# Electromagnetic Probes in Heavy-Ion Collisions III

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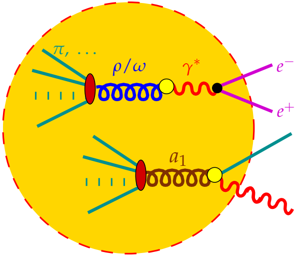
# Outline

1. Electromagnetic probes and vector mesons
    - 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?

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



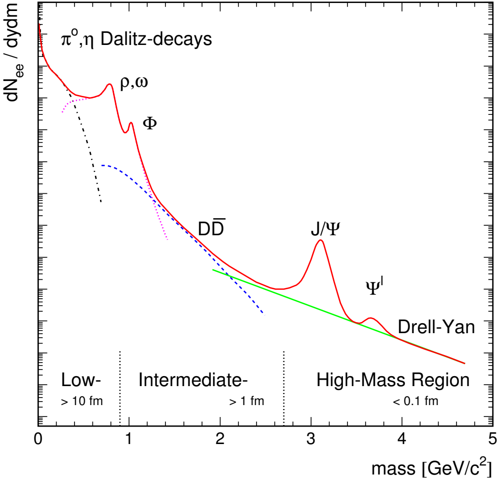


Fig. by A. Drees (from [RW00])

# Vector Mesons and electromagnetic Probes

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

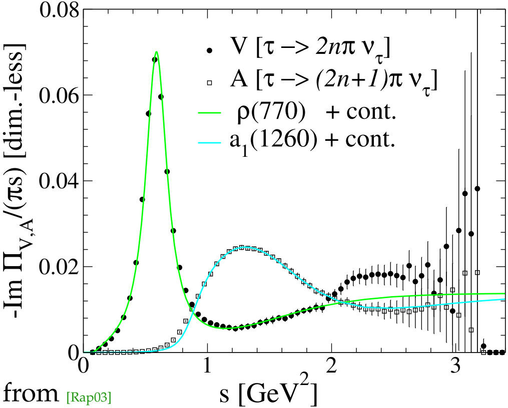
$$\Pi^{<}_{\mu\nu}(q) = \int \mathrm{d}^4 x \exp(\mathrm{i} q \cdot x) \left\langle J_\mu(0) J_\nu(x) \right\rangle_T = -2 n_B(q_0) \Pi^{(\text{ret})}_{\mu\nu}(q)$$

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

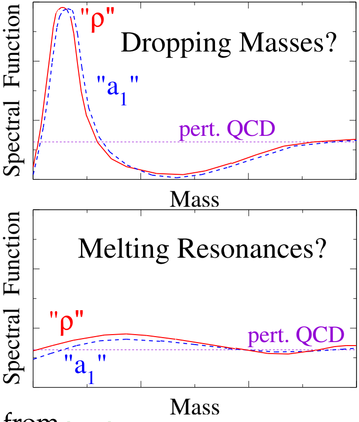
$$\frac{\mathrm{d}N_{e^+e^-}}{\mathrm{d}^4 x \mathrm{d}^4 k} = -g_{\mu\nu} \frac{\alpha^2}{3 q^2 \pi^3} \,\mathrm{Im}\, \Pi^{(\text{ret})}_{\mu\nu}(q) \Big|_{q^2 = M^2_{e^+e^-}} f_B(p_0)$$

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

# Vector mesons and chiral symmetry



from [Rap03]



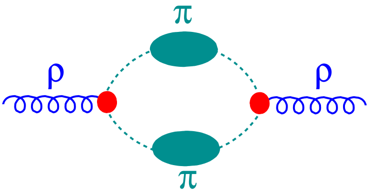
from [Rap05]

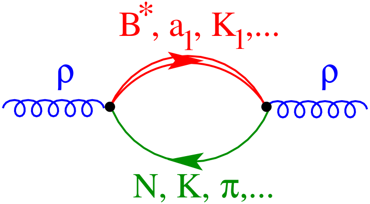
# Realistic hadronic models for light vector mesons

- CERES data: pion-$\rho$ model too simplistic
- many approaches to more realistic models
  - gauged linear $\sigma$-model + vector-meson dominance [Pis95, UBW02]
    gauge-symmetry breaking ⇒ 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

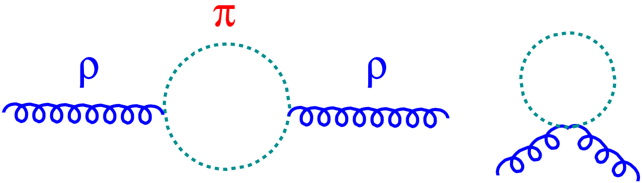


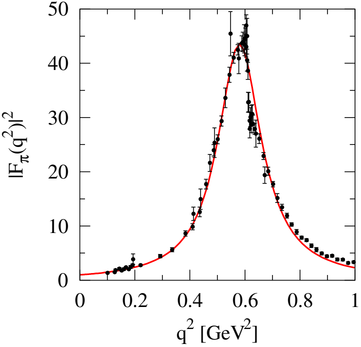


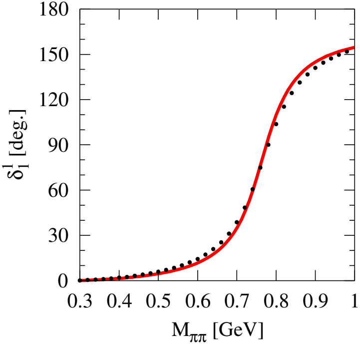
- Baryon (resonances) important, even at RHIC with low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

