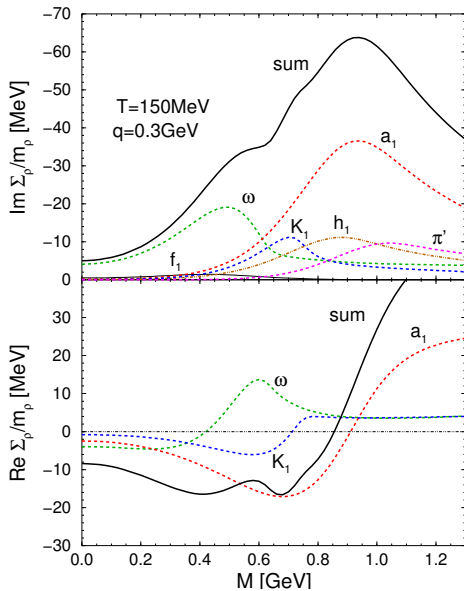


The meson sector (matter)

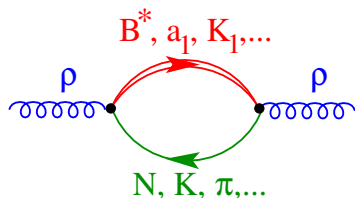
- Pions dressed with **N-hole-**, **Δ -hole** bubbles
- Ward-Takahashi \Rightarrow **vertex corrections** mandatory!



The meson sector

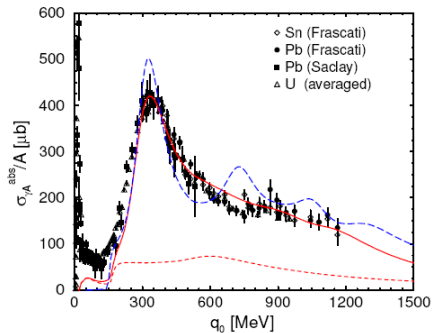
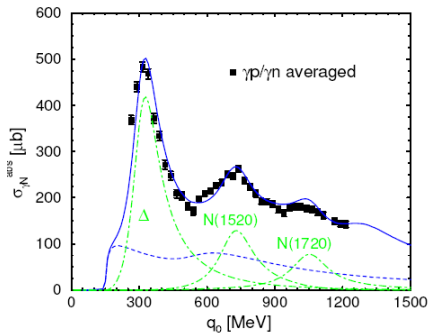


The baryon sector (vacuum)

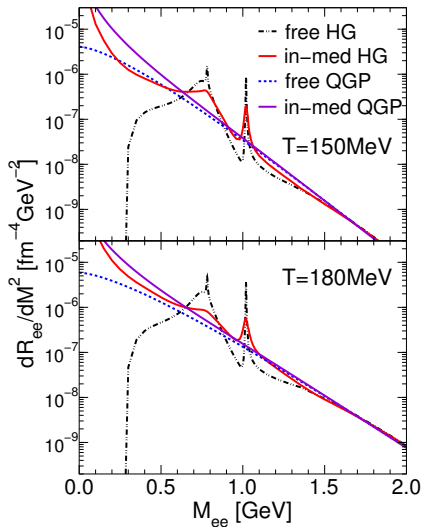


- $P = 1$ -baryons: p -wave coupling to ρ :
 $N(939), \Delta(1232), N(1720), \Delta(1905)$
- $P = -1$ -baryons: s -wave coupling to ρ :
 $N(1520), \Delta(1620), \Delta(1700)$

Photoabsorption on nucleons and nuclei

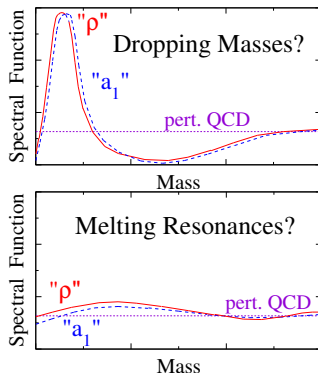
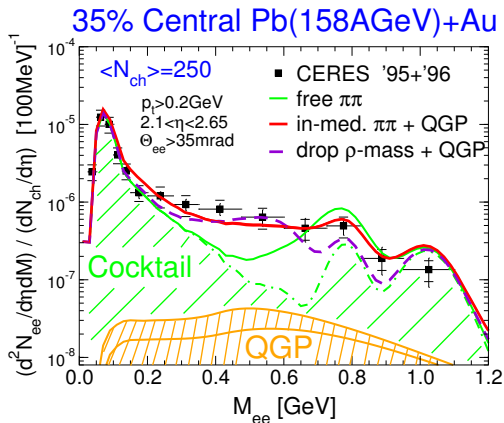


Dilepton rates: Hadron gas \leftrightarrow QGP



- 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.]

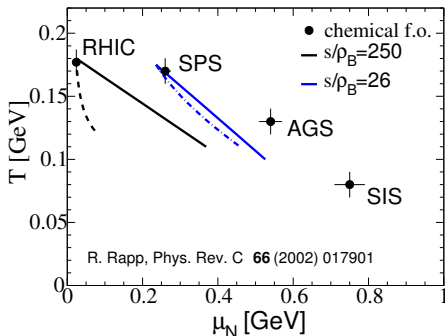
Dilepton rates at SpS



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

Fireball and Thermodynamics

- cylindrical **fireball model**: $V_{\text{FB}} = \pi(z_0 + v_{z0}t + \frac{a_z}{2}t^2) (\frac{a_{\perp}}{2}t^2 + r_0)^2$
- **thermodynamics**:
 - isentropic expansion; S_{tot} fixed by N_{ch} ; $T_c = T_{\text{chem}} = 175 \text{ MeV}$
 - $T > T_c$: 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**:
 - $\mu_N^{\text{chem}} = 232 \text{ MeV}$
 - hadron ratios fixed
 $\Rightarrow \mu_N, \mu_{\pi}, \mu_K, \mu_{\eta}$ at fixed
 $s/\rho_B = 27$
- **thermal freezeout**:
 $(T_{\text{fo}}, \mu_{\pi}^{\text{fo}}) \simeq (120, 80) \text{ MeV}$



