Dileptons in relativistic heavy-ion collisions

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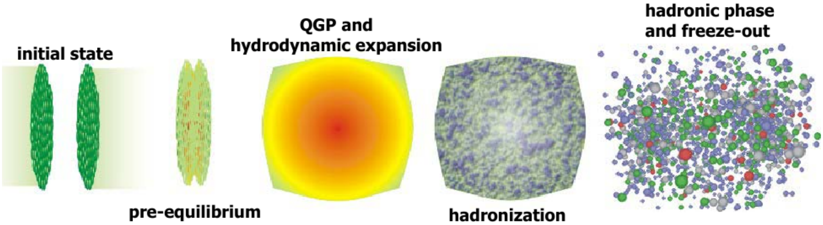
Outline

1. QCD and Chiral Symmetry
   - QCD and accidental symmetries
   - The QCD-phase diagram
   - Vector mesons and electromagnetic probes
2. Sources of Dileptons
   - $q\bar{q}$ annihilation in the QGP (thermal source)
   - In-medium vector mesons (thermal source)
   - Multi-pion processes (thermal source)
   - Meson t-channel exchange (thermal source)
   - ρ decay after thermal freezeout
   - "Primordial" ρ mesons
   - Drell-Yan Annihilation and correlated charm decays
3. Comparison to NA60 data
   - Invariant-mass spectra
   - m_T spectra and slope analysis
   - Sensitivity to T_c and hadro-chemistry
4. Conclusions and Outlook

Heavy-Ion collisions in a Nutshell

- Theory of strong interactions: Quantum Chromo Dynamics, QCD
- At high enough densities/temperatures: hadrons dissolve into a Quark-Gluon Plasma (QGP)
- hope to create QGP in Heavy-Ion Collisions at RHIC (and LHC)
- CERN SPS: collide various nuclei with $158\ \mathrm{GeV}$ per nucleon on a fixed target (center-mass energy: $\sqrt{s} = 17.3\ \mathrm{GeV}$)
- BNL RHIC: collide gold nuclei with center-mass energy of $\sqrt{s} = 200$ GeV per nucleon:



QCD and ("accidental") symmetries

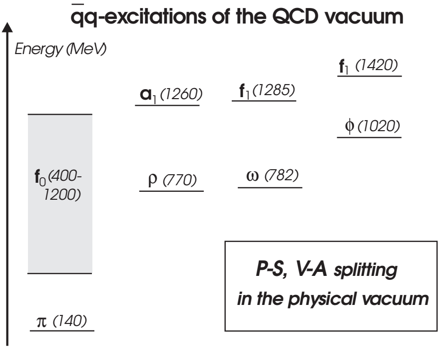
- Theory for strong interactions: QCD

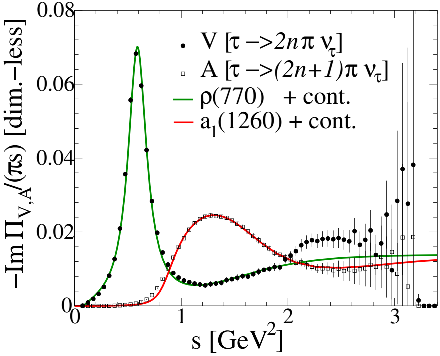
$$\mathscr{L}_{\text{QCD}} = -\frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a + \bar{\psi}(\mathrm{i}\not{D} - \hat{M})\psi$$

- Particle content:
  - ψ: Quarks, including flavor- and color degrees of freedom, $\hat{M} = \mathrm{diag}(m_u, m_d, m_s, \ldots) =$ current quark masses
  - A_μ^a: gluons, gauge bosons of SU(3)$_{\text{color}}$
- Symmetries
  - fundamental building block: local SU(3)$_{\text{color}}$ symmetry
  - in light-quark sector: approximate chiral symmetry
  - chiral symmetry most important connection between QCD and effective hadronic models

Phenomenology and Chiral symmetry

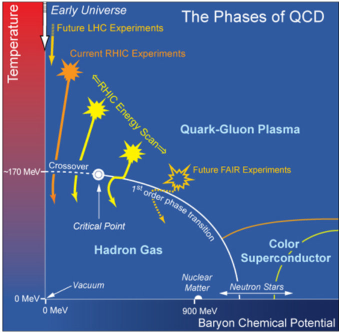
- In vacuum: Spontaneous breaking of chiral symmetry
- ⇒ mass splitting of chiral partners

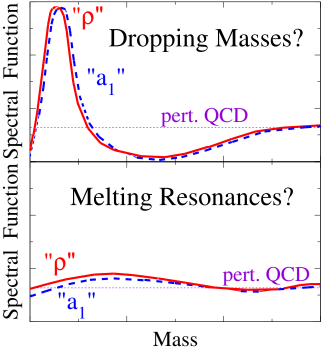




The QCD-phase diagram

- at high temperature/density: restoration of chiral symmetry
- Lattice QCD: $T_c^{\chi} \simeq T_c^{\text{deconf}}$

