

Theoretical Review of Dileptons from Heavy Ion Collisions

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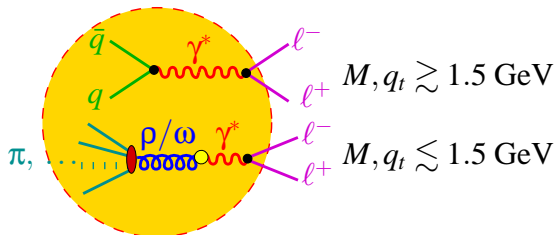
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- 1 QCD, Chiral Symmetry, and Dileptons
- 2 Hadronic Models in Medium
- 3 Models vs. Experiments
- 4 Sensitivities to QCD Matter
- 5 Conclusions

Dileptons and in-medium em. current correlation function



- **Dilepton emission rate** [McLerran, Toimela 85]

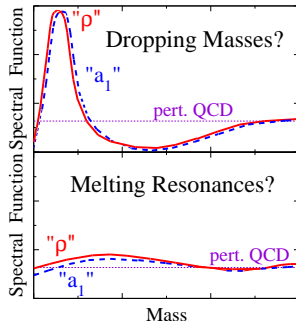
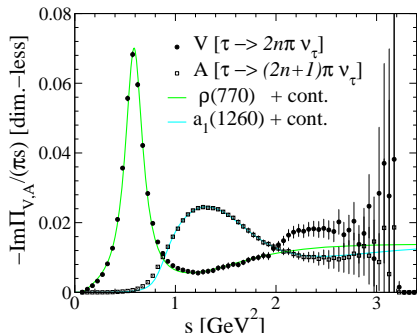
$$\frac{dN_{e^+e^-}}{d^4x d^4q} = -g^{\mu\nu} \frac{\alpha_{\text{em}}^2}{3q^2 \pi^3} \text{Im} \Pi_{\mu\nu}^{(\text{em})}(q) \Big|_{q^2=M_{e^+e^-}^2} f_B(q_0)$$

$$\Pi_{\mu\nu}^{(\text{em})}(q) = \int d^4x \exp(iq \cdot x) \Theta(x_0) \left\langle \left[j_{\mu}^{(\text{em})}(x), j_{\nu}^{(\text{em})}(0) \right] \right\rangle_T$$

- l^+l^- spectra \Leftrightarrow **in-medium em. current-current correlator**
- **Vector dominance** \Rightarrow **in-medium modifications of vector mesons!**

Chiral Symmetry Restoration

- light-quark sector of QCD: **chiral symmetry**
 - spontaneously broken in vacuum ($\langle \bar{q}q \rangle \neq 0$)
 - high temperature/density: **restoration of chiral symmetry**
 - Lattice QCD: $T_c^X \simeq T_c^{\text{deconf}}$



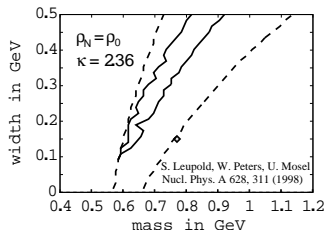
- **Mechanism** of chiral restoration?
 - "dropping masses": $m_{\text{had}} \propto \langle \bar{\psi}\psi \rangle$
 - "melting resonances": broadening of spectra through medium effects

Weinberg sum rules

$$M_n = - \int_0^\infty \frac{ds}{\pi} s^n [\text{Im } \Pi_V(s) - \text{Im } \Pi_A(s)]$$
$$M_{-2} = \frac{1}{3} f_\pi^2 \langle r_\pi^2 \rangle - F_A, \quad M_{-1} = f_\pi^2$$
$$M_0 = 0, \quad M_1 = c\alpha_s \langle (\bar{q}q)^2 \rangle$$

[Weinberg 67; Das et al 67; Kapusta, Shuryak 93]

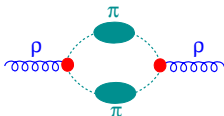
- theory connection of **chiral symm. restoration** with dileptons in HICs
 - Π_V, Π_A from **chiral hadronic model** at finite T, μ_B
 - compare $M_n(T, \mu_B)$ to **IQCD chiral order parameters at finite T**
 - compare Π_V from **hadronic model** to dileptons from HICs
- also QCD sum rules
 - relate **current correlators** to **condensates**
 - VMD \Leftrightarrow **vector-meson spectral functions**