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]

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

- NB:

- covariant notation $d^3\vec{x}d^3\vec{p} = p_{\mu}d\sigma^{\mu}d^3\vec{p} / \sqrt{\vec{p}^2 + m^2}$
- $pu(t, \vec{x}) = \bar{p}_0$: 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**:

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

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

Sources of dilepton emission in heavy-ion collisions

Rest of lecture based on [HR06, HR08]

- ① “core” \Leftrightarrow emission from thermal source [MT85, GK91]

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

- ② “corona” \Leftrightarrow emission from “primordial” mesons (jet-quenching)
- ③ 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 $\propto \frac{\Gamma_{\text{meson} \rightarrow \ell^+ \ell^-}}{\Gamma_{\text{meson}}}$
- initial hard processes: Drell Yan

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

- General: **McLerran-Toimela formula**

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

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

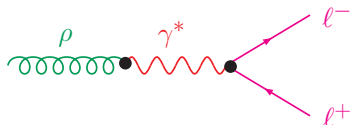
$$\Pi_{\text{em},i}^{\mu\nu} = i \int d^4x \exp(iqx) \Theta(x^0) \left\langle \left[j_{\text{em},i}^\mu(x), j_{\text{em},i}^\nu(x) \right] \right\rangle$$

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

$$-i\Pi_{\text{em},\text{QGP}} = \text{Diagram}$$

Radiation from thermal sources: ρ decays

- model assumption: **vector-meson dominance**



$$\begin{aligned} \frac{dN_{\rho \rightarrow l+l-}^{(MT)}}{d^4x d^4q} &= \frac{M}{q^0} \Gamma_{\rho \rightarrow l+l-}(M) \frac{dN_{\rho}}{d^3\vec{x} d^4q} \\ &= -\frac{\alpha^2}{3\pi^3} \frac{L(M^2)}{M^2} \frac{m_{\rho}^4}{g_{\rho}^2} g_{\mu\nu} \text{Im} D_{\rho}^{\mu\nu}(M, \vec{q}) f_B \left(\frac{q \cdot u - 2\mu_{\pi}(t)}{T(t)} \right) \end{aligned}$$

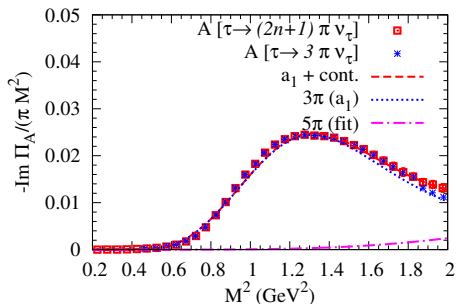
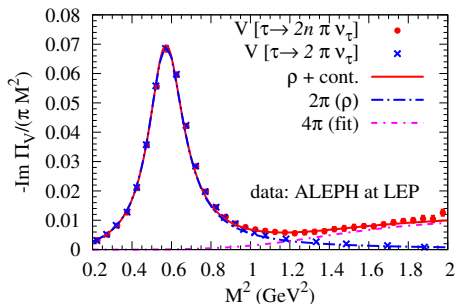
- special case of McLerran-Toimela (MT) formula
- $M^2 = q^2$: invariant mass, M , of dilepton pair
- $L(M^2) = (1 + 2m_l^2/M^2) \sqrt{1 - 4m_l^2/M^2}$: dilepton phase-space factor
- $D_{\rho}^{\mu\nu}(M, \vec{q})$: (four-transverse part of) in-medium ρ propagator at given $T(t)$, $\mu_{\text{meson/baryon}}(t)$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

Radiation from thermal sources: multi- π processes

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

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

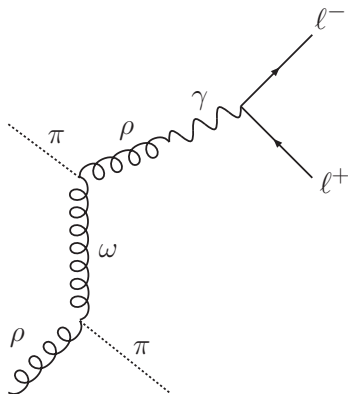
- avoid double counting: leave out two-pion piece and $a_1 \rightarrow \rho + \pi$ (already contained in ρ spectral function)



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

Radiation from thermal sources: Meson t-channel exchange

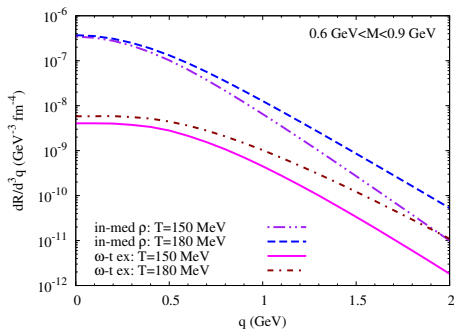
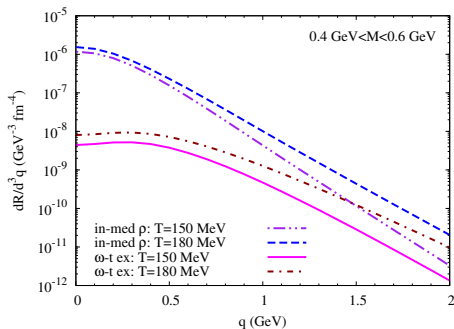
- motivation: q_T spectra too soft compared to NA60 data
- **thermal contributions** not included in models so far



- 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”: $t = t_{fo}$
- then Cooper-Frye formula with $d\sigma^\mu = (d^3\vec{x}, 0, 0, 0)$

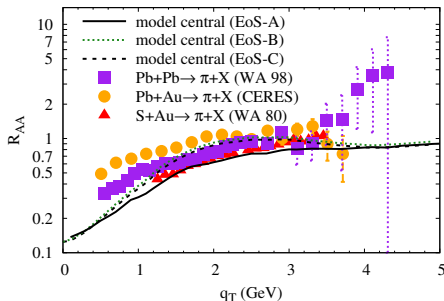
$$\begin{aligned}\frac{dN_{\rho \rightarrow l^+l^-}^{(fo)}}{d^3\vec{x}d^4\vec{q}} &= \frac{\Gamma_{l^+l^-}}{\Gamma_\rho^{\text{tot}}} \frac{dN_i}{d^3\vec{x}d^4q} \\ &= \frac{q_0}{M} \frac{1}{\Gamma_\rho^{\text{tot}}} \left[\frac{dN_{\rho \rightarrow l^+l^-}^{(MT)}}{d^4x d^4q} \right]_{t=t_{fo}}\end{aligned}$$