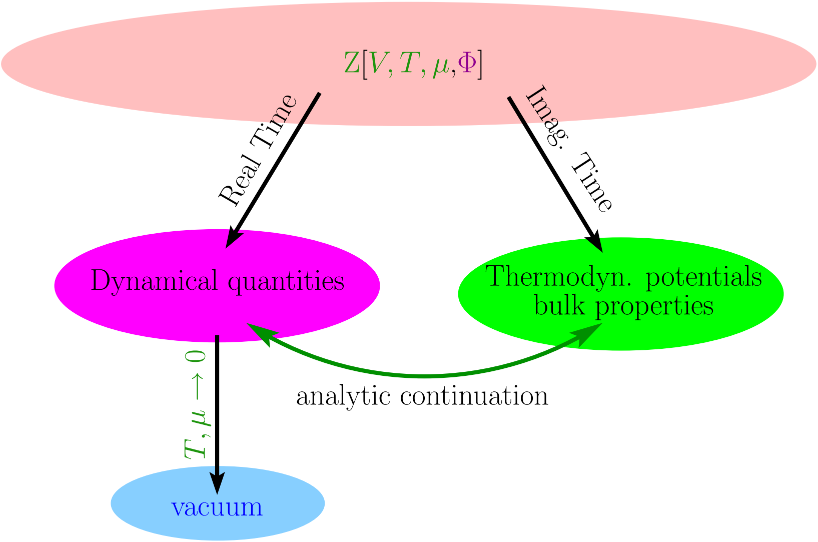




- Mechanism of chiral restoration?
- Two main theoretical ideas
  - "dropping masses": $m_{\text{had}} \propto \langle \bar{\psi}\psi \rangle$
  - "melting resonances": broadening of spectra through medium effects
  - More theoretical question: Realization of chiral symmetry in nature?

Finite Temperature/Density: Idealized theory picture

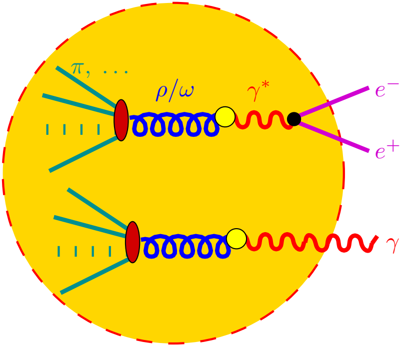
- partition sum: $Z(V, T, \mu_q, \Phi) = \mathrm{Tr}\{\exp[-(\mathbf{H}[\Phi] - \mu_q \mathbf{N})/T]\}$



[. . .,K. Chou, Z. Su, B. Hao, L. Yu 85, N.P. Landsmann, C.G. van Weert 87,. . .]

Electromagnetic probes in heavy-ion collisions

- $\gamma, \ell^{\pm}$: no strong interactions
- reflect whole "history" of collision:
  - from pre-equilibrium phase
  - from thermalized medium QGP and hot hadron gas
  - from VM decays after thermal freezeout



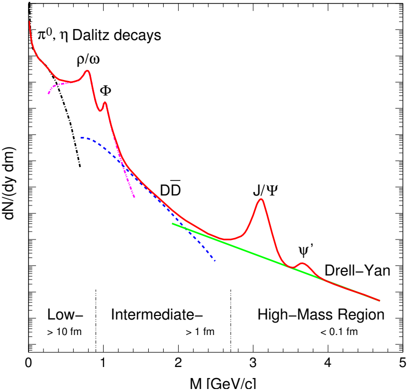


Fig. by A. Drees

Vector Mesons and electromagnetic Probes

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

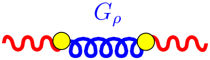
  [L. McLerran, T. Toimela 85, H. A. Weldon 90, C. Gale, J.I. Kapusta 91]

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

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

$$\frac{\mathrm{d}N_{e^+e^-}}{\mathrm{d}^4 x \mathrm{d}^4 q} = -g^{\mu\nu} \frac{\alpha^2}{3 q^2 \pi^3} \, \mathrm{Im} \, \Pi^{(\mathrm{ret})}_{\mu\nu}(q) \Big|_{q^2 = M^2_{e^+e^-}} f_B(q_0)$$

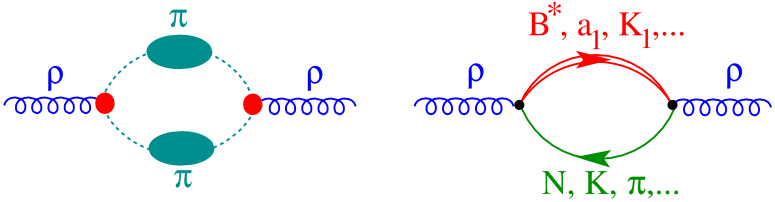
- to lowest order in α: $e^2 \Pi_{\mu\nu} \simeq \Sigma^{(\gamma)}_{\mu\nu}$
- vector-meson dominance model:

