The Dilepton Probe from SIS to RHIC

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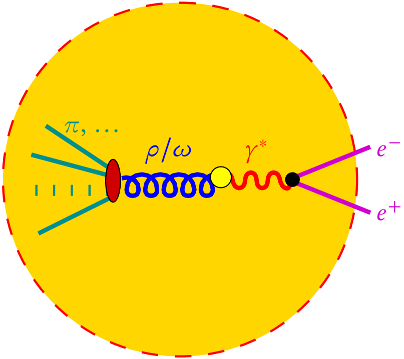
Outline

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



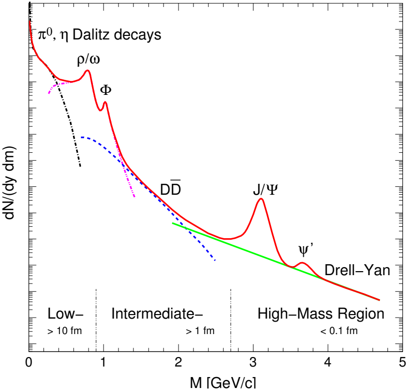


Fig. by A. Drees

Vector Mesons and electromagnetic Probes

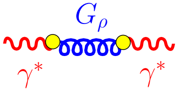
- $\ell^+\ell^-$ thermal emission rates $\Leftrightarrow$ em. current-correlation function, $\Pi_{\mu\nu}$

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

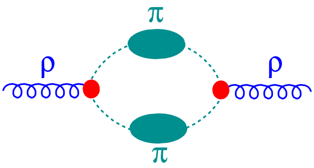
$$\frac{\mathrm{d}N_{e^+e^-}}{\mathrm{d}^4x\mathrm{d}^4q} = -g^{\mu\nu}\frac{\alpha^2}{3q^2\pi^3}\,\mathrm{Im}\,\Pi^{(\mathrm{ret})}_{\mu\nu}(q)\Big|_{q^2=M^2_{e^+e^-}}\,f_B(q_0)$$

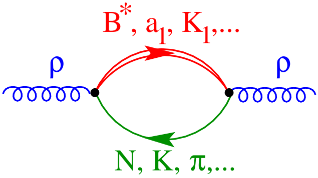
- vector-meson dominance model:

$$\Pi_{\mu\nu} =$$



- hadronic many-body theory for vector mesons

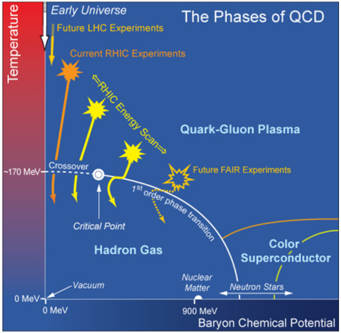


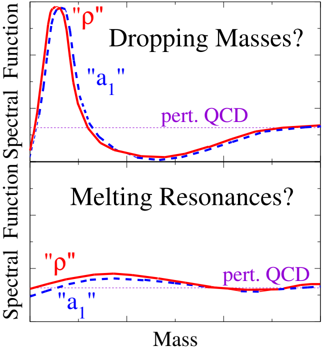


- elementary processes $\Leftrightarrow$ cut self-energy diagrams

Relation to the QCD-phase diagram

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

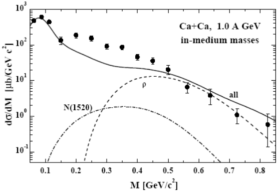




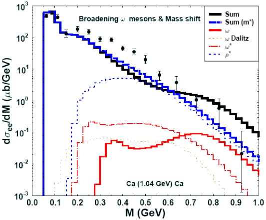
- Mechanism of chiral restoration?
- Two main theoretical ideas
  - "dropping masses": $m_{\text{had}} \propto \langle \bar{\psi}\psi \rangle$
  - "melting resonances": broadening of spectra through medium effects
  - More theoretical question: Realization of chiral symmetry in nature?