- use vacuum ρ shape with in-medium width $\Gamma_\rho^{\text{tot}} \simeq 260 \text{ MeV}$
- 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**

$$P_{\text{esc}} = \exp \left(- \int dt \sigma_{\rho}^{\text{abs}}(t) \varrho(t) \right),$$
$$\sigma_{\rho}^{\text{abs}}(t) = \begin{cases} \sigma_{\text{ph}} = 0.4 \text{ mb} & \text{for } t < q_0/m_{\rho} \tau_f \\ \sigma_{\text{had}} = 5 \text{ mb} & \text{for } t > q_0/m_{\rho} \tau_f \end{cases}$$



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

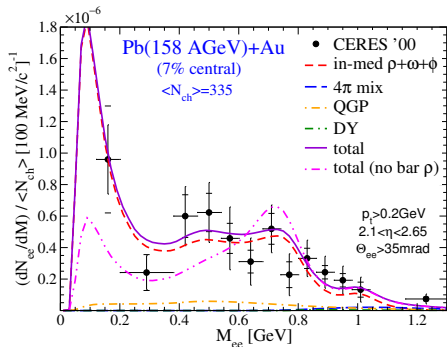
- **invariant-mass spectrum** for DY pairs

$$\left. \frac{dN_{DY}^{AA}}{dMdy} \right|_{b=0} = \frac{3}{4\pi R_0^2} A^{4/3} \frac{d\sigma_{DY}^{NN}}{dMdy}$$
$$\frac{d\sigma_{DY}^{NN}}{dMdy} = K \frac{8\pi\alpha}{9sM} \sum_{q=u,d,s} e_q^2 [q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)]$$

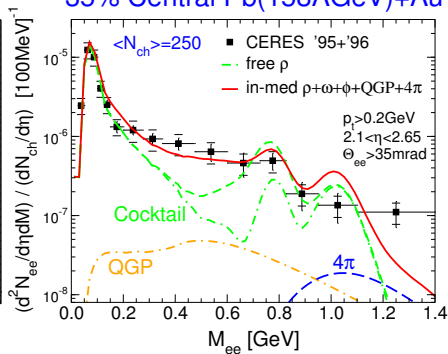
- **parton distribution functions**: GRV94LO
- **higher-order effects**
 - K factor
 - non-zero pair q_T : for IMR and HMR fitted by **Gaussian spectrum** (NA50 procedure)
- extrapolation to LMR: constrained by photon point $M \rightarrow 0$
- Correlated decays of D and \bar{D} mesons
 - use data (provided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

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 $M \rightarrow 2m_e$

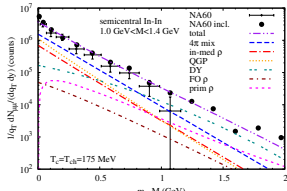
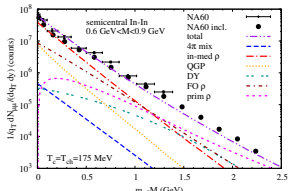
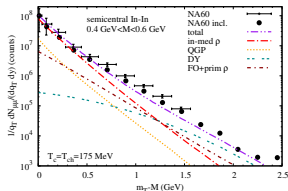
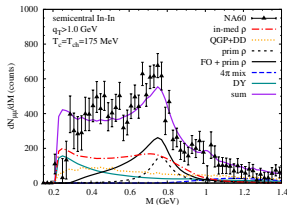
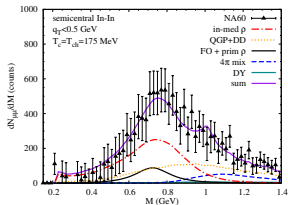
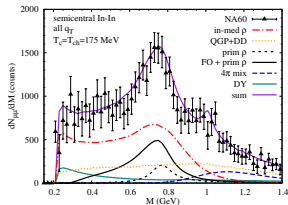


35% Central Pb(158 AGeV)+Au



NA60 vs. Hadronic many-body theory

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



• M spectra

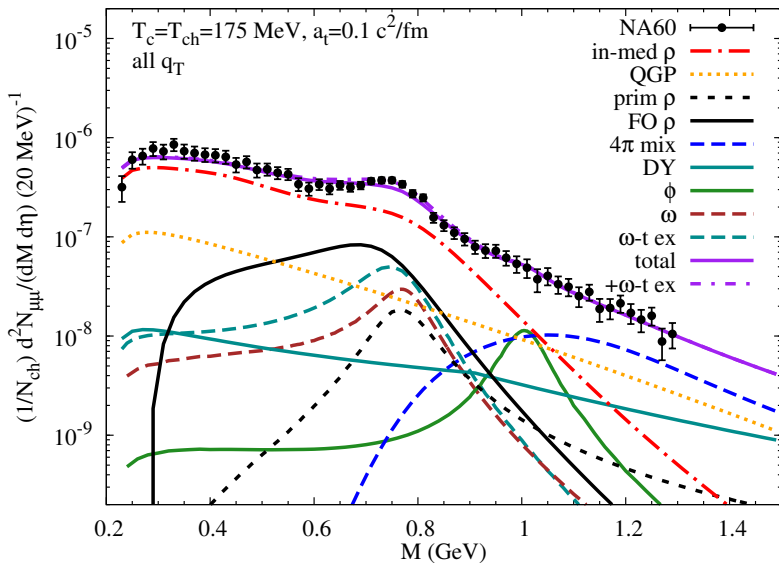
- consistent with predicted broadening of ρ meson
- $M < 1$ GeV: thermal ρ ; $M > 1$ GeV: thermal multi-pion processes