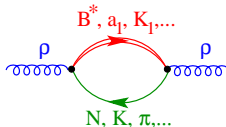
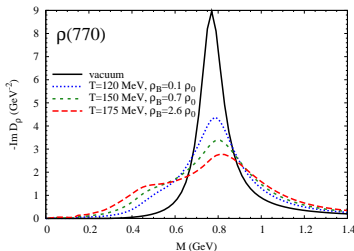
Hadronic many-body theory

- pion-cloud modifications and **baryonic/mesonic excitations**

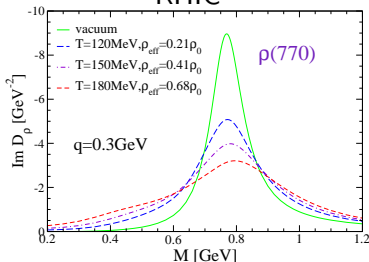
[Chanfray et al, Herrmann et al, Ko et al, Rapp et al, Klingl et al, Post et al, Friman et al, . . .]



SPS



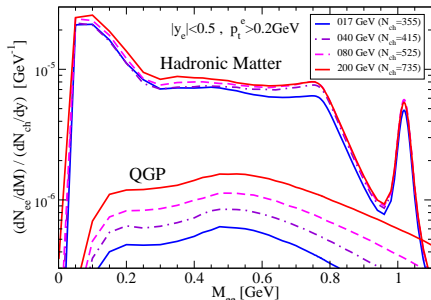
RHIC



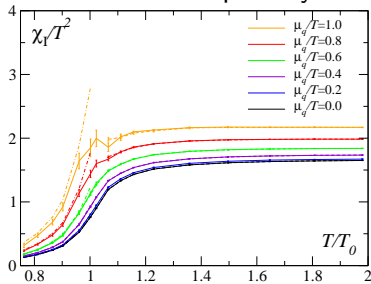
- **substantial broadening of vector mesons with little mass shift!**
 - baryon effects prevalent ($\rho_B + \rho_{\bar{B}}$, not $\rho_B - \rho_{\bar{B}}$, relevant!)
 - different approaches consistent if constrained by data ($\gamma N, \gamma A, \pi N \rightarrow \rho N$)

Hadronic models vs. lattice QCD

Dilepton Excitation Function in Central Au-Au ($N_{\text{part}}=330$)



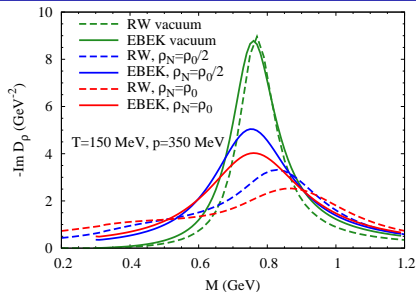
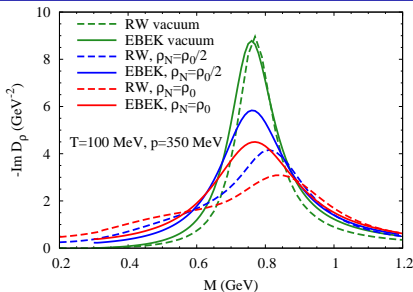
Isovector Susceptibility



$$\chi_{q,I} = \frac{\partial p}{\partial \mu_{q,I}}, \quad \mu_q = \mu_u + \mu_d, \quad \mu_I = \mu_u - \mu_d$$

- excitation function from top SPS to top RHIC energies:
 - little change in hadronic contribution [Rapp 02]
- IQCD: Smooth behavior of susceptibilities in $I = 1$ channel [Allton et al 04]
 - consistent with no mass shift in $I = 1$ channel
 - NB: χ_q ($I = 0$) shows peak at $T \rightarrow T_c$: signature of phase transition!