# The meson sector (vacuum)

- most important for $\rho$-meson: pions

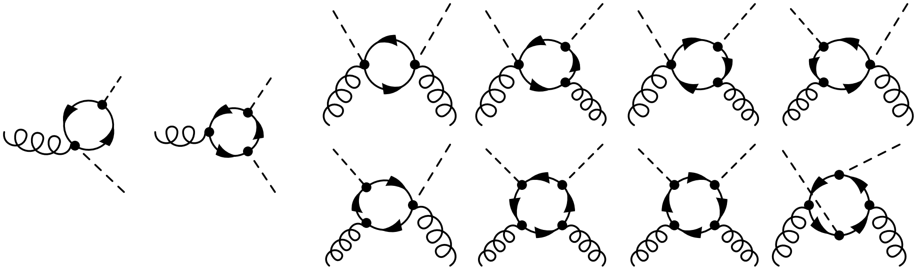




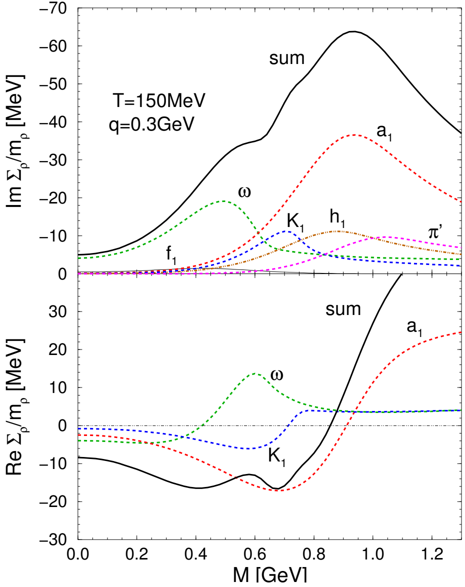


# The meson sector (matter)

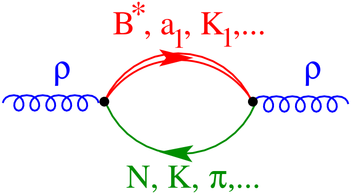
- Pions dressed with N-hole-, Δ-hole bubbles
- Ward-Takahashi ⇒ vertex corrections mandatory!



# The meson sector

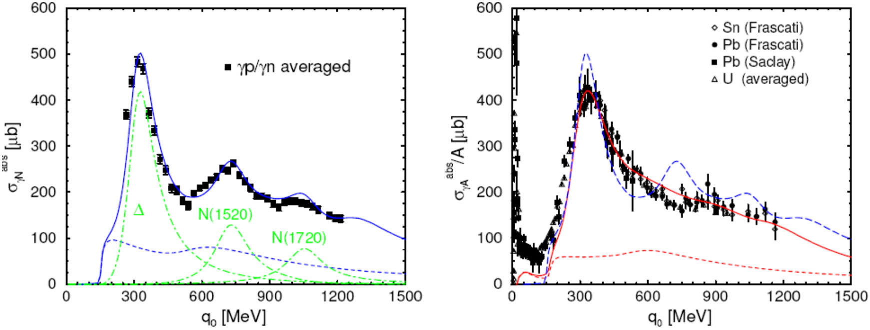


# The baryon sector (vacuum)

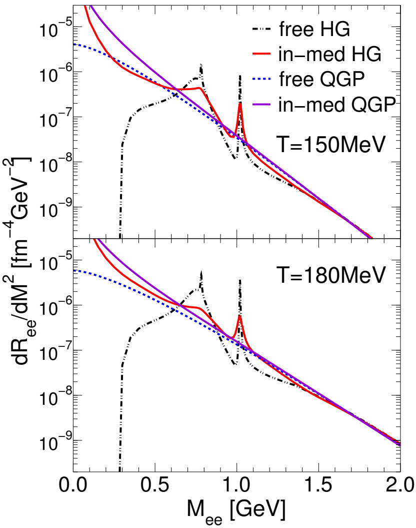


- $P = 1$-baryons: $p$-wave coupling to $\rho$:
  N(939), Δ(1232), N(1720), Δ(1905)
- $P = -1$-baryons: $s$-wave coupling to $\rho$:
  N(1520), Δ(1620), Δ(1700)

# Photoabsorption on nucleons and nuclei

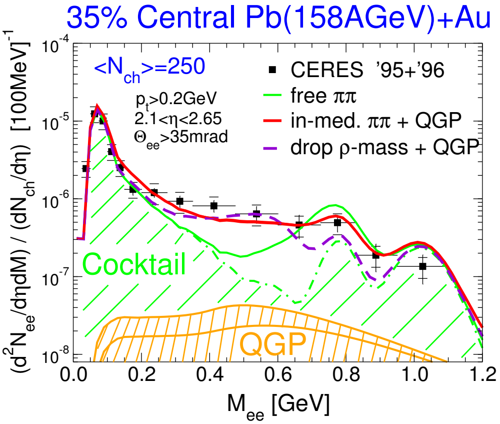


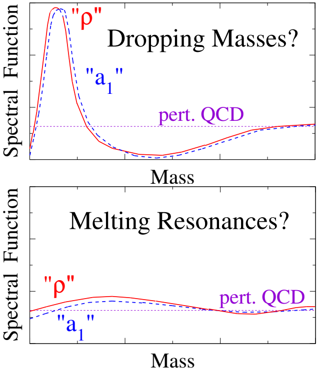
# Dilepton rates: Hadron gas ↔ QGP



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

# Dilepton rates at SpS

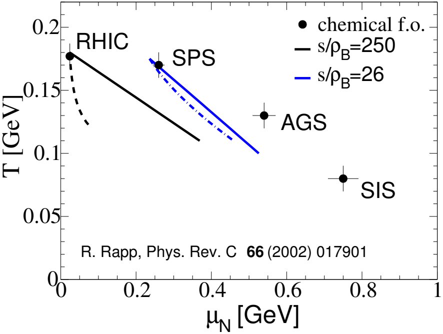




- how to decide about scenario experimentally?
- need compare (more) precise data to detailed model!