• m_t spectra

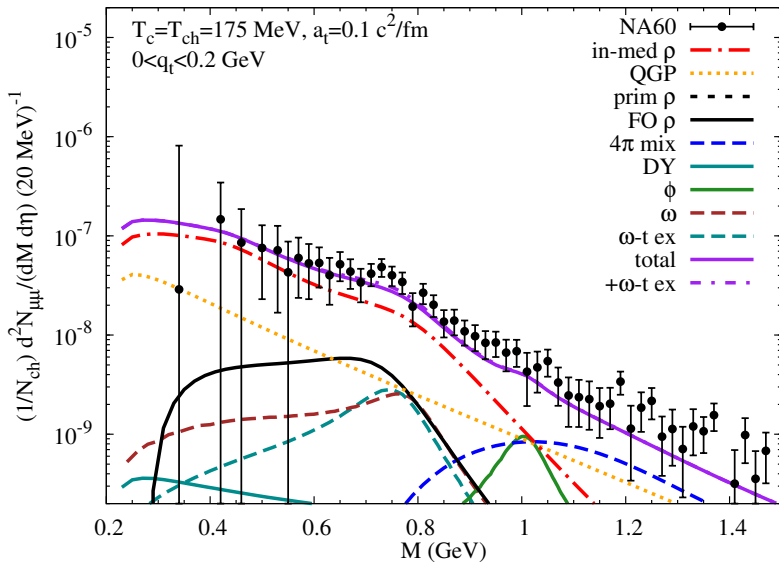
- $q_t < 1$ GeV: thermal radiation
- $q_t > 1$ GeV: freeze-out + hard primordial ρ , Drell-Yan

[HvH, Rapp 07]

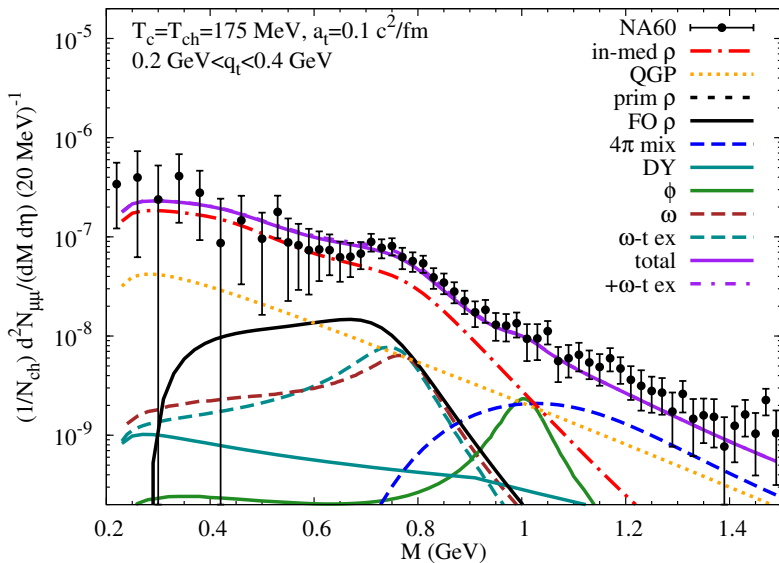
M spectra (in p_T slices)



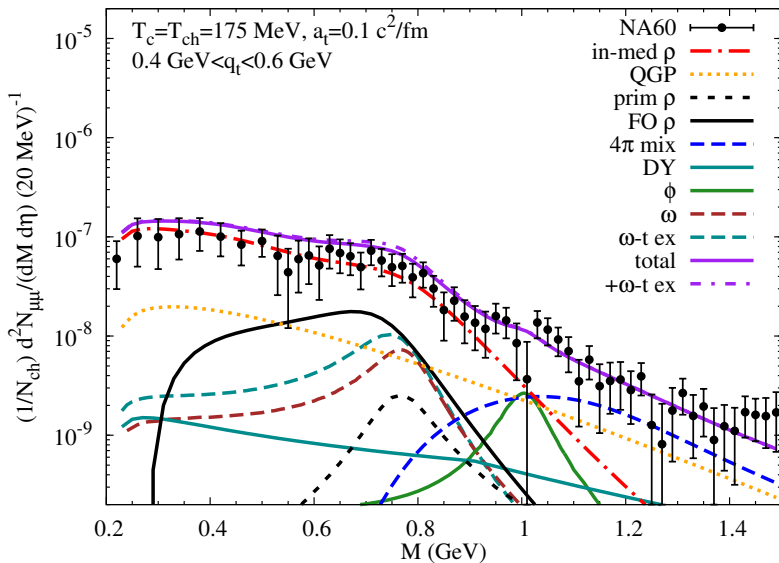
M spectra (in p_T slices)