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

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

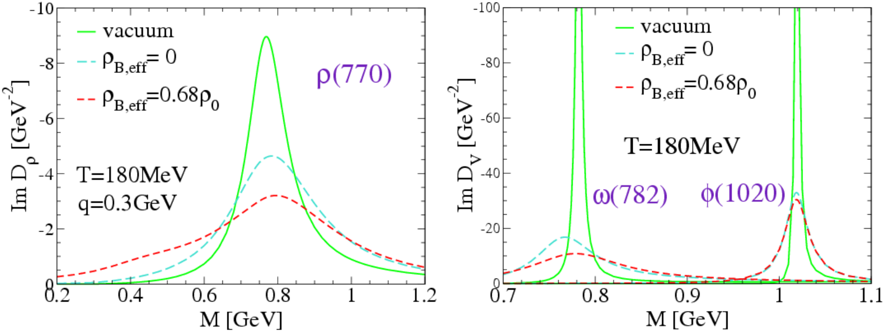
Hadronic many-body theory

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



- 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]

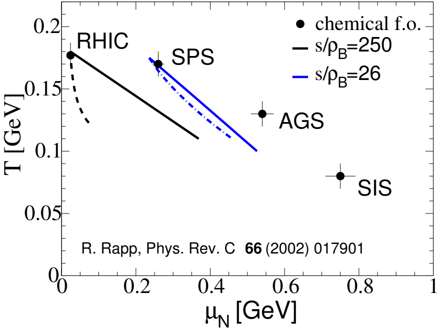
- baryon effects important
  - large contribution to broadening of the peak
  - responsible for most of the strength at small M

Fireball and Thermodynamics

- cylindrical fireball model: $V_{\rm FB} = \pi(z_0 + v_{z0}t + \frac{a_z}{2}t^2)\left(\frac{a_\perp}{2}t^2 + r_0\right)^2$
- thermodynamics:
  - isentropic expansion; $S_{\rm tot}$ fixed by $N_{\rm ch}$; $T_c = T_{\rm chem} = 175$ MeV
  - $T > T_c$: massless gas for QGP with $N_f^{\rm eff} = 2.3$
  - mixed phase: $f_{\rm HG}(t) = [s_c^{\rm QGP} - s(t)]/[s_c^{\rm QGP} - s_c^{\rm HG}]$
  - $T < T_c$: hadron-resonance gas
- $\Rightarrow T(t), \mu_{\rm baryon,meson}(t)$
- chemical freezeout:
  - $\mu_N^{\rm chem} = 232$ MeV
  - hadron ratios fixed

    $\Rightarrow \mu_N, \mu_\pi, \mu_K, \mu_\eta$ at fixed $s/\varrho_B = 27$
- thermal freezeout:

  $(T_{\rm fo}, \mu_\pi^{\rm fo}) \simeq (120, 80)$ 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]

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

- 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:

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

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

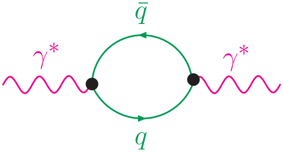
- General: McLerran-Toimela formula

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

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

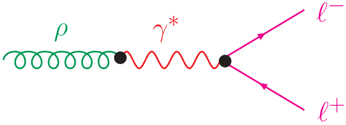
$$\Pi^{\mu\nu}_{\mathrm{em},i} = \mathrm{i}\int \mathrm{d}^4x \exp(\mathrm{i}qx)\Theta(x^0)\left\langle\left[j^{\mu}_{\mathrm{em},i}(x), j^{\nu}_{\mathrm{em},i}(x)\right]\right\rangle$$

- 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



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

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

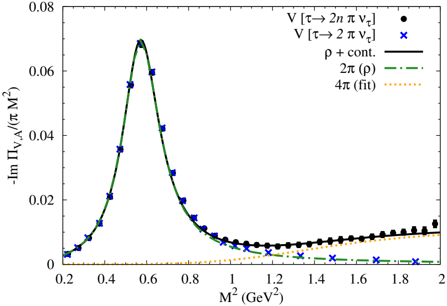
- special case of McLerran-Toimela (MT) formula
- $M^2 = q^2$: invariant mass, M, of dilepton pair
- $L(M^2) = (1 + 2m_l^2/M^2)\sqrt{1 - 4m_l^2/M^2}$: dilepton phase-space factor
- $D_\rho^{\mu\nu}(M,\vec{q})$: (four-transverse part of) in-medium ρ propagator at given $T(t)$, $\mu_{\mathrm{meson/baryon}}(t)$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

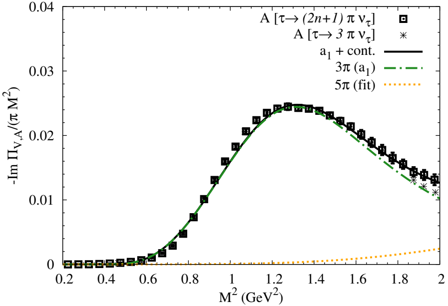
Radiation from thermal sources: multi-π processes

- 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 $a_1 \to \rho + \pi$ (already contained in ρ spectral function)

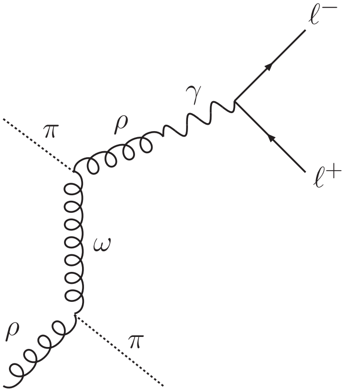




Data: [R. Barate et al (ALEPH Collaboration) 98]