# Fireball and Thermodynamics

- cylindrical fireball model: $V_{\text{FB}} = \pi(z_0 + v_{z0} t + \frac{a_z}{2} t^2) \left(\frac{a_\perp}{2} t^2 + r_0\right)^2$
- thermodynamics:
  - isentropic expansion; $S_{\text{tot}}$ fixed by $N_{\text{ch}}$; $T_c = T_{\text{chem}} = 175$ 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
    $s/\varrho_B = 27$
- thermal freezeout:
  $(T_{\text{fo}}, \mu_\pi^{\text{fo}}) \simeq (120, 80)$ MeV



R. Rapp, Phys. Rev. C **66** (2002) 017901

# 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 ⇒ hardening of $p_T$ spectra
- phase-space distribution for bosonic resonances:

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

- $D_i(p)$: propagator of resonance,
  $A_i(p) = -2\,\mathrm{Im}\,D_i(p)$: 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]

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

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

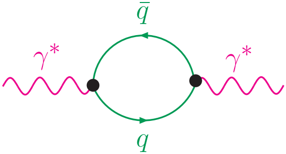
$$\frac{\mathrm{d}N^{(\mathrm{MT})}_{l^+l^-}}{\mathrm{d}^4x\mathrm{d}^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M^2)}{M^2}g_{\mu\nu}\mathrm{Im}\sum_i \Pi^{\mu\nu}_{\mathrm{em},i}(M,\vec{q})f_B\left(\frac{q\cdot u-\mu_i(t)}{T(t)}\right)$$

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

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

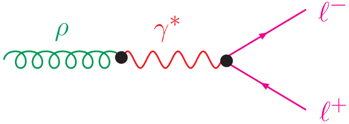
- in QGP phase: $q\bar{q}$ annihilation
- HTL improved electromagnetic current correlator

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



# Radiation from thermal sources: $\rho$ decays

- model assumption: vector-meson dominance



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

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

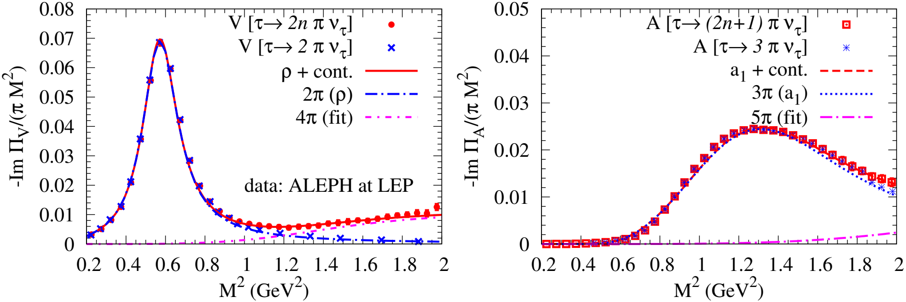
- special case of McLerran-Toimela (MT) formula
- $M^2=q^2$: invariant mass, $M$, of dilepton pair
- $L(M^2)=(1+2m_l^2/M^2)\sqrt{1-4m_l^2/M^2}$: dilepton phase-space factor
- $D_\rho^{\mu\nu}(M,\vec{q})$: (four-transverse part of) in-medium $\rho$ propagator at given $T(t)$, $\mu_{\mathrm{meson/baryon}}(t)$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

# Radiation from thermal sources: multi-$\pi$ processes

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

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

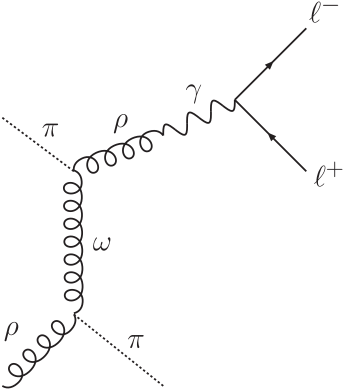
- avoid double counting: leave out two-pion piece and $a_1 \rightarrow \rho + \pi$ (already contained in $\rho$ spectral function)



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

# Radiation from thermal sources: Meson t-channel exchange

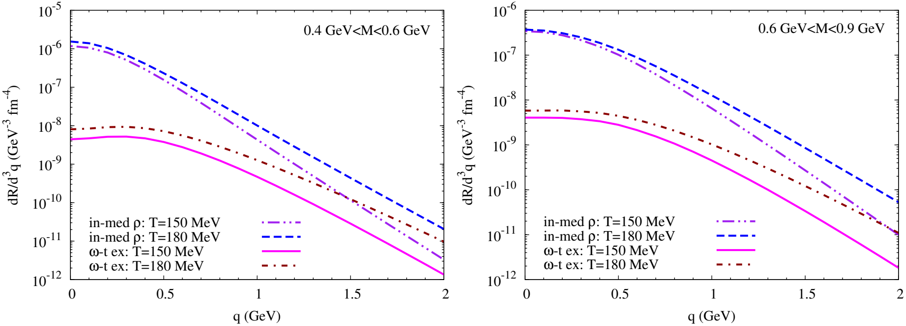
- motivation: $q_T$ spectra too soft compared to NA60 data
- thermal contributions not included in models so far



- also for $\pi$, $a_1$

# Radiation from thermal sources: Meson t-channel exchange

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



# $\rho$ decay after thermal freezeout

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

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

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

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

  like hadron spectra!

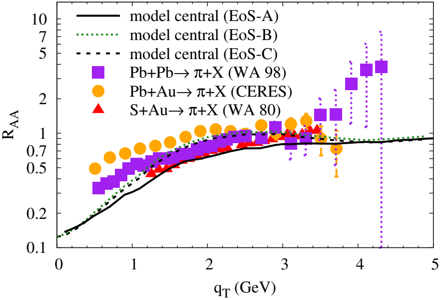
- $\Leftrightarrow$ $l^+l^-$ from thermal sources softer by Lorentz factor $M/q^0$ compared to $l^+l^-$ from decay of freeze-out $\rho$'s

# Decay of “primordial” $\rho$ mesons

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

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

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



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

# Drell-Yan Annihilation and correlated charm decays

- invariant-mass spectrum for DY pairs

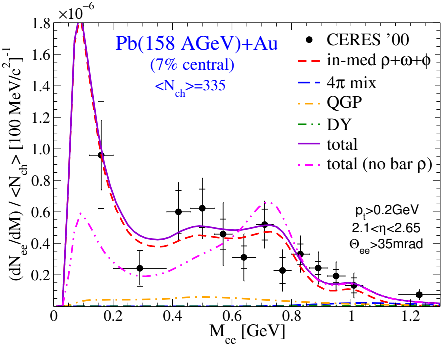
$$\left.\frac{\mathrm{d}N_{\mathrm{DY}}^{AA}}{\mathrm{d}M\mathrm{d}y}\right|_{b=0} = \frac{3}{4\pi R_0^2} A^{4/3} \frac{\mathrm{d}\sigma_{\mathrm{DY}}^{NN}}{\mathrm{d}M\mathrm{d}y}$$