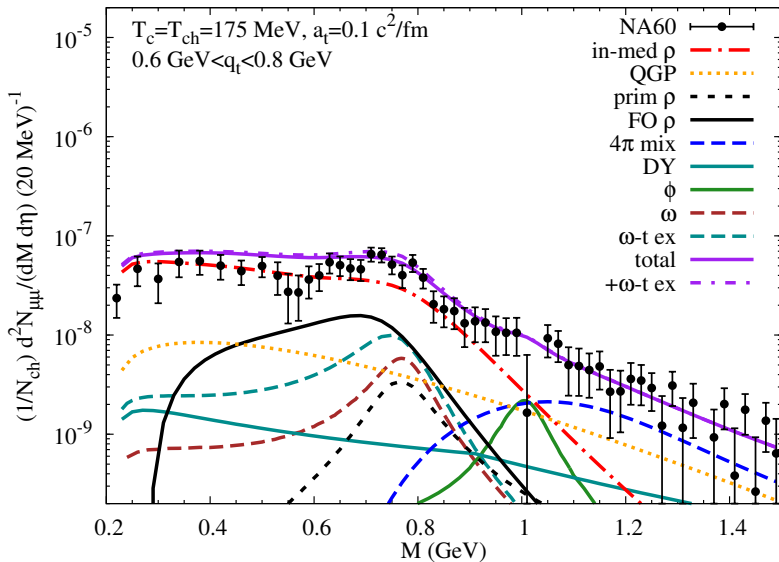
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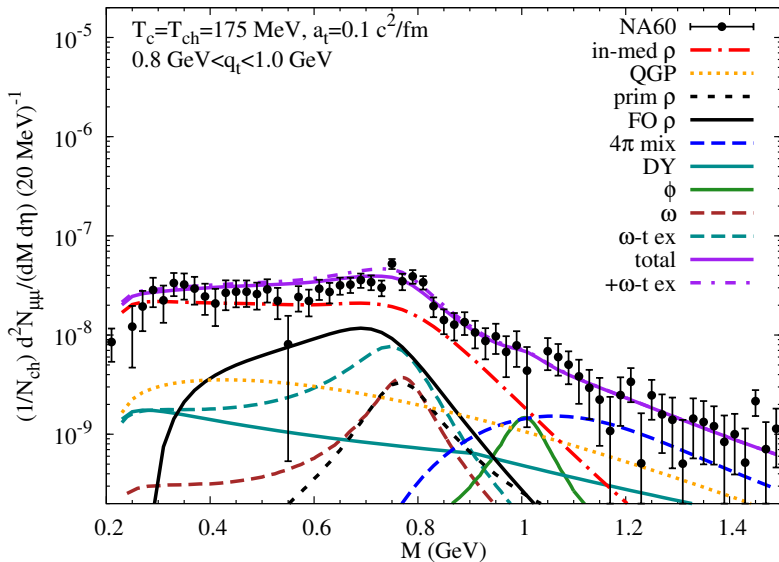
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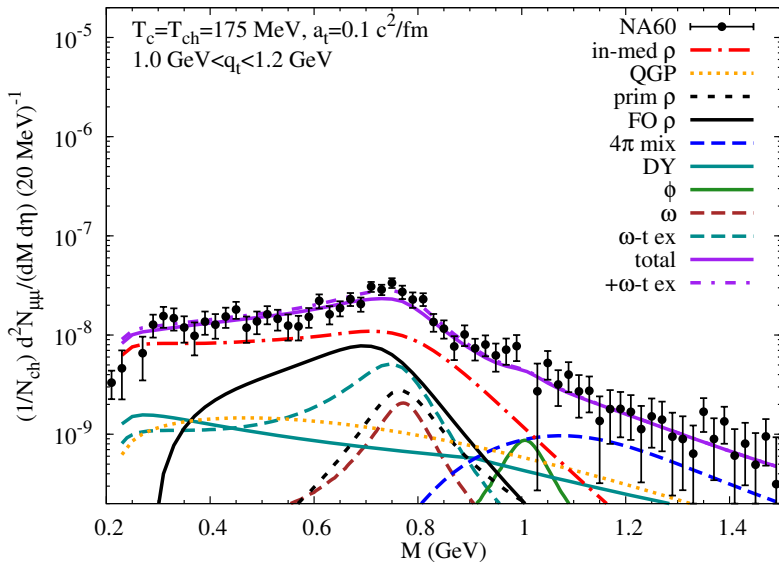
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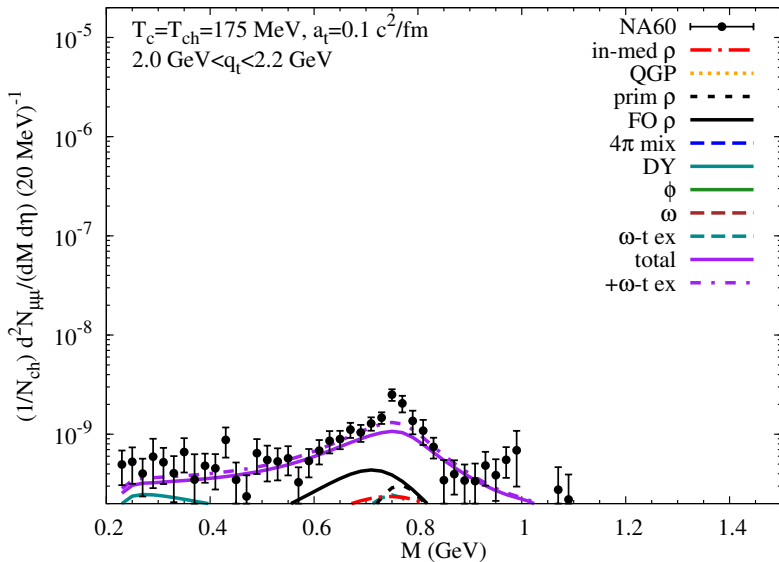
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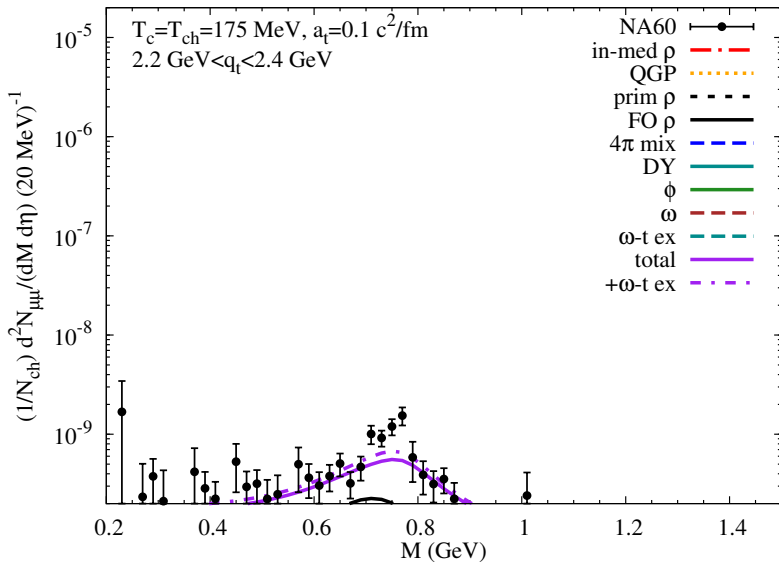
M spectra (in p_T slices)



M spectra (in p_T slices)