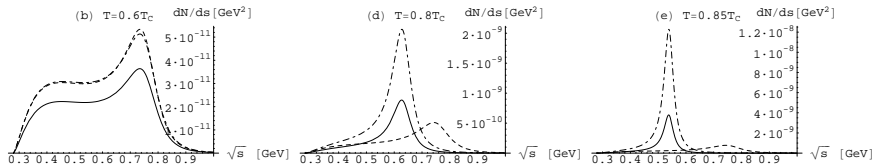
ρ meson in hot hadronic matter



- **EBEK:** [Eletsky, Belkacem, Ellis, Kapusta 01]
 - empirical $\rho + B/M$ scattering amplitudes + Pomeron/Regge background
 - $T\rho$ approximation for finite-T effects
- **RW:** Hadronic many-body theory [Rapp, Wambach 99]
- **Somewhat different results**
 - more broadening and level repulsion:
in-med modifications of pion-cloud + ρBN interactions

Chiral approaches

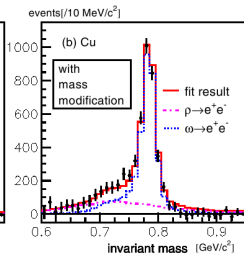
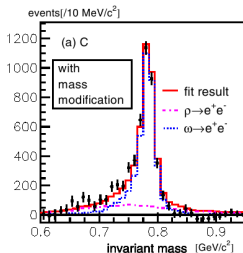
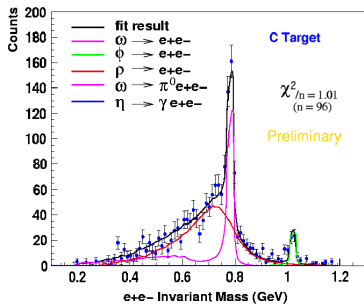
- Chiral reduction formalism [Steele et al 96]
 - leading order in π and N density + chiral reduction formulas
⇒ in-medium current correlators in terms of vacuum correlators
 - no Dyson resummation!
- Hidden local symmetry [Bando et al 85; Harada, Yamawaki 01,...]
 - Vector manifestation of chiral symmetry: ρ_{long} chiral partner of π
⇒ dropping ρ mass + violation of vector dominance ($T > T_{\text{flash}} = 0.7T_c$)



[Harada, Sasaki 07]

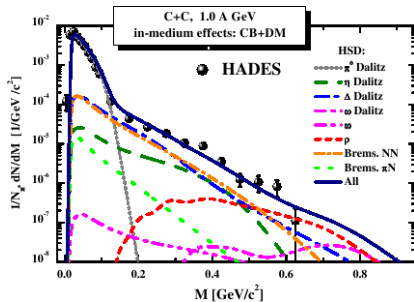
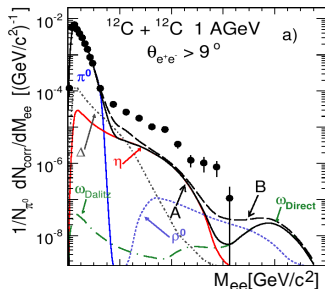
- dilepton rates similar to more simple dropping mass models

Elementary reactions ($\gamma + A, p + A$)



- left: JLab $\gamma + A \rightarrow e^+ + e^-$ [CLAS Collab. 07]
 - Theory: Boltzmann Uehling Uhlenbeck (BUU) transport [Effenberger et al 00]
 - good agreement: **no mass shift, broadening of the ρ : $\Gamma_\rho \sim 220$ MeV**
- right: KEK $p+A \rightarrow e^+ + e^-$ [E325 Collaboration 07]
 - fit to dropping-mass ansatz: $m^*/m = (1 - C\rho/\rho_0)$
 - $C = 0.092 \pm 0.002$, no broadening**
 - Contradiction with JLab**
 - ρ/ω ratio small; yield for $M > 0.85$ GeV?

1-2 AGeV A-A: HADES and DLS

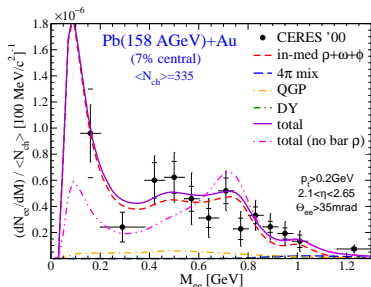


- **HADES confirms DLS**
- Theory: transport model (HSD); coll. broadening + dropping mass [Bratkovskaya, Cassing 07]
 - moderate sensitivity to vector-meson medium effects!
 - solution of DLS puzzle
 - improved e^+e^- Bremsstrahlung [de Jong, Mosel 97; Kaptari, Kämpfer 06]
 - updated η - and Δ -Dalitz contributions