- dileptons from heavy-ion collisions at DLS at $E = 1A$ GeV

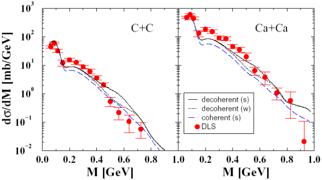
  [Porter et al, PRL **79**, 1229 (1997)]
- large enhancement at low invariant masses unexplained
- DLS puzzle



[Bratkovskaya et al (1999)]



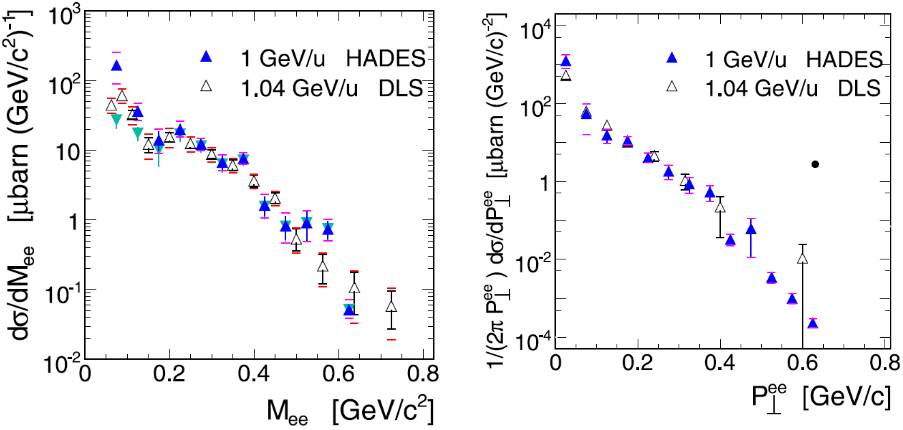
[Ernst et al (1998)]



[Fuchs et al (2003)]

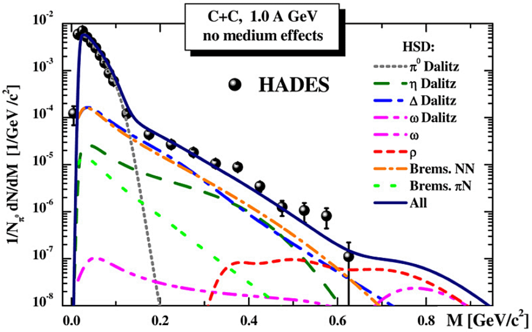
- DLS measurement confirmed by HADES at GSI

[Sudol et al, EPJC **62**, 81 (2009)]



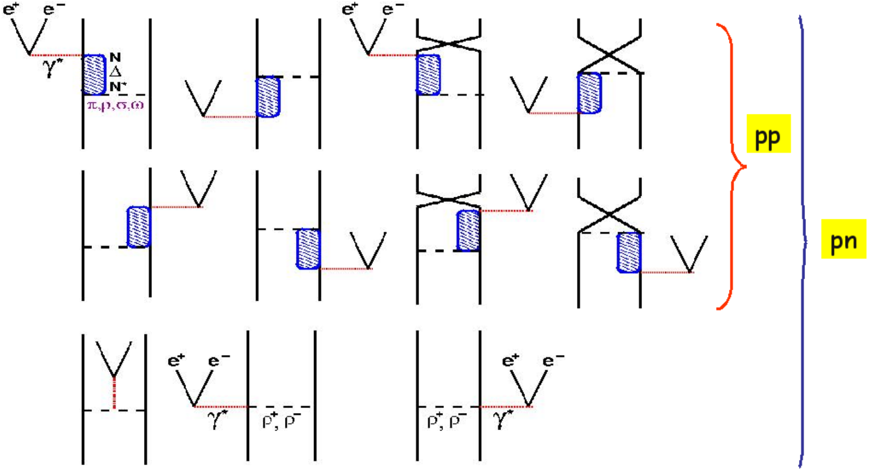
Theoretical “HADES Puzzle”

- one-boson-exchange models by Kaptari/Kämpfer, Shyam/Mosel,... ⇒ importance of elementary pp- and pn-Bremsstrahlung cross section
- also Δ-Dalitz decays
- in CC collisions: little medium effects!



