Theoretical Review of Dileptons from Heavy Ion Collisions

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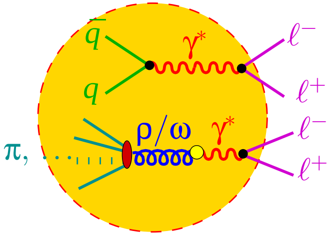
Outline

Dileptons and in-medium em. current correlation function



$M, q_t \gtrsim 1.5\,\text{GeV}$

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- Dilepton emission rate [McLerran, Toimela 85]

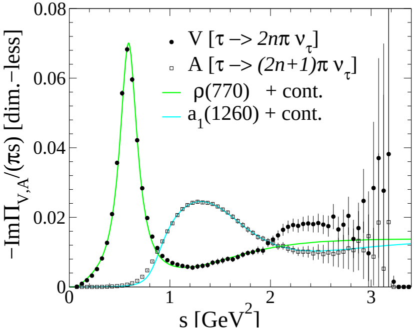
$$\frac{\mathrm{d}N_{e^+e^-}}{\mathrm{d}^4x\mathrm{d}^4q} = -g^{\mu\nu}\frac{\alpha_{\mathrm{em}}^2}{3q^2\pi^3}\,\mathrm{Im}\,\Pi_{\mu\nu}^{(\mathrm{em})}(q)\Big|_{q^2=M_{e^+e^-}^2} f_B(q_0)$$

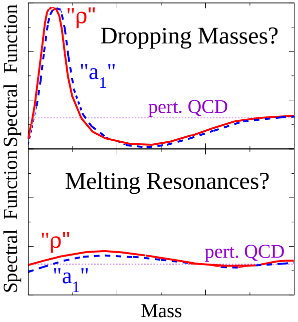
$$\Pi_{\mu\nu}^{(\mathrm{em})}(q) = \int \mathrm{d}^4x \exp(\mathrm{i}q\cdot x)\Theta(x_0)\left\langle\left[j_\mu^{(\mathrm{em})}(x), j_\nu^{(\mathrm{em})}(0)\right]\right\rangle_T$$

- $\ell^+\ell^-$ 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: $T_c^\chi \simeq T_c^{\text{deconf}}$





- 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

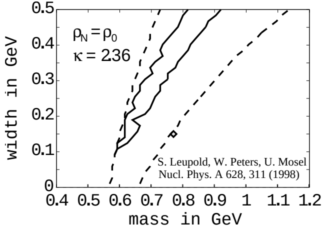
$$M_n = -\int_0^\infty \frac{\mathrm{d}s}{\pi} s^n [\mathrm{Im}\,\Pi_V(s) - \mathrm{Im}\,\Pi_A(s)]$$

$$M_{-2} = \frac{1}{3} f_\pi^2 \left\langle r_\pi^2 \right\rangle - F_A, \quad M_{-1} = f_\pi^2$$

$$M_0 = 0, \quad M_1 = c\alpha_s \left\langle (\bar{q}q)^2 \right\rangle$$

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

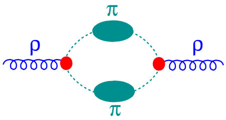
- theory connection of chiral symm. restoration with dileptons in HICs
  - Π_V, Π_A from chiral hadronic model at finite T, μ_B
  - compare $M_n(T, \mu_B)$ to lQCD chiral order parameters at finite T
  - compare Π_V from hadronic model to dileptons from HICs
- also QCD sum rules
  - relate current correlators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

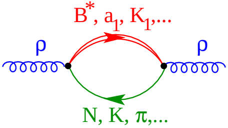


Hadronic many-body theory

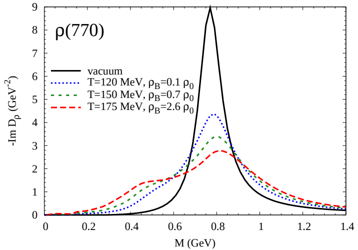
- pion-cloud modifications and baryonic/mesonic excitations