Radiation from thermal sources: Meson t-channel exchange

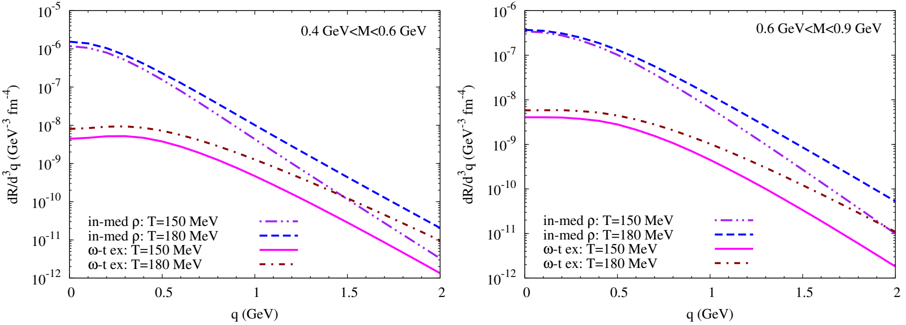
- motivation: q_T spectra too soft compared to NA60 data
- thermal contributions not included in models so far



- 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 $\mathrm{d}\sigma^\mu = (\mathrm{d}^3\vec{x}, 0, 0, 0)$

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

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

- use vacuum 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!

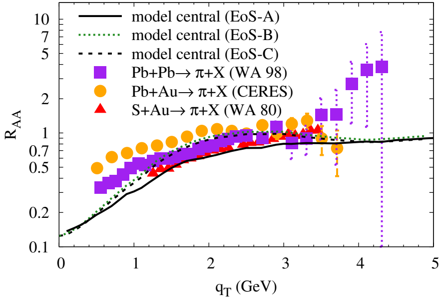
- $\Leftrightarrow$ l^+l^- from thermal sources softer by Lorentz factor M/q^0 compared to l^+l^- from decay of freeze-out ρ's

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

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

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



- check with pion R_{AA} data
- "primordial 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

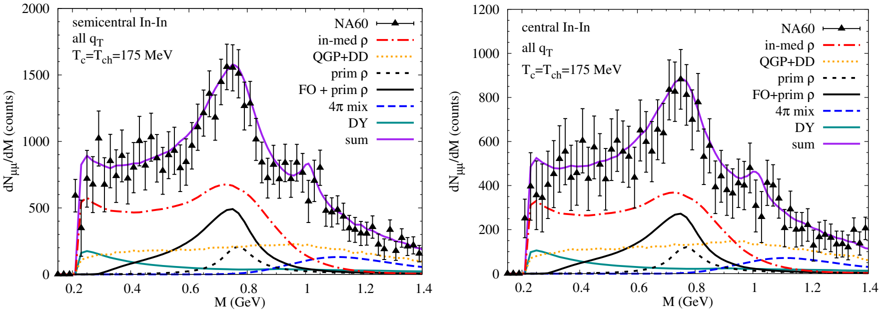
$$\left.\frac{\mathrm{d}N_{\mathrm{DY}}^{AA}}{\mathrm{d}M\mathrm{d}y}\right|_{b=0} = \frac{3}{4\pi R_0^2} A^{4/3} \frac{\mathrm{d}\sigma_{\mathrm{DY}}^{NN}}{\mathrm{d}M\mathrm{d}y}$$

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

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

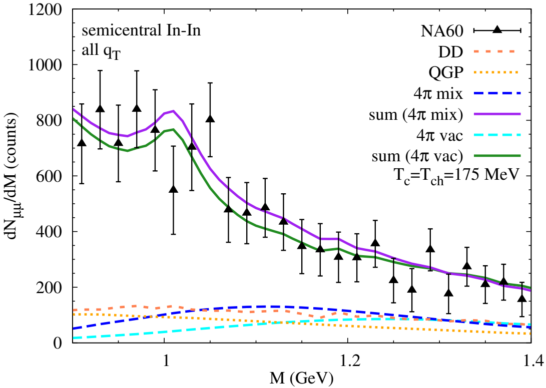
Excess spectra

- Fireball with "standard" EoS-A ($T_c = T_{\text{chem}} = 175$ MeV)
- overall normalization ⇔ total fireball lifetime
- relative normalization of thermal radiation fixed by rates
- rates integrated over time, volume, $\vec{q}$ including NA60 acceptance