CERES vs. Hadronic many-body theory

- Dilepton emission from thermal source
- thermal fireball evolution (isentropic QGP/MIX + hadron gas)

$$\frac{dN_{\ell\ell}^{\text{therm}}}{dM} \propto - \int_{\text{FB}} d^4x \int \frac{d^3q}{Mq_0} \text{Im} \Pi^{(\text{em})}(q_0, \vec{q}) f_B(q_0) \text{Acc}$$

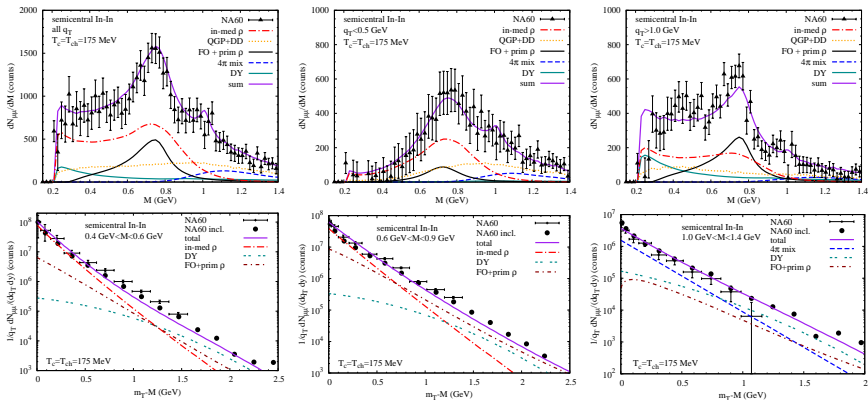


- **baryon effects** essential!
 - many-body effects ⇔ very low-mass excess

[HvH, R. Rapp 07]

NA60 vs. Hadronic many-body theory + HR fireball

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



- M spectra

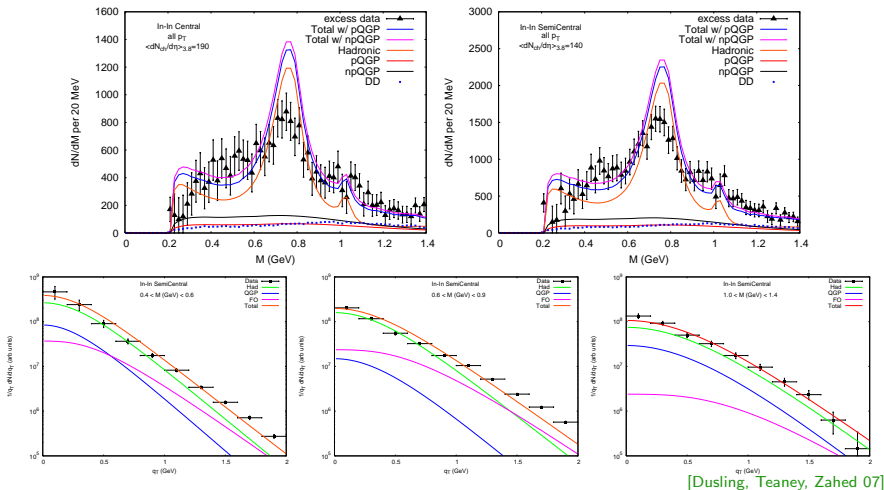
[HvH, Rapp 07]

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

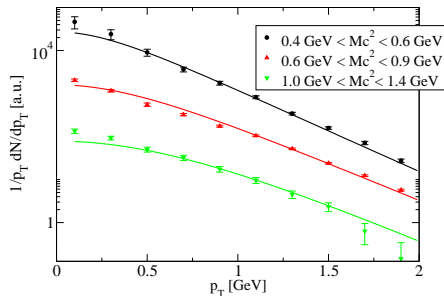
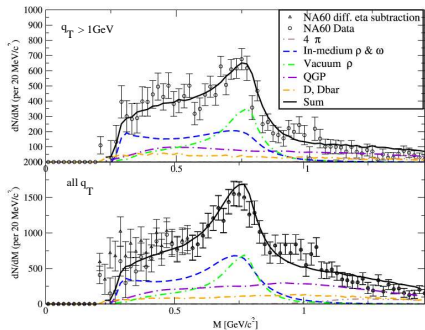
NA 60 vs. Chiral reduction formalism + hydrodynamics



[Dusling, Teaney, Zahed 07]

- low-mass + IMR spectrum described
- ρ : lack of broadening (due to low-density approximation)
- q_T spectra: only thermal + freezeout, no primordial ρ