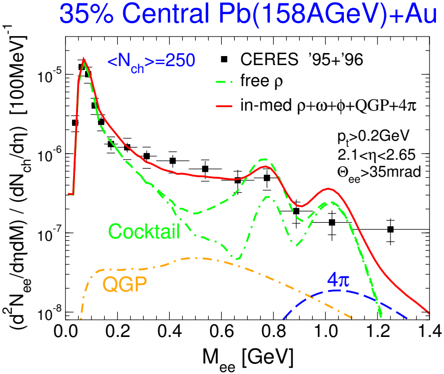
$$\frac{\mathrm{d}\sigma_{\mathrm{DY}}^{NN}}{\mathrm{d}M\mathrm{d}y} = K\frac{8\pi\alpha}{9sM} \sum_{q=u,d,s} e_q^2 \left[q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)\right]$$

- 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 $\bar{D}$ mesons
  - use data (provided by NA60 collaboration)

# CERES/NA45 dielectron spectra

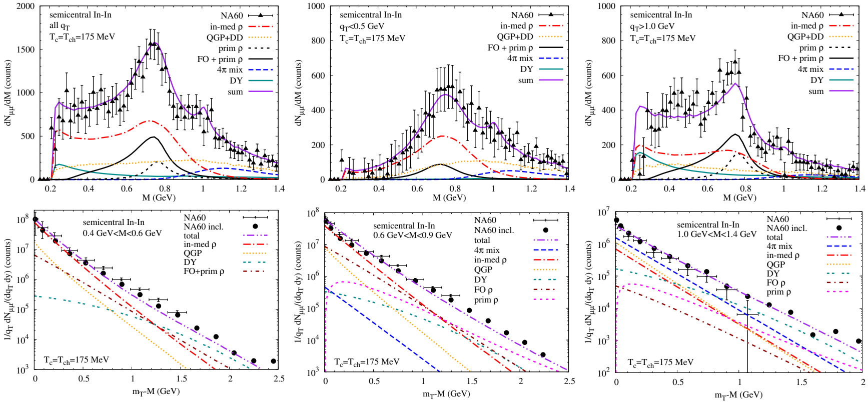
- good agreement also for dielectron spectra in 158 GeV Pb-Au
- further check of low-mass tail from baryon effects down to $M \to 2m_e$





# NA60 vs. Hadronic many-body theory

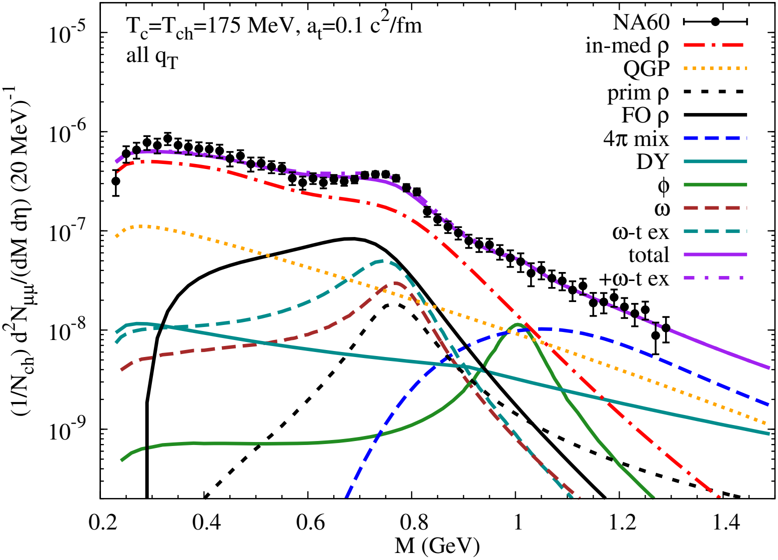
- $\rho, \omega, \phi$ multi-$\pi$, QGP, freeze-out+primordial $\rho$, Drell-Yan



- $M$ spectra
  - consistent with predicted broadening of $\rho$ meson
  - $M <$ 1GeV: thermal $\rho$; $M > 1$ GeV: thermal multi-pion processes
- $m_t$ spectra
  - $q_t < 1$ GeV: thermal radiation
  - $q_t > 1$ GeV: freeze-out + hard primordial $\rho$, Drell-Yan

[HvH, Rapp 07]

# M spectra (in $p_T$ slices)



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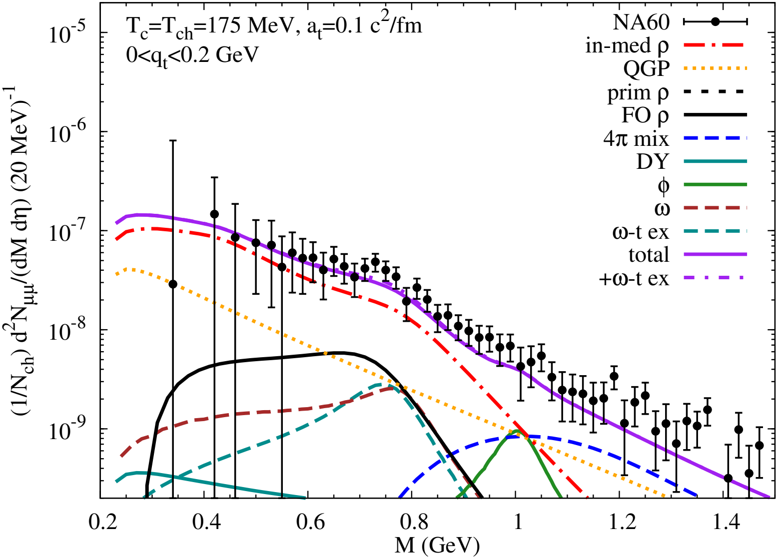