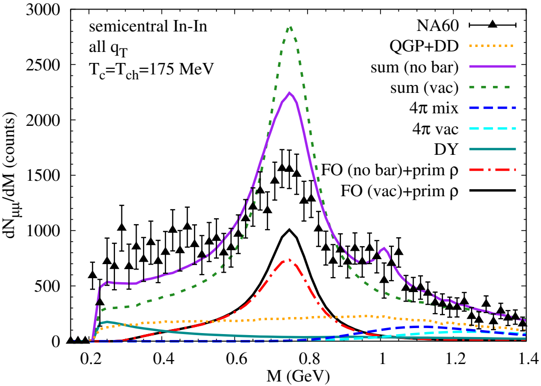
- good description of data

Excess spectra: IMR and multi-pion contributions



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

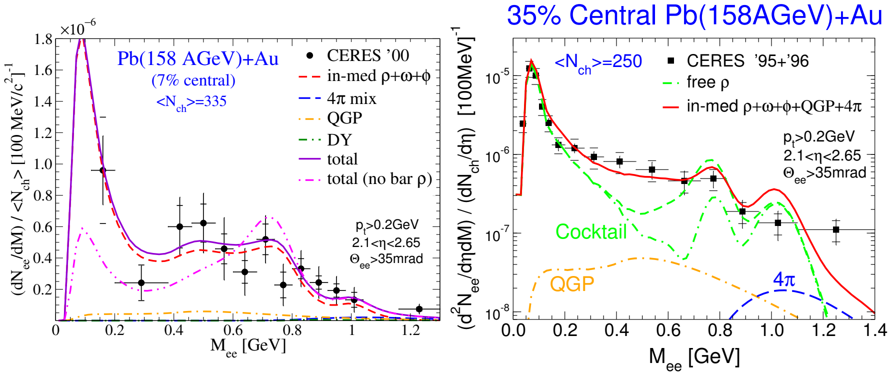
Excess spectra: baryon effects



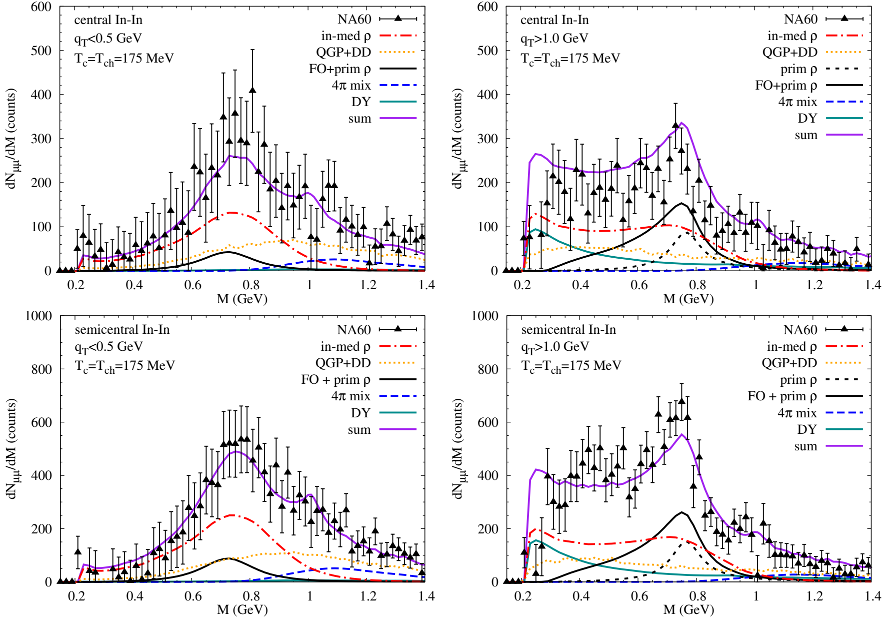
- in-medium VM spectral functions without baryon effects
  - not enough broadening around $M = m_\rho^{\mathrm{vac}}$
  - lack of strength at low mass $M \to m_{\mathrm{thr}} = 2m_\mu$

CERES/NA45 dielectron spectra

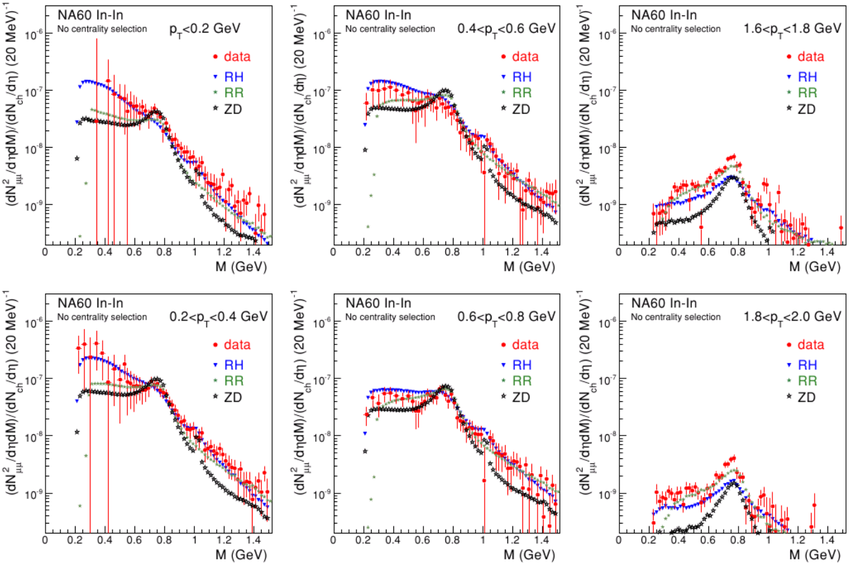
- good agreement also for dielectron spectra in $158\,\mathrm{GeV}$ Pb-Au
- allows further check of low-mass tail from baryon effects down to $M \to 2m_e$