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

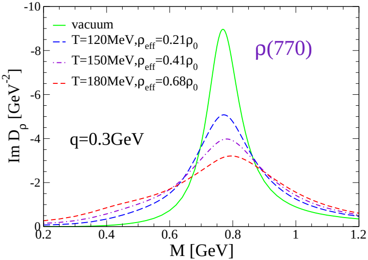




SPS

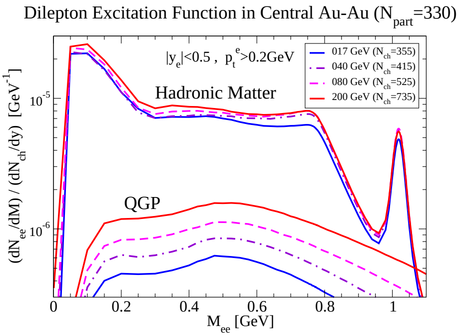


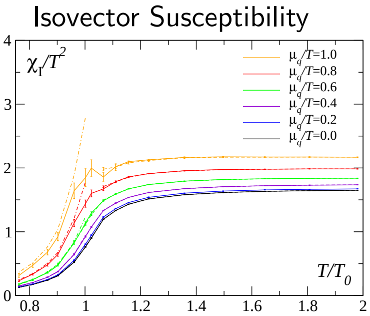
RHIC



- 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 (γN, γA, $\pi N \rightarrow \rho N$)

Hadronic models vs. lattice QCD

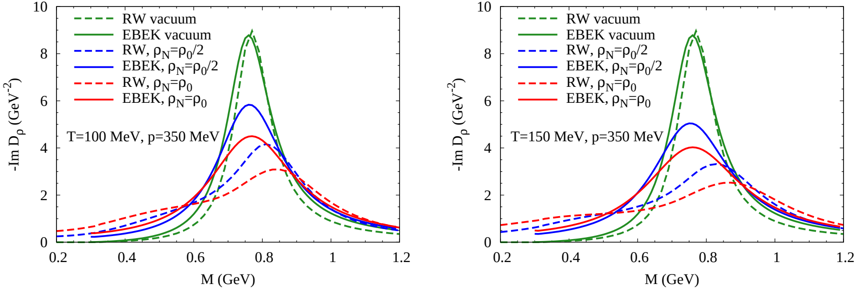




$$\chi_{q,I} = \frac{\partial p}{\partial \mu_{q,I}}, \quad \mu_q = \mu_u + \mu_d, \quad \mu_I = \mu_u - \mu_d$$

- excitation function from top SPS to top RHIC energies: little change in hadronic contribution [Rapp 02]
- lQCD: 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 $T \to T_c$: signature of phase transition!

ρ meson in hot hadronic matter

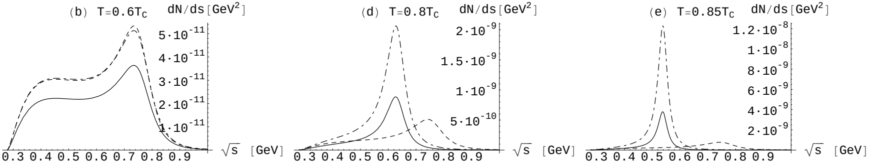


- EBEK: [Eletsky, Belkacem, Ellis, Kapusta 01]
  - empirical $\rho + B/M$ scattering amplitudes $+$ Pomeron/Regge background
  - $T\rho$ approximation for finite-T effects
- RW: Hadronic many-body theory [Rapp, Wambach 99]
- Somewhat different results
  - more broadening and level repulsion: in-med modifications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

- Chiral reduction formalism [Steele et al 96]
  - leading order in π and N density + chiral reduction formulas

  $\Rightarrow$ 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

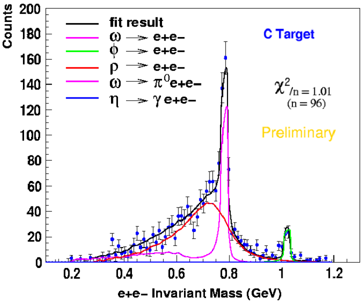
  $\Rightarrow$ dropping ρ mass + violation of vector dominance $(T > T_{\text{flash}} = 0.7 T_c)$