Theoretical "HADES Puzzle"

- one-boson-exchange model by Shyam/Mosel
- Bremsstrahlung in pp and pn collisions



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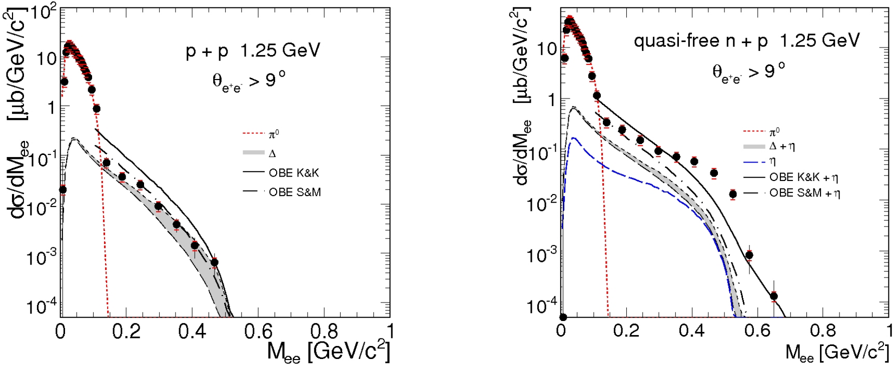
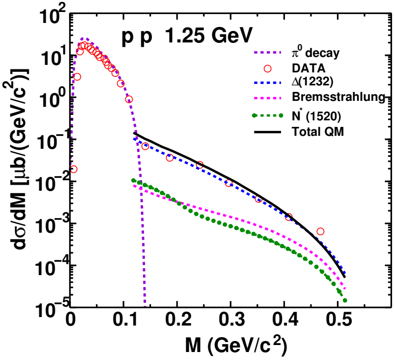
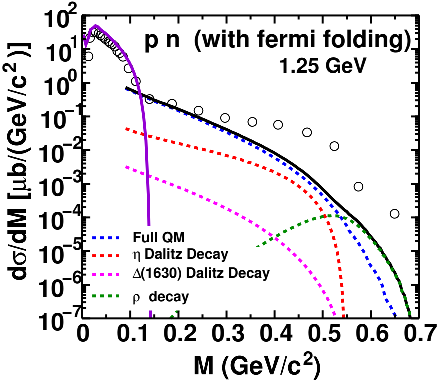


- elementary pp- and pn-cross sections
- discrepancy between models (KK vs. SM); resolution work in progress
  only difference: pseudo-scalar vs. pseudo-vector couplings
  (should be on-shell equivalent!)
- discrepancy of between theory and experiment in pn bremsstrahlung

Recent update



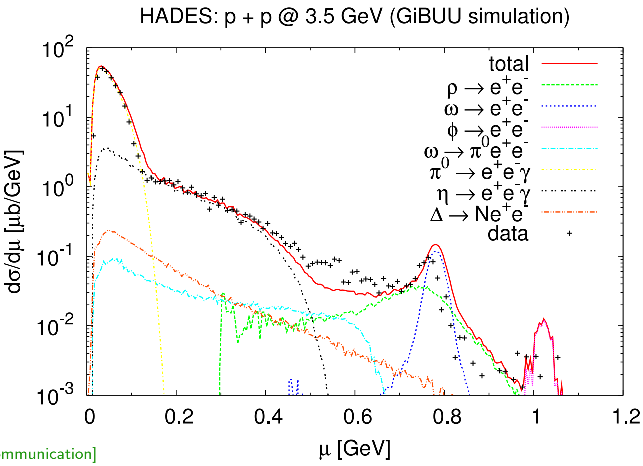


[Shyam, private comm.]

- pn: inclusion of Fermi motion (additional channels!)