Excess spectra: q_T binning

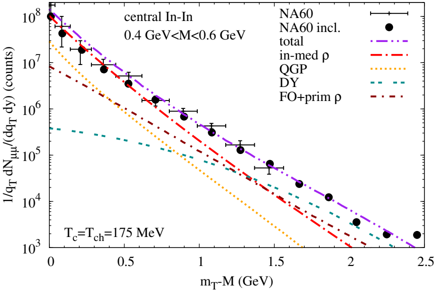


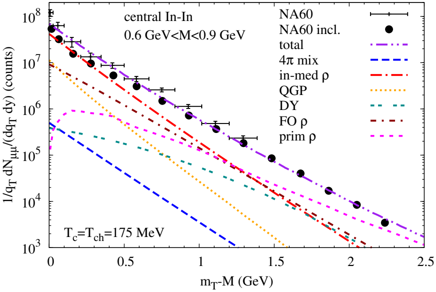
Excess spectra: acceptance-corrected mass spectra

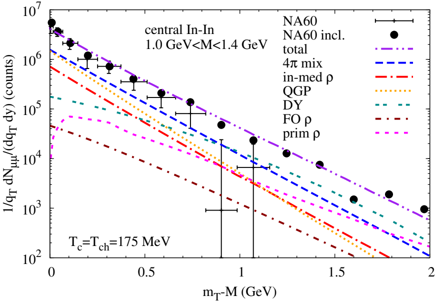


ZD: [K. Dusling, D. Teaney, I. Zahed 2007], RR: [J. Ruppert, T. Renk et al 2008], RH: [HvH, R. Rapp 2008]

m_T spectra (central)

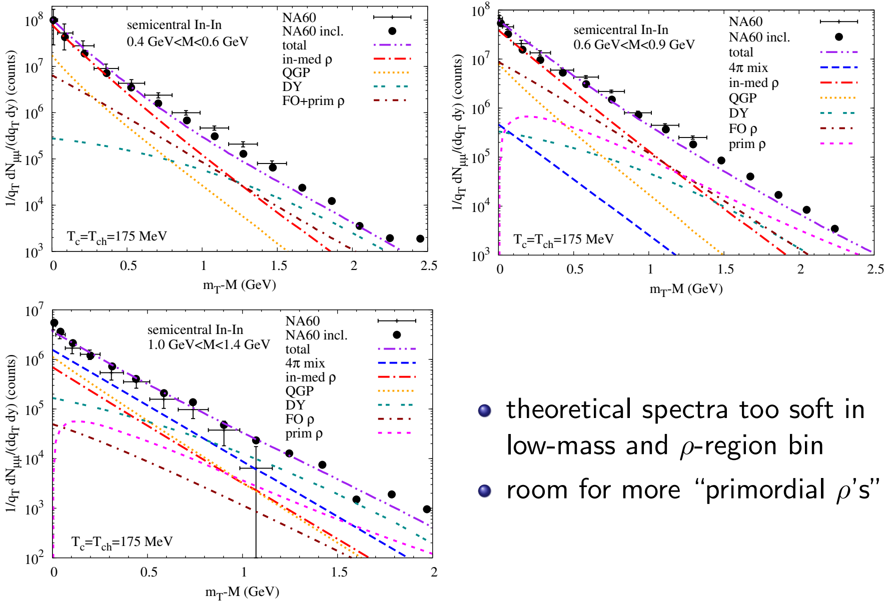






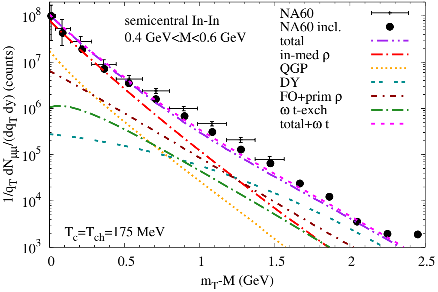
- fixed normalization in $0 \leq q_T \leq 0.5$ GeV bin
- satisfactory description of data
- high-mass bin slightly overestimated
- hard probes important for $q_T \geq 1$ GeV

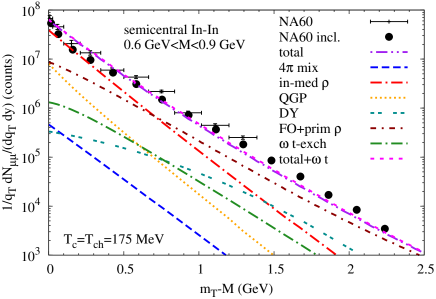
m_T spectra (semicentral)

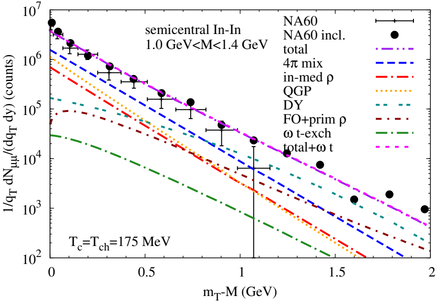


- theoretical spectra too soft in low-mass and ρ-region bin
- room for more "primordial ρ's"