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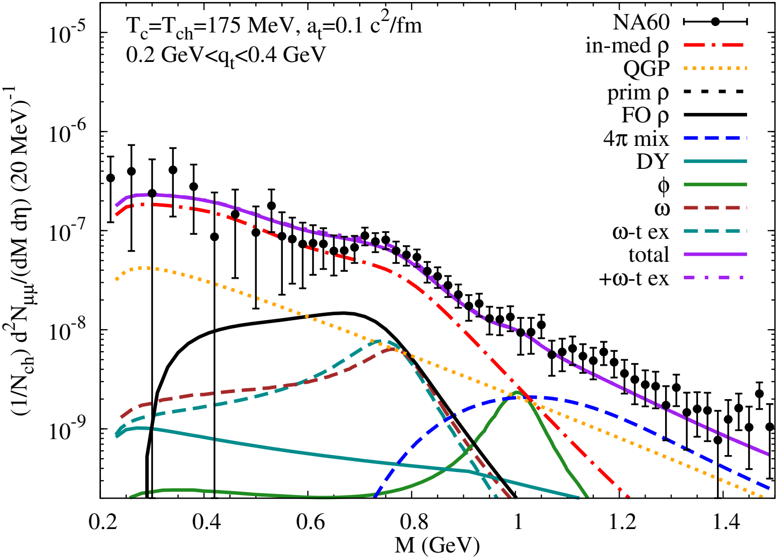

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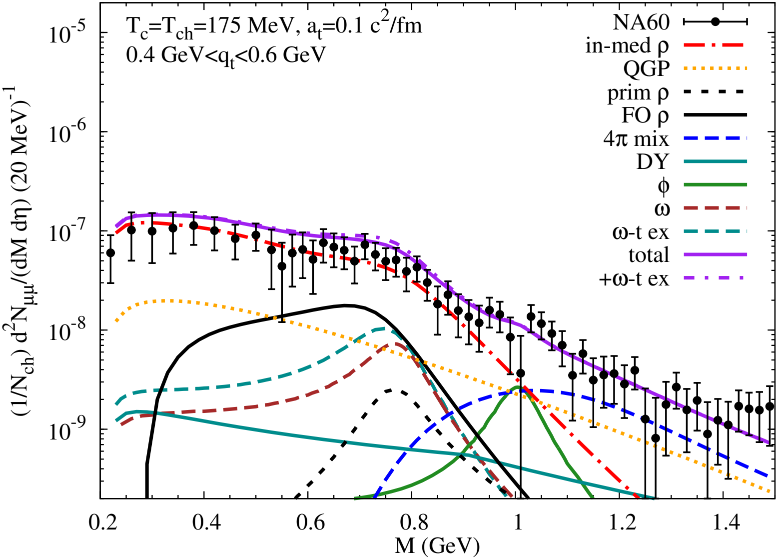

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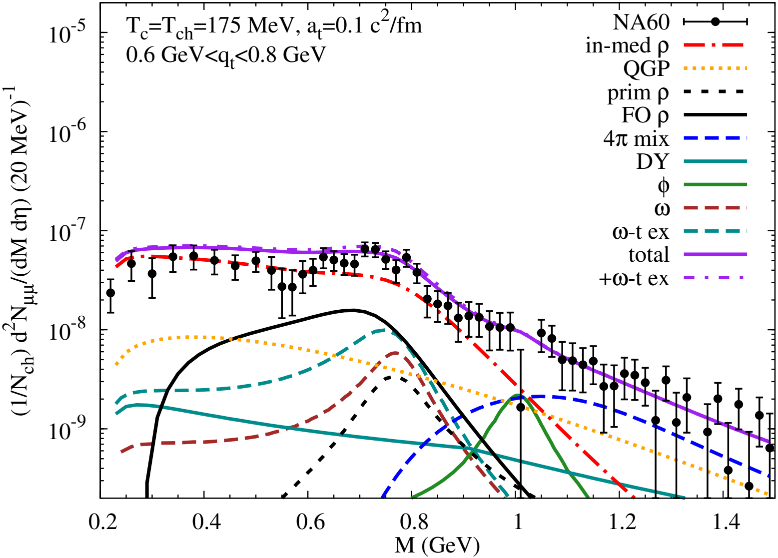

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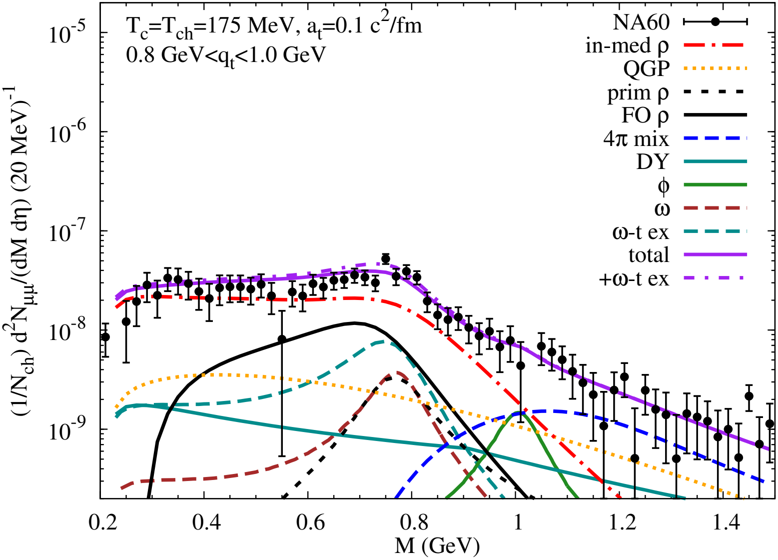