GiBUU (preliminary)

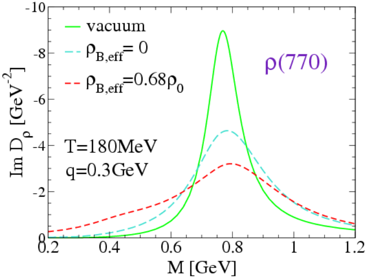
- Gießen Boltzmann-Uehling-Uhlenbeck transport model
- describes pp data
- pn: similar problems as with OBE models (work in progress)

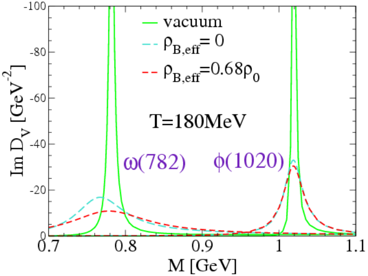


[J. Weil, private communication]

Dileptons at SPS and RHIC

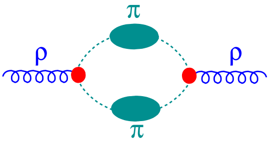
- radiation from thermal sources: Hadronic many-body theory

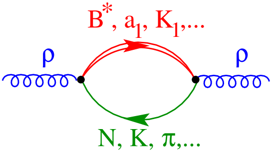




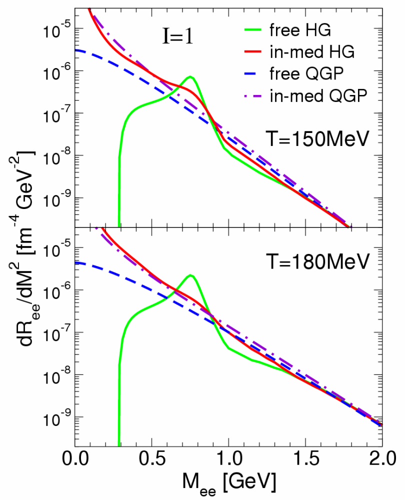
[R. Rapp, J. Wambach 99]

- baryon effects important
- $n_B + n_{\bar{B}}$ relevant quantity (not net-baryon density)!





Dilepton rates: Hadron gas $\leftrightarrow$ QGP



- in-medium hadron gas matches with QGP
- similar results also for γ rates
- "quark-hadron duality"!?
- consistent with chiral-symmetry restoration
- "resonance melting" rather than "dropping masses"

Sources of dilepton emission in heavy-ion collisions

1. initial hard processes: Drell Yan
2. "core" $\Leftrightarrow$ emission from thermal source [McLerran, Toimela 1985]

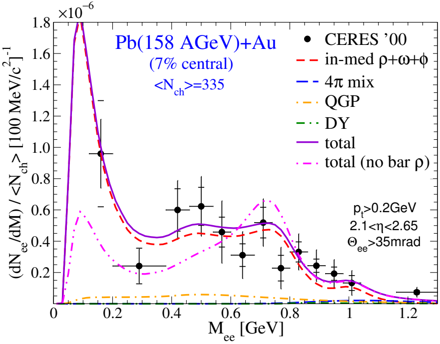
$$\frac{1}{q_T}\frac{\mathrm{d}N^{(\text{thermal})}}{\mathrm{d}M\mathrm{d}q_T} = \int \mathrm{d}^4x \int \mathrm{d}y \int M \mathrm{d}\varphi \frac{\mathrm{d}N^{(\text{thermal})}}{\mathrm{d}^4x\mathrm{d}^4q} \text{Acc}(M, q_T, y)$$

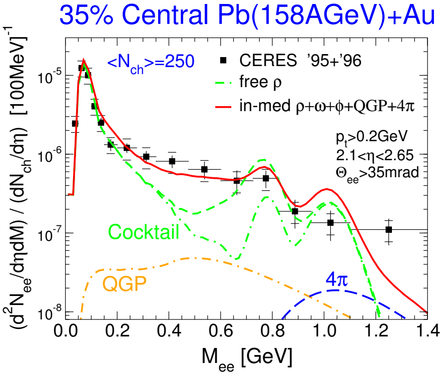
   use cylindrical thermal fireball with QGP, mixed and hadronic phase
3. "corona" $\Leftrightarrow$ emission from "primordial" mesons (jet-quenching)
4. after thermal freeze-out $\Leftrightarrow$ emission from "freeze-out" mesons [Cooper, Frye 1975]