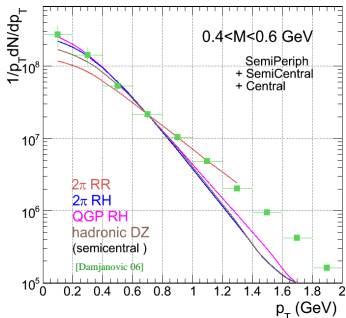
NA60 vs. empirical spectral functions + RR fireball



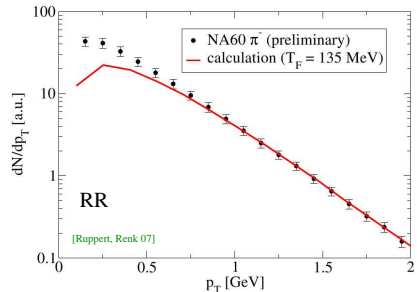
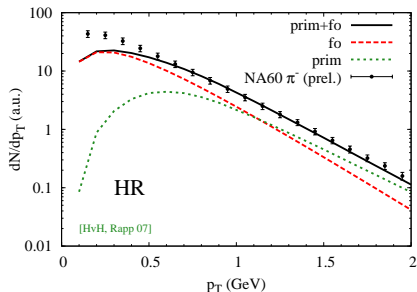
[Ruppert et al 07]

- only thermal + freeze-out
- large QGP contribution
- sensitivity of spectral functions to data?!

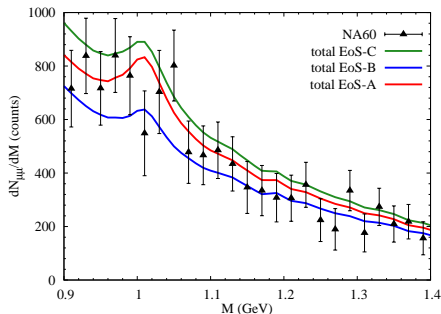
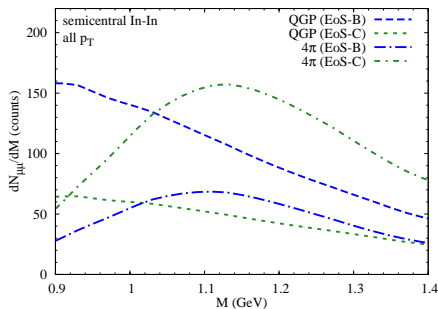
Sensitivity I: Fireball models vs. hydrodynamics



- HR fireball [HvH, Rapp 06, 07]
 - thermal dileptons: agrees with hydro
 - pions: need "primordial" hard comp.
 - low p_T : resonance decays
 - consistent with measured $R_{AA}^{(\pi)}$
- RR fireball [Ruppert, Renk 07]
 - dileptons: harder than hydro
 - pions: thermal only



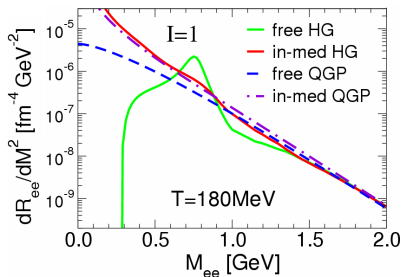
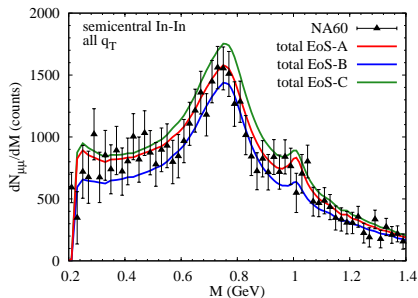
Sensitivity II: Intermed. mass region – QGP vs. hadron gas



[HvH, Rapp 07]

- EoS-B: $T_c = T_{\text{chem}} = 160$ MeV (large QGP part)
EoS-C: $T_c = 190$ MeV, $T_{\text{chem}} = 160$ MeV (small QGP part)
- volume $\leftrightarrow T$: emission dominated by temperatures around T_c
(QGP vs. high-density hadronic phase)
- description of spectra comparable for different EoS