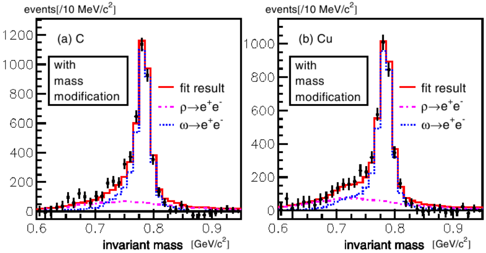


[Harada, Sasaki 07]

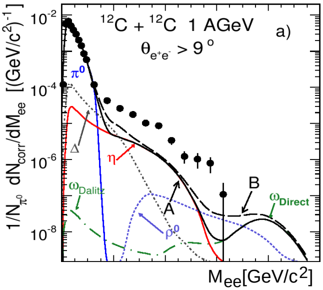
- dilepton rates similar to more simple dropping mass models

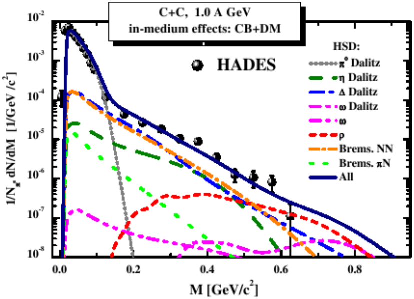
Elementary reactions ($\gamma + \text{A}$, $p + \text{A}$)





- 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: $m^*/m = (1 - C\varrho/\varrho_0)$
  - $C = 0.092 \pm 0.002$, no broadening
  - Contradiction with JLab
  - ρ/ω ratio small; yield for $M > 0.85$ GeV?



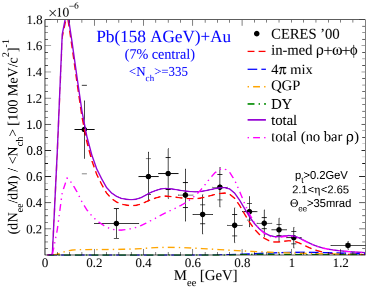


- HADES confirms DLS
- Theory: transport model (HSD); coll. broadening + dropping mass [Bratkovskaya, Cassing 07]
  - moderate sensitivity to vector-meson medium effects!
  - solution of DLS puzzle
    - improved e^+e^- Bremsstrahlung [de Jong, Mosel 97; Kaptari, Kämpfer 06]
    - updated η- and Δ-Dalitz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

CERES vs. Hadronic many-body theory

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

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

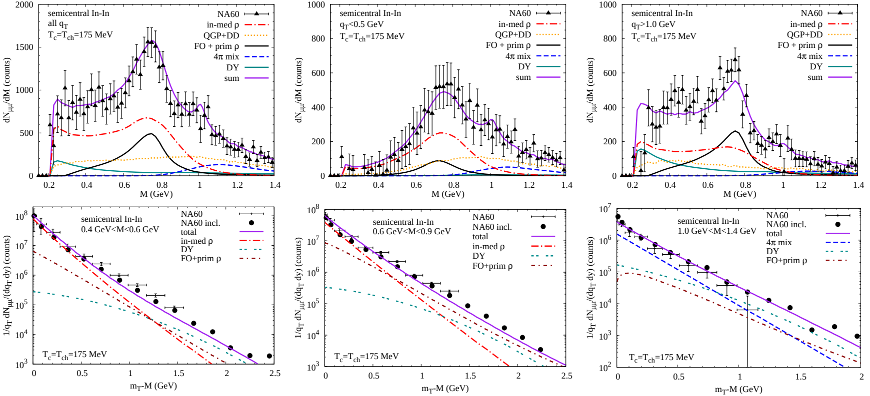


[HvH, R. Rapp 07]