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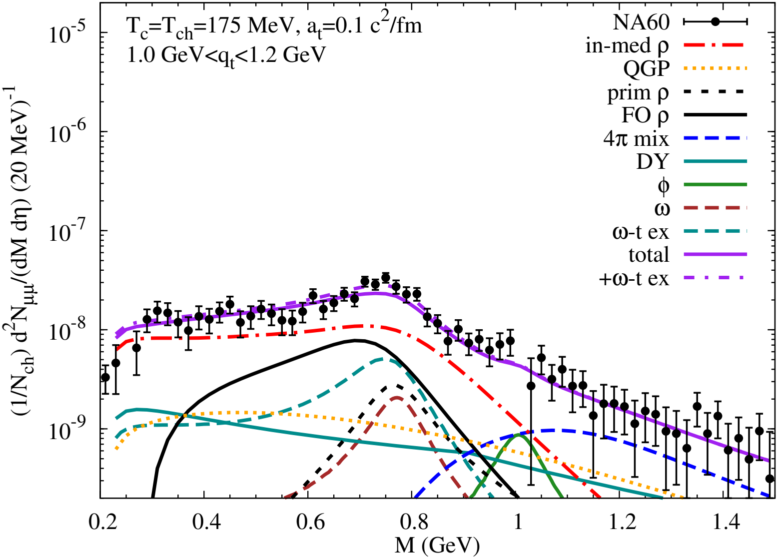
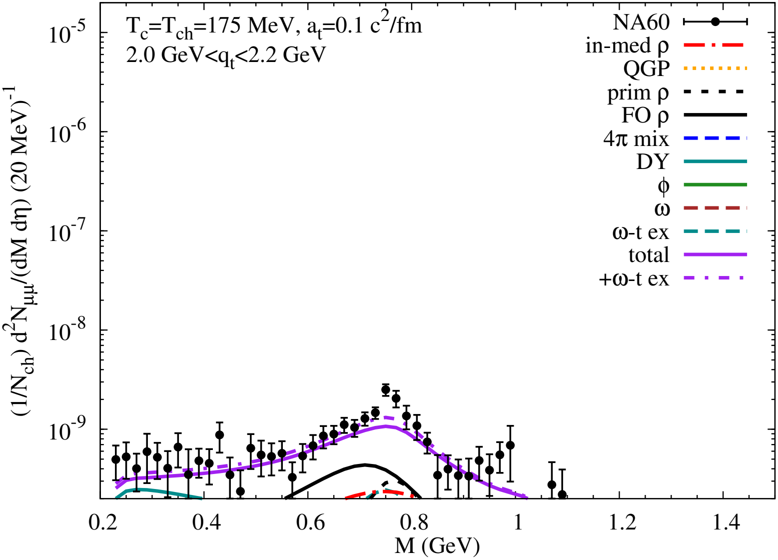
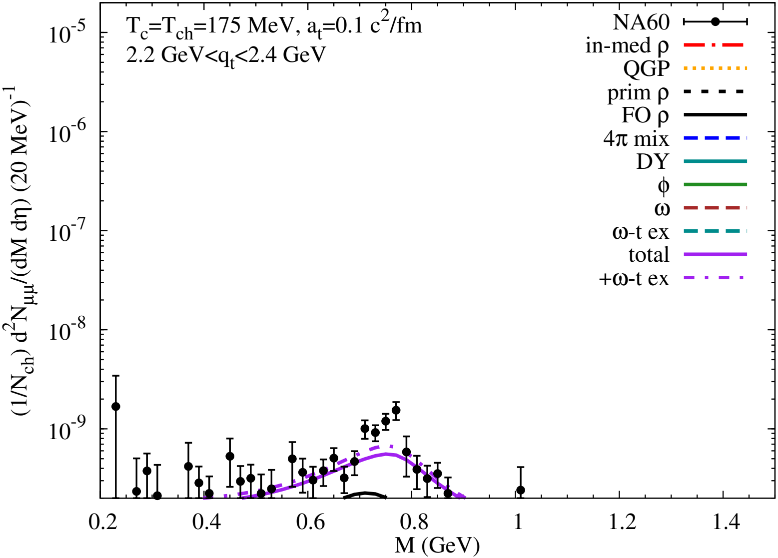