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

CERES/NA45 dielectron spectra

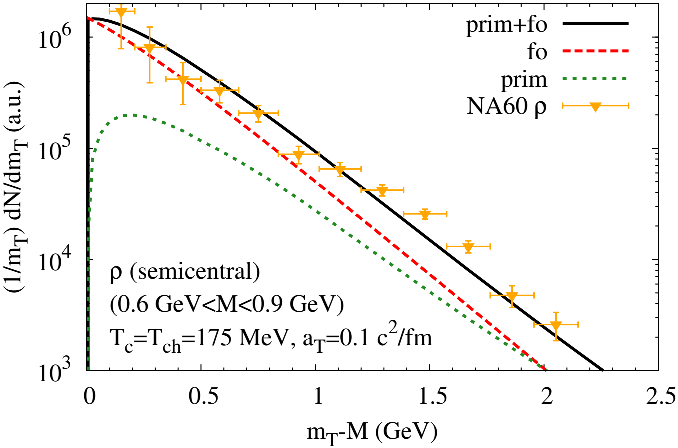
- good agreement also for dielectron spectra in $158\ \text{GeV}$ Pb-Au
- low-mass tail from baryon effects





Hadron spectra

- NA60: Extracted hadronic p_T spectra from $\mu^+\mu^-$ "cocktail"
- analysis of "cocktail": hadron-m_T spectra
- comparison to fireball evolution $\Leftrightarrow$ fixes radial acceleration
- "sequential freeze-out" due to different coupling strength



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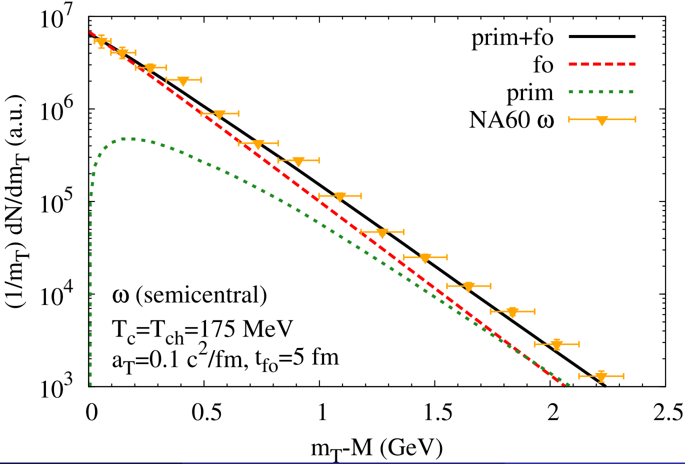

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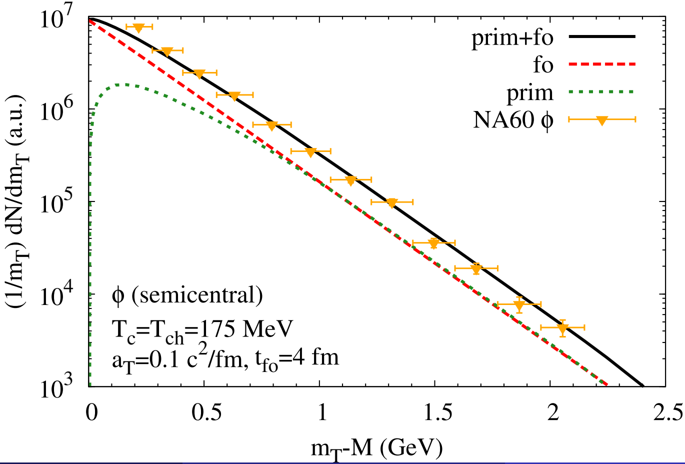
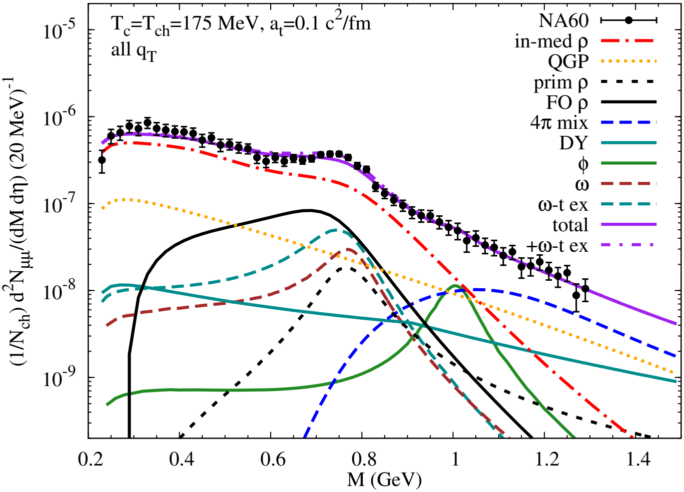