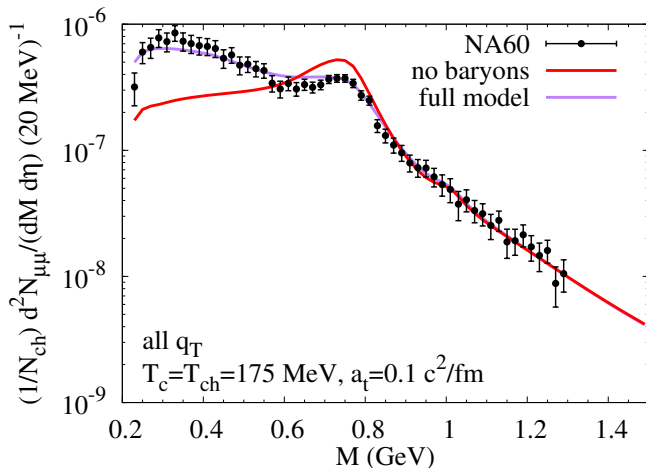


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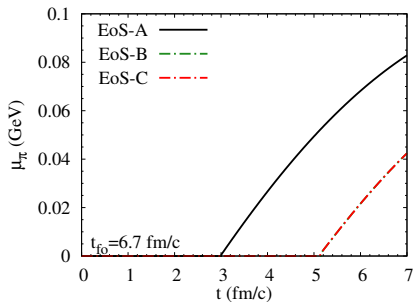
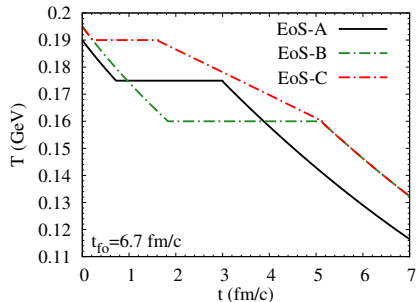
Importance of baryon effects

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

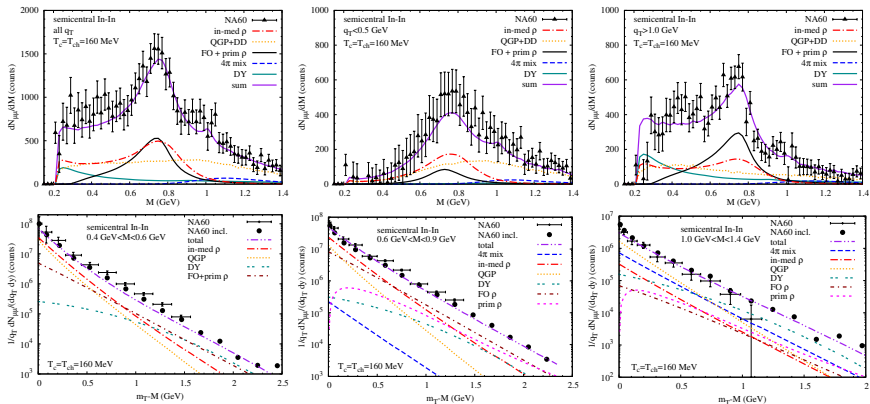


Sensitivity to T_c and hadro-chemistry

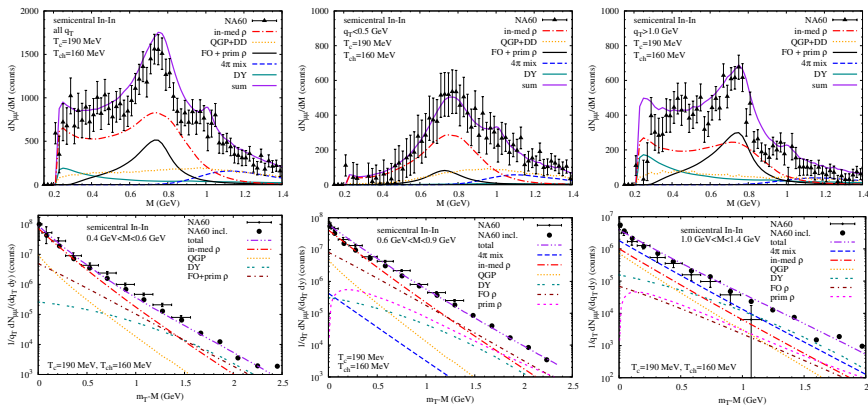
- recent lattice QCD: $T_c \simeq 190\text{-}200\text{ MeV}$ or $T_c \simeq 150\text{-}160\text{ MeV}$?
- thermal-model fits to hadron ratios: $T_{\text{chem}} \simeq 150\text{-}160\text{ MeV}$



- EoS-A: $T_c = T_{\text{chem}} = 175\text{ MeV}$
- EoS-B: $T_c = T_{\text{chem}} = 160\text{ MeV}$
- EoS-C: $T_c = 190\text{ MeV}$, $T_{\text{chem}} = 160\text{ MeV}$
 - $T_c \geq T \geq T_{\text{chem}}$: 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



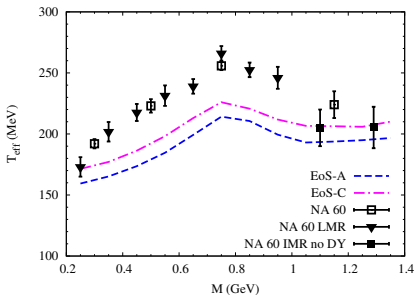
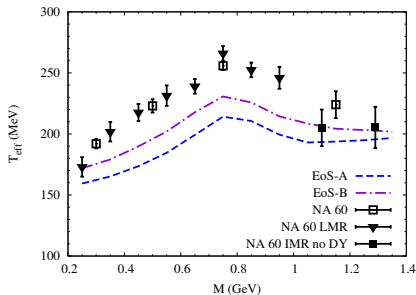
- mass spectra comparable to EoS-A \leftrightarrow slight reduction of fireball lifetime
- in IMR **multi-pion** \gg **QGP** contribution
- higher hadronic temperatures + high-density hadronic phase \Rightarrow harder q_T spectra
- better agreement with data