Sensitivity to meson t-channel exchange contributions



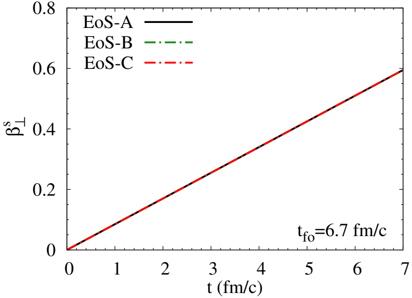


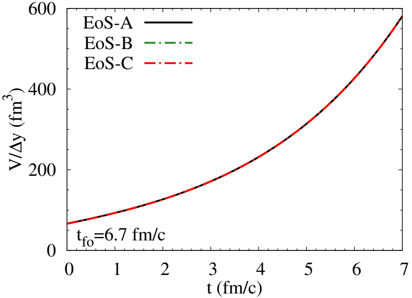


- use $2\times$ of ω-t exchange to account for other mesons (e.g., a_1, π)
- hardest among thermal sources
- abolute strength not sufficient to resolve discrepancy with data

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

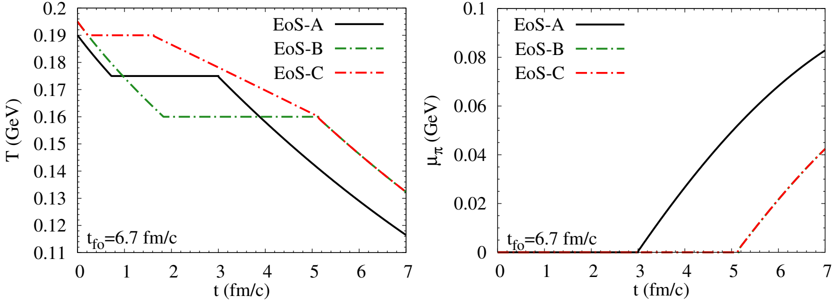




- EoS-A: $T_c = T_{\text{chem}} = 175$ MeV
- EoS-B: $T_c = T_{\text{chem}} = 160$ MeV
- EoS-C: $T_c = 190$ MeV, $T_{\text{chem}} = 160$ MeV
  - $T_c \geq T \geq T_{\text{chem}}$: hadron gas in chemical equilibrium
- keep fireball parameters the same (including life time)

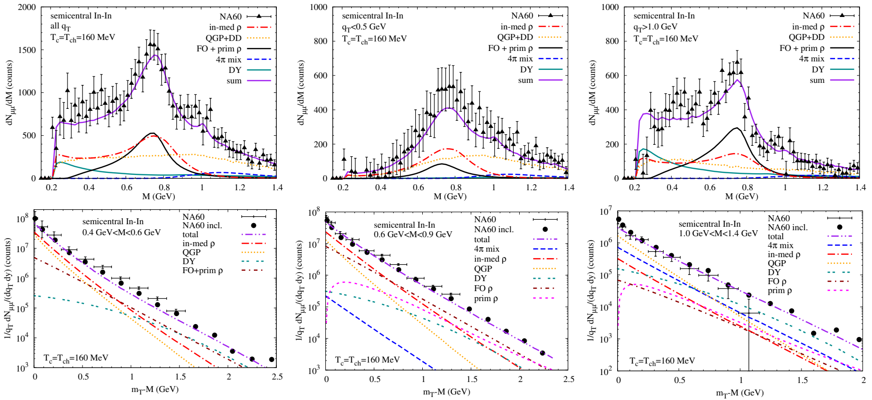
Sensitivity to T_c and hadro-chemistry

- 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



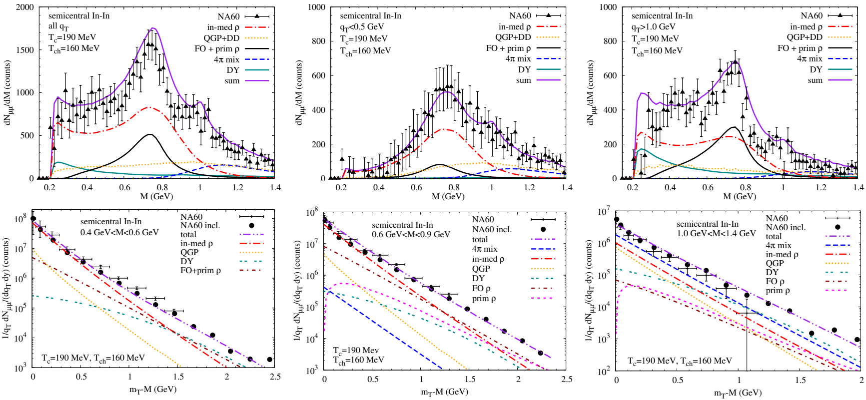
- EoS-A: $T_c = T_{\text{chem}} = 175$ MeV
- EoS-B: $T_c = T_{\text{chem}} = 160$ MeV
- EoS-C: $T_c = 190$ MeV, $T_{\text{chem}} = 160$ MeV
  - $T_c \geq T \geq T_{\text{chem}}$: hadron gas in chemical equilibrium
- keep fireball parameters the same (including life time)