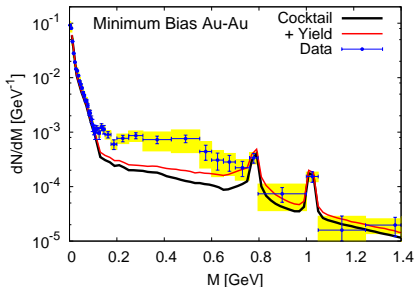
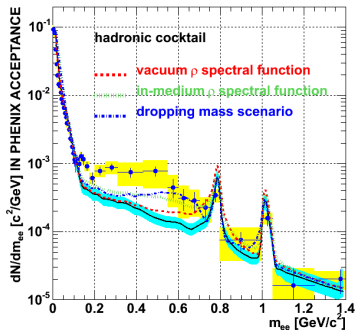
Sensitivity III: Critical temperature and freeze-out



- EoS-A: $T_c = T_{\text{chem}} = 175 \text{ MeV}$;
 EoS-B: $T_c = T_{\text{chem}} = 160 \text{ MeV}$
EoS-C: $T_c = 190 \text{ MeV}$, $T_{\text{chem}} = 160 \text{ MeV}$
 - norm depends on t_{fireball} (kept fixed here)!
 - description of spectra comparable
 - reason for insensitivity to EoS and hadro-chemistry [HvH, Rapp 07]:
 - hadronic and partonic radiation "dual" for $T \sim T_c$
 (pQCD: $\Pi_V \equiv \Pi_A \Rightarrow$ compatible with chiral symmetry restoration!)

PHENIX e^+e^- -mass spectrum

min. bias 200 A GeV Au+Au
minimum bias Au+Au @ $\sqrt{s} = 200$ GeV



- hadronic many-body theory

[Rapp 01, 02]

(for $N_{\text{part}} = 125$)

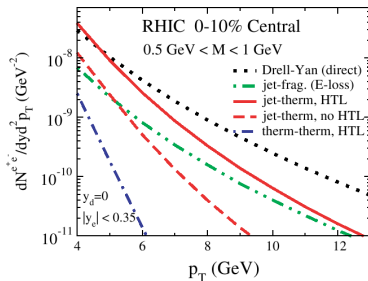
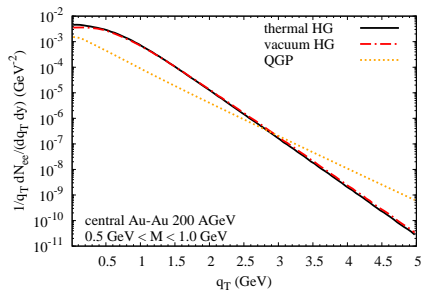
- LMR enhancement cannot be described!

- chiral reduction formalism

[Dusling, Zahed 07]

(central scaled by N_{part})

Predictions: e^+e^- - q_T spectra at RHIC



- theory: thermal [Rapp 08 (unpublished)]; hard contributions [Turbide et al 06]
- hard contributions (jet-thermal) take over for $q_T \gtrsim 3 \text{ GeV}$

Conclusions and Outlook

- Models for vector (ρ) mesons in medium
 - hadronic many-body theory
 - broadening, small mass shifts of spectra (baryon effects prevalent)
 - hadron-parton duality of dilepton rates (QGP portion depends on T_c)
 - chiral reduction formalism
 - low-density approximation, no broadening
 - HLS+Vector Manifestation
 - dropping mass, no vector dominance near T_c
- Theory vs. Experiment
 - Elementary reactions
 - JLAB: BUU transport with broadening (with no mass shift)
 - KEK: Dropping-mass ansatz
 - Heavy-ion collisions
 - HADES (DLS): HSD transport; improved Bremsstrahlung and Δ Dalitz
 - CERES, NA60: Hadronic many-body theory robust due to duality involved mix of contributions at high q_T
 - PHENIX: Low-mass enhancement can not be described!

- Not covered in this talk: Thermal Photons
 - Same em. correlator as for dileptons!
 - Hadronic many body theory: improvement in description of WA98 data
[Liu, Rapp 06]
 - Possibility to measure T_{initial} :

$$\frac{dN_{\ell\ell}/dq_T}{dN_{\gamma}/dq_T}$$

[Alam et al 07]

- Connection between chiral symmetry restoration and dilepton data
 - hadronic chiral model at finite $T \Rightarrow \Pi_V$ and Π_A
 - confront Π_V with dilepton data
 - check moments of $\Pi_V - \Pi_A$ with IQCD via Weinberg sum rules