Inverse-slope analysis

- to extract T_{eff} fit to

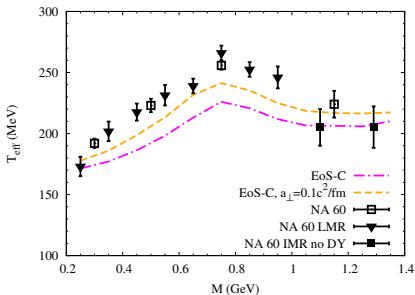
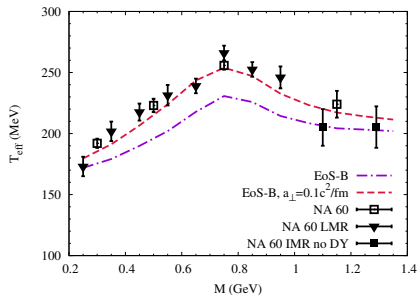
$$\frac{1}{q_T} \frac{dN}{dq_T} = \frac{1}{m_T} \frac{dN}{dm_T} = C \exp\left(-\frac{m_T}{T_{\text{eff}}}\right)$$

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



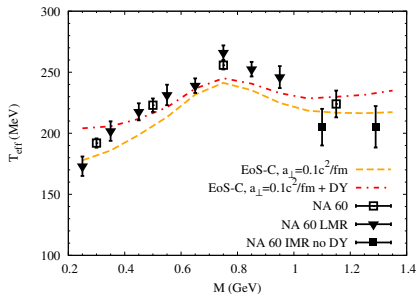
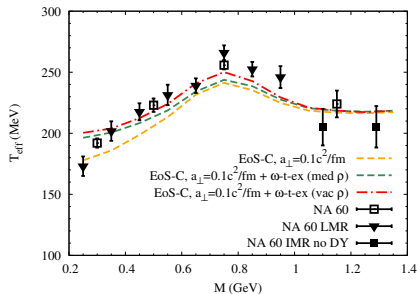
- standard fireball acceleration: **too soft q_T spectra**
- lower T_c in EoS-B and EoS-C helps (higher hadronic temperatures)
- NB: here, Drell Yan contribution taken out

Inverse-slope analysis



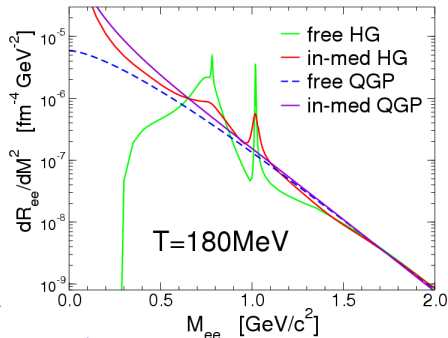
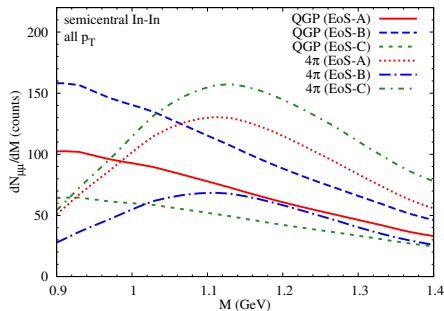
- enhance fireball acceleration to $a_{\perp} = 0.1c^2/\text{fm}$
- effective at all stages of **fireball evolution**
- agreement in IMR not spoiled \Leftrightarrow **dominated from earlier stages**
- EoS-B harder \Leftrightarrow **relative contribution of harder freezeout ρ decays vs. thermal ρ 's larger**

Inverse-slope analysis



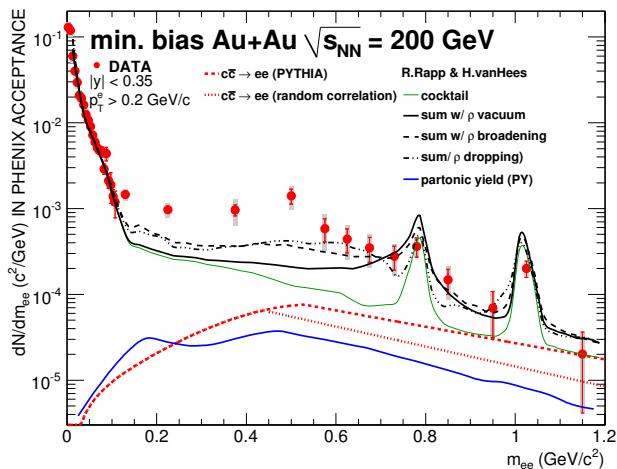
- **sensitivity to contributions from meson t -channel exchange**
 - hardens low-mass region
 - using vacuum ρ in t -channel contribution: enhances slope in ρ region
- **sensitivity to Drell-Yan contribution**
 - for IMR: describes effect seen in data (open vs. solid square data point)
 - in LMR: too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

IMR: QGP vs. multi-pion radiation



- different critical and freeze-out temperatures
 $T_c = 160 \dots 190 \text{ MeV}$, $T_{\text{chem}} = 160 \dots 175 \text{ MeV}$
- 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!

- huge enhancement in the LMR unexplained yet!



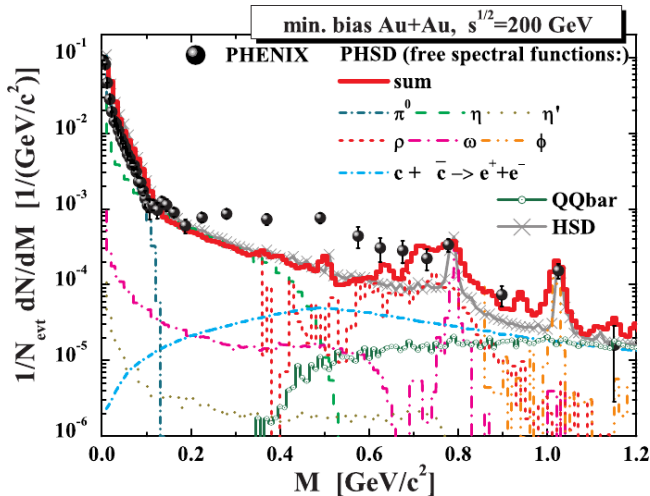
model: Rapp, HvH

[A⁺10]

for new data from hadron blind PHENIX setup, see lectures by I. Tserruya

Dileptons@RHIC: PHENIX (2007)

- huge enhancement in the LMR unexplained yet!