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



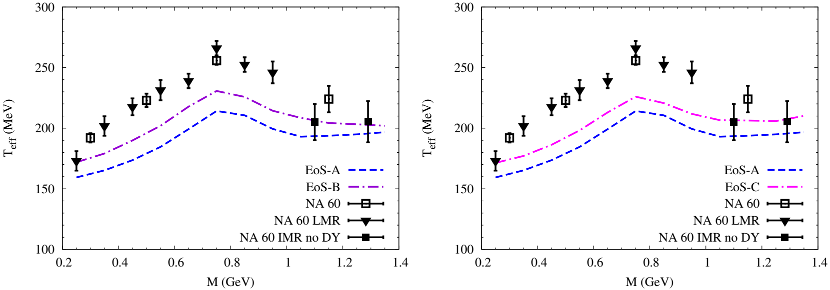
- mass spectra comparable to EoS-A ↔ slight reduction of fireball lifetime
- in IMR multi-pion ≫ QGP contribution
- higher hadronic temperatures + high-density hadronic phase ⇒ harder q_T spectra
- better agreement with data

Inverse-slope analysis

- to extract T_{eff} fit to

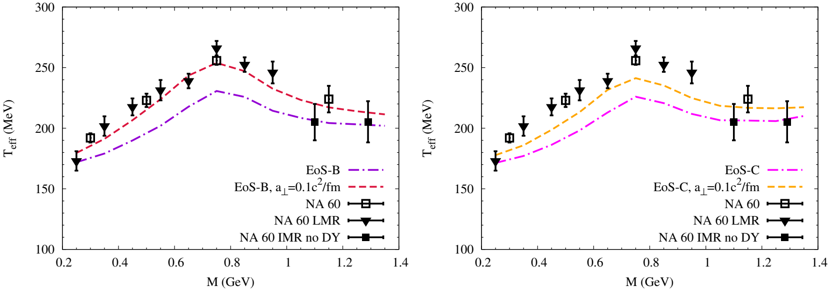
$$\frac{1}{q_T}\frac{\mathrm{d}N}{\mathrm{d}q_T} = \frac{1}{m_T}\frac{\mathrm{d}N}{\mathrm{d}m_T} = C\exp\left(-\frac{m_T}{T_{\text{eff}}}\right)$$

- fit of theoretical q_T spectra: 1 GeV $< q_T < 1.8$ GeV



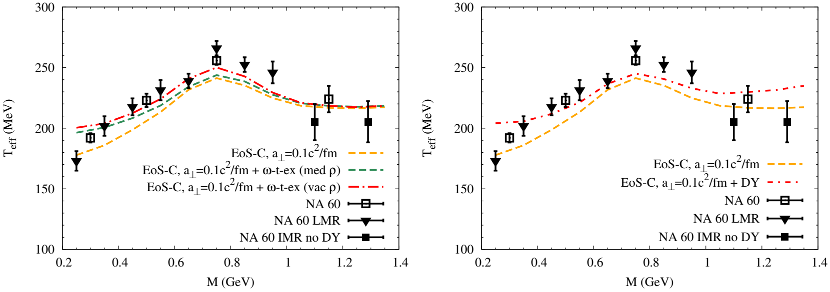
- standard fireball acceleration: too soft q_T spectra
- lower T_c in EoS-B and EoS-C helps (higher hadronic temperatures)
- NB: here, Drell Yan contribution taken out

Inverse-slope analysis



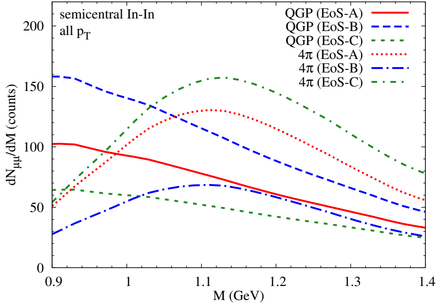
- enhance fireball acceleration to $a_\perp = 0.1c^2/\text{fm}$
- effective at all stages of fireball evolution
- agreement in IMR not spoiled ⇔ dominated from earlier stages
- EoS-B harder ⇔ relative contribution of harder freezeout ρ decays vs. thermal ρ's larger

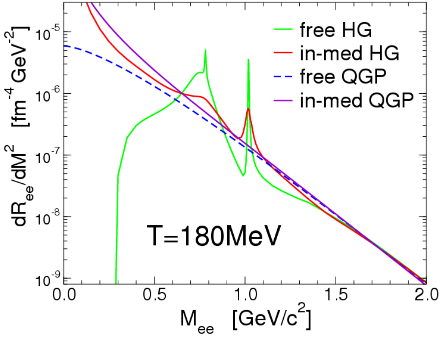
Inverse-slope analysis



- 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





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

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

- radiation maximal for $T = T_{\max} = M/5.5$
- hadronic and partonic radiation "dual" for $T \sim T_c$

  compatible with chiral-symmetry restoration!

Conclusions and Outlook

- dilepton spectra ⇔ 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 $160 \text{ MeV} \leq T \leq 190 \text{ MeV}$
      ⇔ "parton-hadron" duality of rates
      ⇔ compatible with chiral-symmetry restoration!
  - dimuons in In-In (NA60), Pb-Au (CERES/NA45), γ in Pb-Pb (WA98)

Conclusions and Outlook

- fireball/freeze-out dynamics $\Leftrightarrow$ m_T spectra and effective slopes
  - “non-thermal sources” important for $q_T \gtrsim 1 \text{ GeV}$
  - lower T_c $\Rightarrow$ higher hadronic temperatures $\Rightarrow$ 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
  - understand recent PHENIX results (large dilepton excess in LMR)
  - 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!

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