# M spectra (in $p_T$ slices)

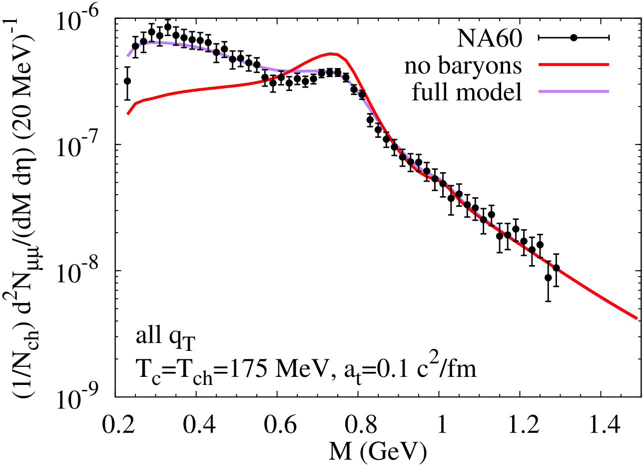


# M spectra (in $p_T$ slices)



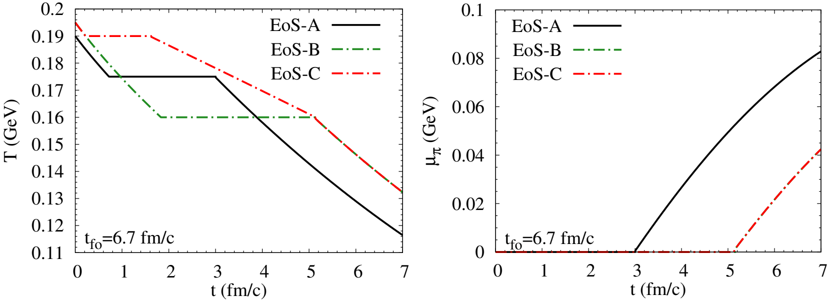
# Importance of baryon effects

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



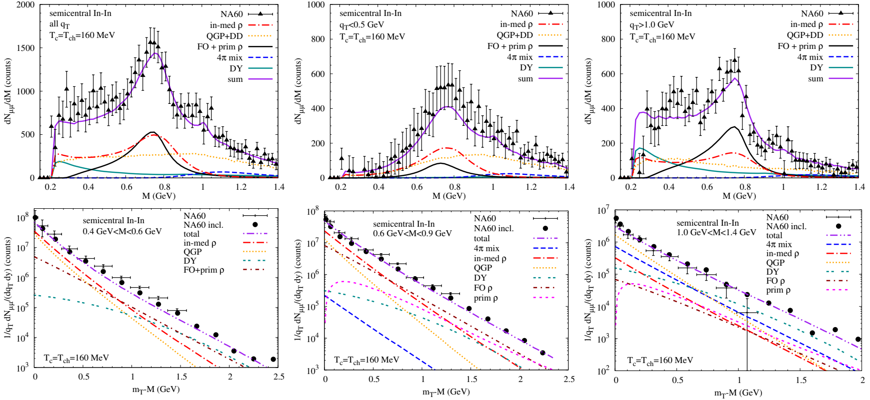
# Sensitivity to $T_c$ and hadro-chemistry

- 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



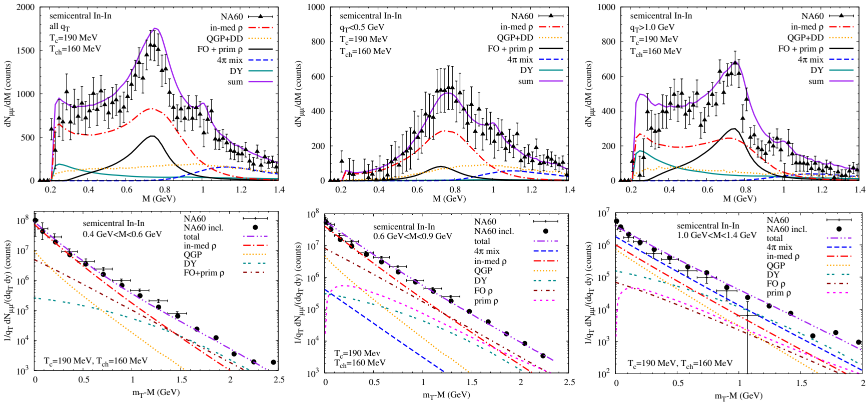
- EoS-A: $T_c = T_{\text{chem}} = 175$ MeV
- EoS-B: $T_c = T_{\text{chem}} = 160$ MeV
- EoS-C: $T_c = 190$ MeV, $T_{\text{chem}} = 160$ MeV
  - $T_c \geq T \geq T_{\text{chem}}$: hadron gas in chemical equilibrium
- keep fireball parameters the same (including life time)

# 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



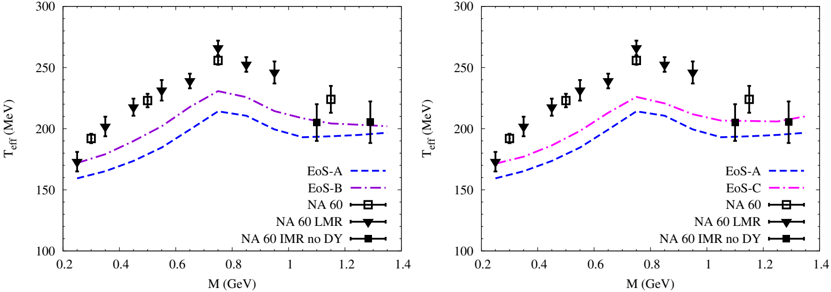
- mass spectra comparable to EoS-A ↔ slight reduction of fireball lifetime
- in IMR multi-pion ≫ QGP contribution
- higher hadronic temperatures + high-density hadronic phase ⇒ harder $q_T$ spectra
- better agreement with data

# Inverse-slope analysis

- to extract $T_{\text{eff}}$ fit to

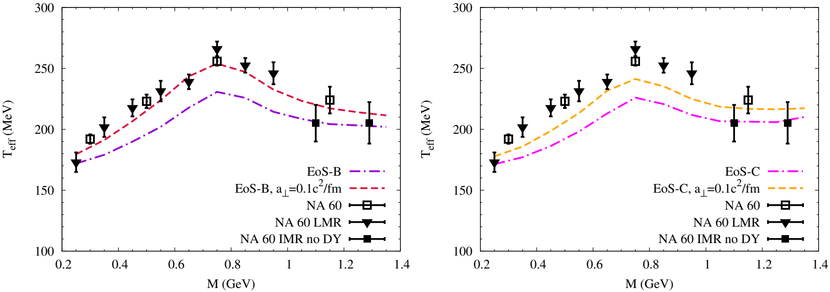
$$\frac{1}{q_T}\frac{\mathrm{d}N}{\mathrm{d}q_T} = \frac{1}{m_T}\frac{\mathrm{d}N}{\mathrm{d}m_T} = C \exp\left(-\frac{m_T}{T_{\text{eff}}}\right)$$

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



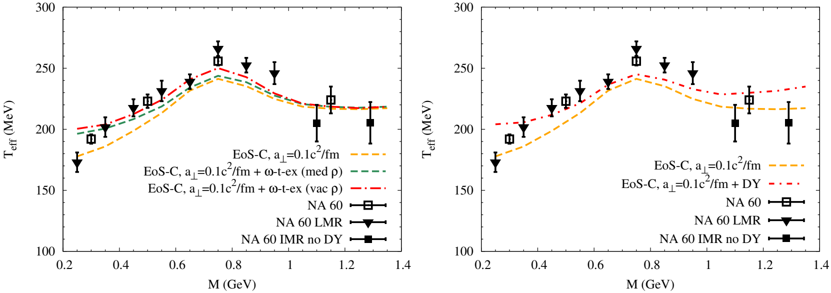
- standard fireball acceleration: too soft $q_T$ spectra
- lower $T_c$ in EoS-B and EoS-C helps (higher hadronic temperatures)
- NB: here, Drell Yan contribution taken out