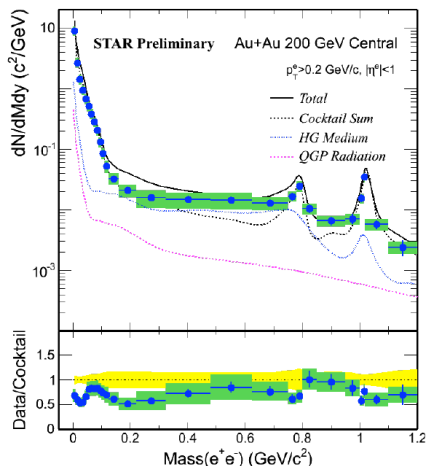


model: PHSD

[LCBM11]

for new data from hadron blind PHENIX setup, see lectures by I. Tserruya

Dileptons@RHIC: STAR (QM 2012)



[F. Geurts, talk at Quark Matter 2012]

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

Conclusions and Outlook

- dilepton spectra \Leftrightarrow in-medium em. current correlator
- model for dilepton sources
 - radiation from thermal sources: QGP, ρ , ω , ϕ , $4\pi\dots$
 - 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) Au-Au (RHIC)???
 - also γ in Pb-Pb (WA98), in Au-Au (PHENIX) [HGR11]

- 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
 - **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!**

- [A⁺10] A. Adare, et al., Detailed measurement of the e^+e^- pair continuum in $p + p$ and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and implications for direct photon production, *Phys. Rev. C* **81** (2010) 034911.
<http://dx.doi.org/10.1103/PhysRevC.81.034911>
- [BK84] M. Bando, T. Kugo, Is the ρ Meson a Dynamical Gauge Boson of Hidden Local Symmetry, *Phys. Rev. Lett.* **54** (1984) 1215.
<http://link.aps.org/abstract/PRL/v54/p1215>
- [GK91] C. Gale, J. I. Kapusta, Vector Dominance Model at Finite Temperature, *Nucl. Phys. B* **357** (1991) 65.
[http://dx.doi.org/10.1016/0550-3213\(91\)90459-B](http://dx.doi.org/10.1016/0550-3213(91)90459-B)
- [HGR11] H. van Hees, C. Gale, R. Rapp, Thermal Photons and Collective Flow at the Relativistic Heavy-Ion Collider, *Phys. Rev. C* **84** (2011).
<http://dx.doi.org/10.1103/PhysRevC.84.054906>

Bibliography II

- [HR06] H. van Hees, R. Rapp, Comprehensive interpretation of thermal dileptons at the SPS, *Phys. Rev. Lett.* **97** (2006) 102301.
<http://link.aps.org/abstract/PRL/V97/E102301>
- [HR08] H. van Hees, R. Rapp, Dilepton Radiation at the CERN Super Proton Synchrotron, *Nucl. Phys. A* **806** (2008) 339.
<http://dx.doi.org/10.1016/j.nuclphysa.2008.03.009>
- [HY03] M. Harada, K. Yamawaki, Hidden local symmetry at loop: A new perspective of composite gauge boson and chiral phase transition, *Phys. Rept.* **381** (2003) 1.
[http://dx.doi.org/10.1016/S0370-1573\(03\)00139-X](http://dx.doi.org/10.1016/S0370-1573(03)00139-X)
- [LCBM11] O. Linnyk, W. Cassing, E. Bratkovskaya, J. Manninen, Dilepton production in the strongly interacting quark-gluon plasma, *Nucl. Phys. A* **855** (2011) 273.
<http://dx.doi.org/10.1016/j.nuclphysa.2011.02.057>

- [LSY95] S. H. Lee, C. Song, H. Yabu, Photon - vector meson coupling and vector meson properties at low temperature pion gas, *Phys. Lett. B* **341** (1995) 407.
http://www.sciencedirect.com/science?_ob=GatewayURL&_origin=SPIRES&_method=citationSearch&_volkey=03702693%23341%23407&_version=1&md5=05053a52e85b02fde34213175c490b2a
- [Mei88] U. G. Meissner, Low-Energy Hadron Physics from Effective Chiral Lagrangians with Vector Mesons, *Phys. Rept.* **161** (1988) 213.
[http://dx.doi.org/10.1016/0370-1573\(88\)90090-7](http://dx.doi.org/10.1016/0370-1573(88)90090-7)
- [MT85] L. D. McLerran, T. Toimela, Photon and dilepton emission from the quark-gluon plasma: some general considerations, *Phys. Rev. D* **31** (1985) 545.
<http://link.aps.org/abstract/PRD/V31/P545>

Bibliography IV

- [Pis95] R. D. Pisarski, Where does the ρ go? Chirally symmetric vector mesons in the quark - gluon plasma, Phys. Rev. D **52** (1995) 3773.
<http://dx.doi.org/10.1103/PhysRevD.52.R3773>
- [Rap03] R. Rapp, Dileptons in high-energy heavy-ion collisions, Pramana **60** (2003) 675.
<http://dx.doi.org/10.1007/BF02705167>
- [Rap05] R. Rapp, The vector probe in heavy-ion reactions, J. Phys. G **31** (2005) S217.
<http://arxiv.org/abs/nucl-th/0409054>
- [RW99] R. Rapp, J. Wambach, Low mass dileptons at the CERN-SPS: Evidence for chiral restoration?, Eur. Phys. J. A **6** (1999) 415.
<http://dx.doi.org/10.1007/s100500050364>
- [RW00] R. Rapp, J. Wambach, Chiral symmetry restoration and dileptons in relativistic heavy-ion collisions, Adv. Nucl. Phys. **25** (2000) 1.
<http://arxiv.org/abs/hep-ph/9909229>

- [UBW02] M. Urban, M. Buballa, J. Wambach, Temperature dependence of ρ and a_1 meson masses and mixing of vector and axial-vector correlators, Phys. Rev. Lett. **88** (2002) 042002.
<http://dx.doi.org/10.1103/PhysRevLett.88.042002>