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

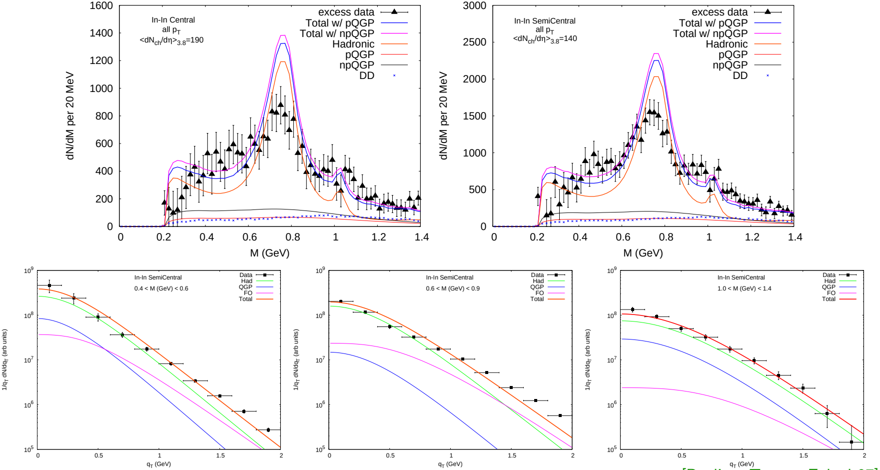
NA60 vs. Hadronic many-body theory + HR fireball

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



- M spectra [HvH, Rapp 07]
  - consistent with predicted broadening of ρ meson
  - $M <$ 1GeV: thermal ρ; $M > 1$ GeV: thermal multi-pion processes
- m_t spectra
  - $q_t < 1$ GeV: thermal radiation
  - $q_t > 1$ GeV: freeze-out + hard primordial ρ, Drell-Yan

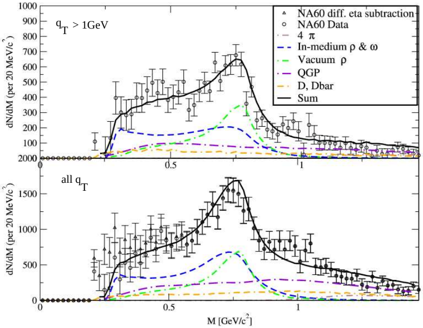
NA 60 vs. Chiral reduction formalism + hydrodynamics

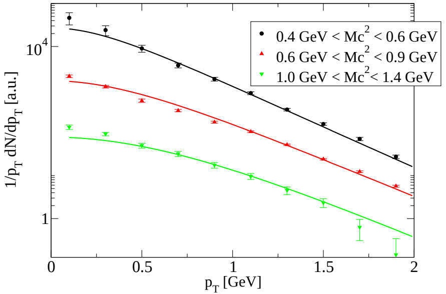


[Dusling, Teaney, Zahed 07]

- 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

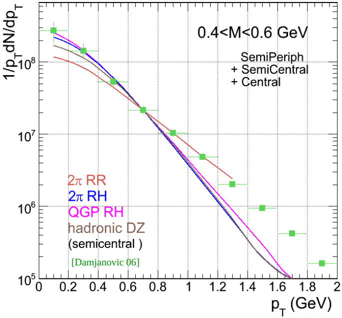


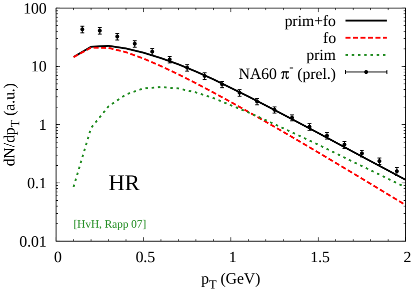


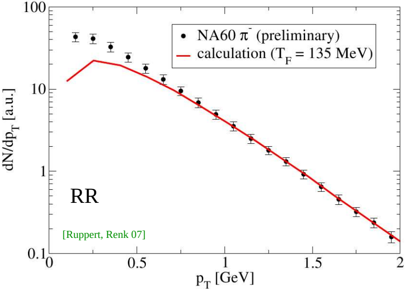
[Ruppert et al 07]