# Inverse-slope analysis



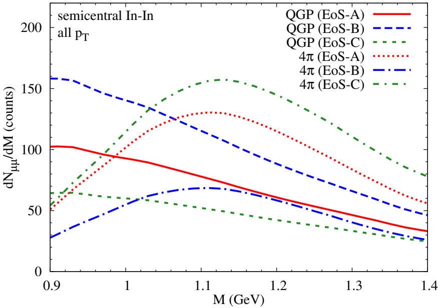
- enhance fireball acceleration to $a_\perp = 0.1c^2/\text{fm}$
- effective at all stages of fireball evolution
- agreement in IMR not spoiled ⇔ dominated from earlier stages
- EoS-B harder ⇔ relative contribution of harder freezeout $\rho$ decays vs. thermal $\rho$'s larger

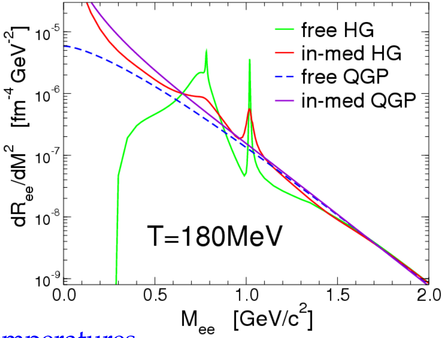
# Inverse-slope analysis



- sensitivity to contributions from meson *t*-channel exchange
  - hardens low-mass region
  - using vacuum $\rho$ in $t$-channel contribution: enhances slope in $\rho$ 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

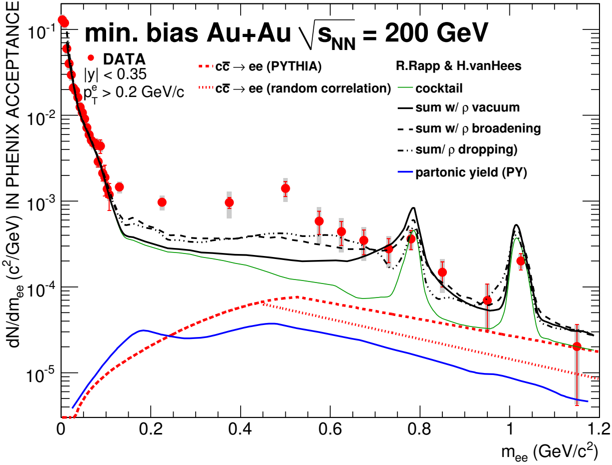




- different critical and freeze-out temperatures
  $T_c = 160 \ldots 190$ MeV, $T_{\text{chem}} = 160 \ldots 175$ MeV
- $M$- and $p_T$ spectra comparably well described!
- reason: $T$ vs. volume $\Rightarrow$ maximal $l^+ l^-$ emission for $T = T_{\max} = M/5.5$
- hadronic and partonic radiation "dual"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

# Dileptons@RHIC: PHENIX (2007)

- huge enhancement in the LMR unexplained yet!

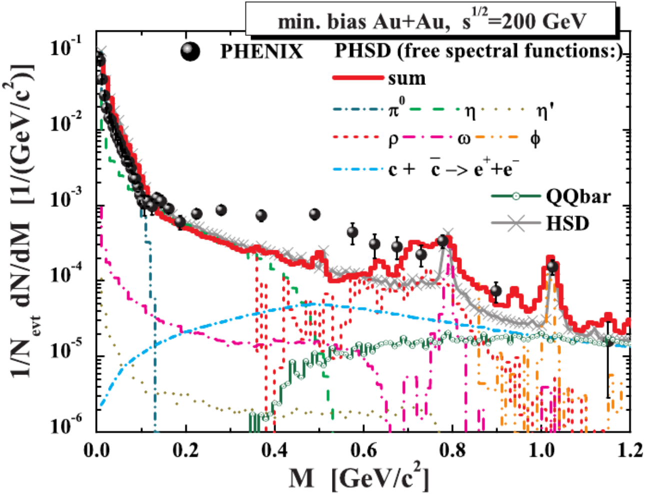


model: Rapp, HvH
[A+10]

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

# Dileptons@RHIC: PHENIX (2007)

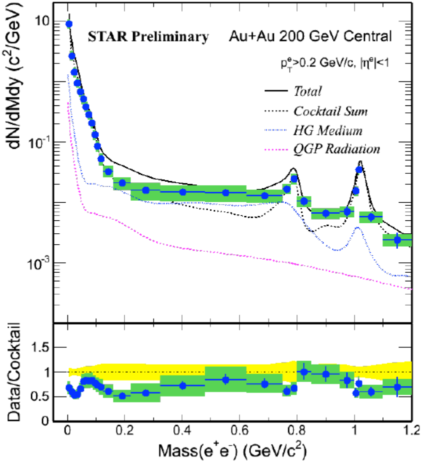
- huge enhancement in the LMR unexplained yet!



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 ⇔ in-medium em. current correlator
- model for dilepton sources
  - radiation from thermal sources: QGP, $\rho$, $\omega$, $\phi$, $4\pi$...
  - $\rho$-decay after thermal freeze-out
  - decays of non-thermalized primordial $\rho$'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 $\rho$ 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 MeV $\leq T \leq$ 190 MeV
      ⇔ "parton-hadron" duality of rates
      ⇔ compatible with chiral-symmetry restoration!
  - dimuons in In-In (NA60), Pb-Au (CERES/NA45) Au-Au (RHIC)?!?
  - also $\gamma$ in Pb-Pb (WA98), in Au-Au (PHENIX) [HGR11]

# Conclusions and Outlook

- fireball/freeze-out dynamics ⇔ $m_T$ spectra and effective slopes
  - "non-thermal sources" important for $q_T \gtrsim 1$ GeV
  - lower $T_c \Rightarrow$ 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
  - vector- should be complemented with axial-vector-spectral functions ($a_1$ as chiral partner of $\rho$)
  - constrained with lQCD via in-medium Weinberg chiral sum rules
  - direct connection to chiral phase transition!

# Bibliography I

[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 $\rho$ 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`

[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`

[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`

# Bibliography III

[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`

[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 $\rho$ 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`

# Bibliography V

[UBW02] M. Urban, M. Buballa, J. Wambach, Temperature dependence of $\rho$ 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`