M spectra (in p_T slices)

- norm corrected by $\sim 3\%$ due to centrality correction (min-bias data: $\langle N_{\rm ch} \rangle = 120$, calculation $N_{\rm ch} = 140$)



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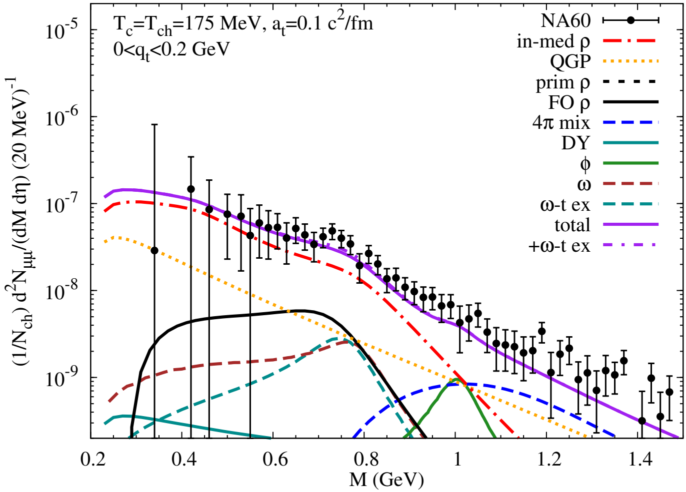

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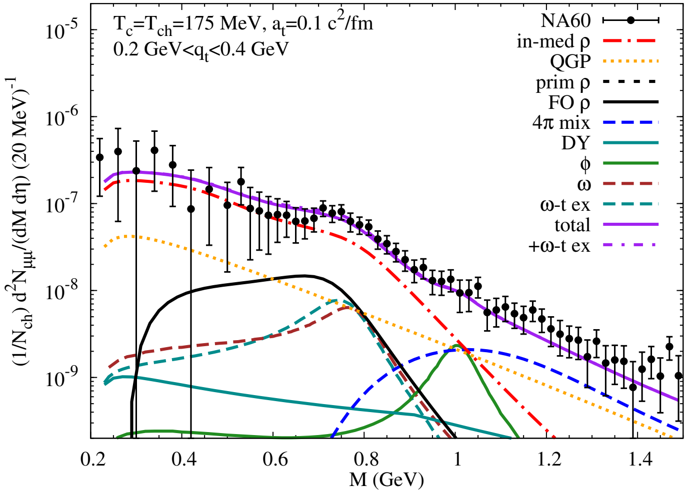