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

Sensitivity I: Fireball models vs. hydrodynamics

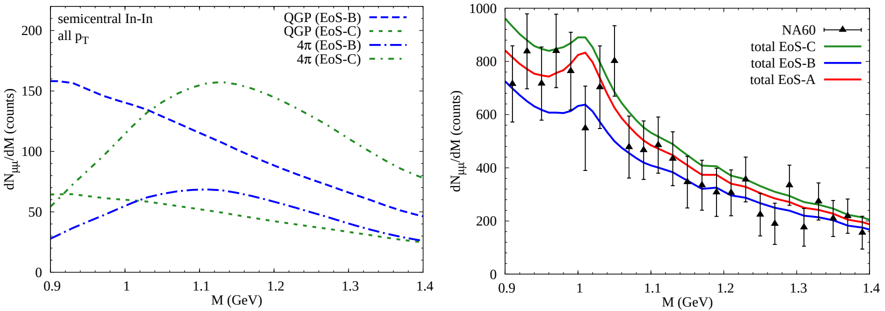






- HR fireball [HvH, Rapp 06, 07]
  - thermal dileptons: agrees with hydro
  - pions: need “primordial” hard comp.
    low p_T: resonance decays
    consistent with measured $R_{AA}^{(\pi)}$
- RR fireball [Ruppert, Renk 07]
  - dileptons: harder than hydro
  - pions: thermal only

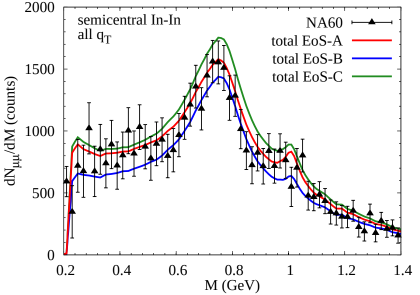
Sensitivity II: Intermed. mass region – QGP vs. hadron gas

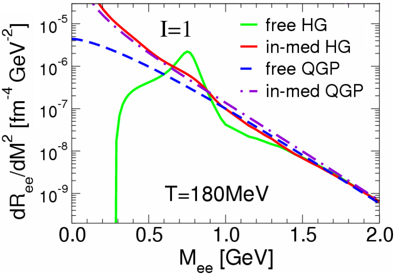


[HvH, Rapp 07]

- 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

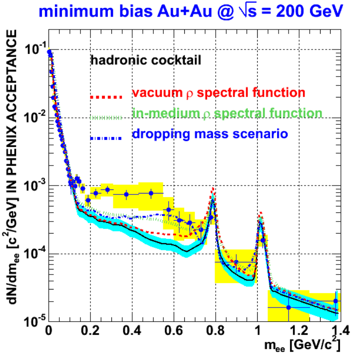




- EoS-A: $T_c = T_{\text{chem}} = 175$ MeV; EoS-B: $T_c = T_{\text{chem}} = 160$ MeV
  EoS-C: $T_c = 190$ MeV, $T_{\text{chem}} = 160$ MeV
  - norm depends on t_{fireball} (kept fixed here)!
  - description of spectra comparable
  - reason for insensitivity to EoS and hadro-chemistry [HvH, Rapp 07]:
  - 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

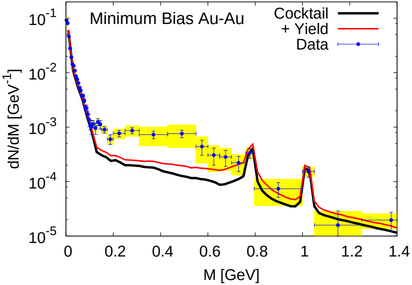
min. bias $200A$GeV Au+Au



- hadronic many-body theory

  [Rapp 01, 02]

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



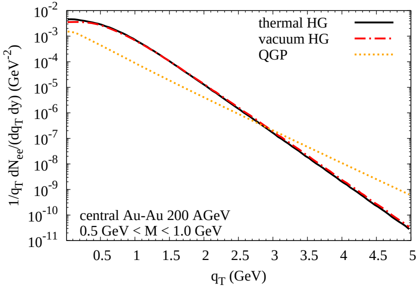
- chiral reduction formalism

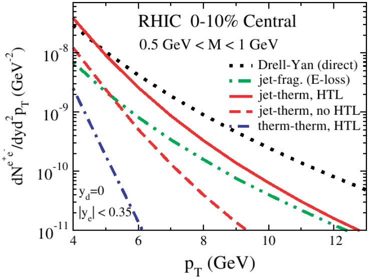
  [Dusling, Zahed 07]

  (central scaled by N_{part})

- LMR enhancement cannot be described!

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 $q_T \gtrsim 3$ 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!

Conclusions and Outlook

- 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}:

$$\frac{\mathrm{d}N_{\ell\ell}/\mathrm{d}q_T}{\mathrm{d}N_\gamma/\mathrm{d}q_T}$$

    [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 lQCD via Weinberg sum rules