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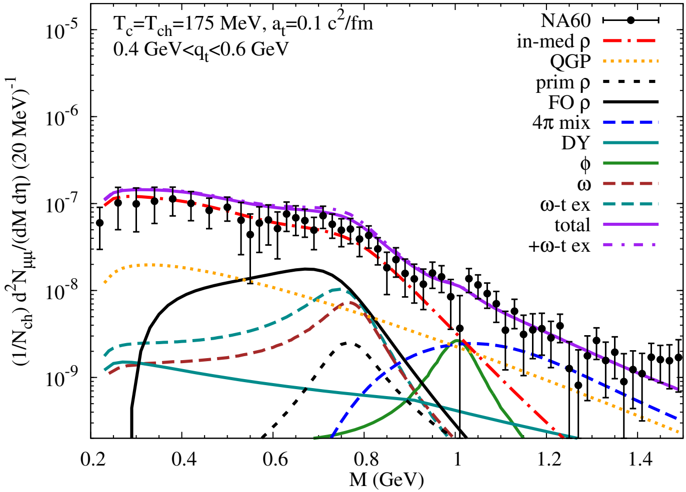

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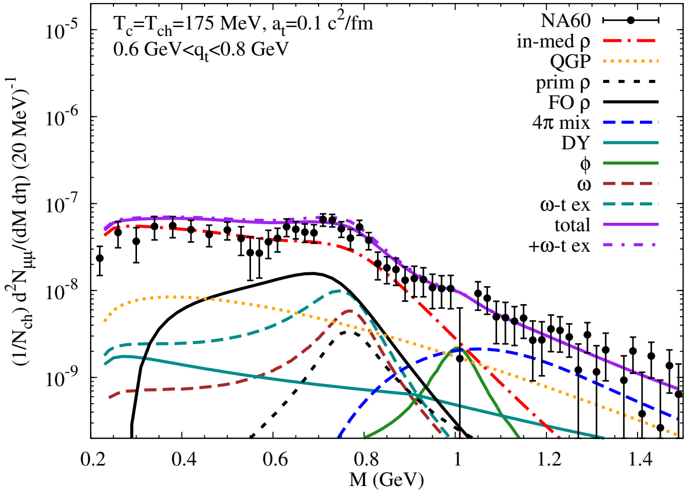

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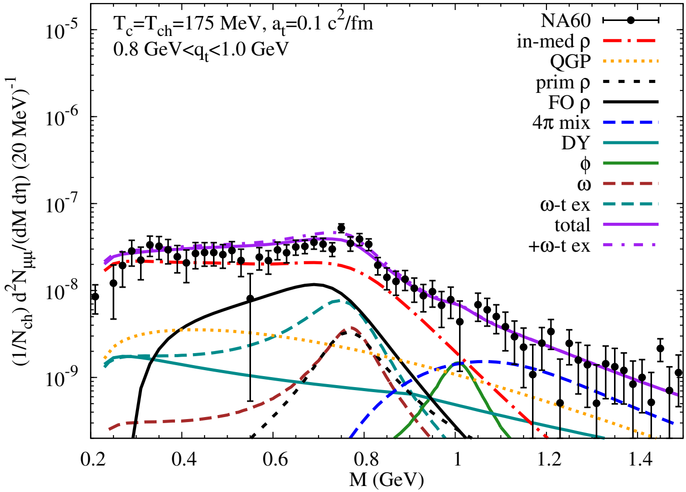

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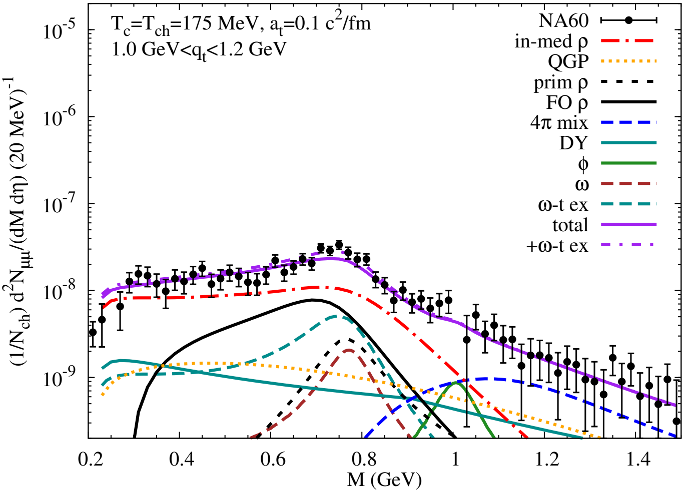

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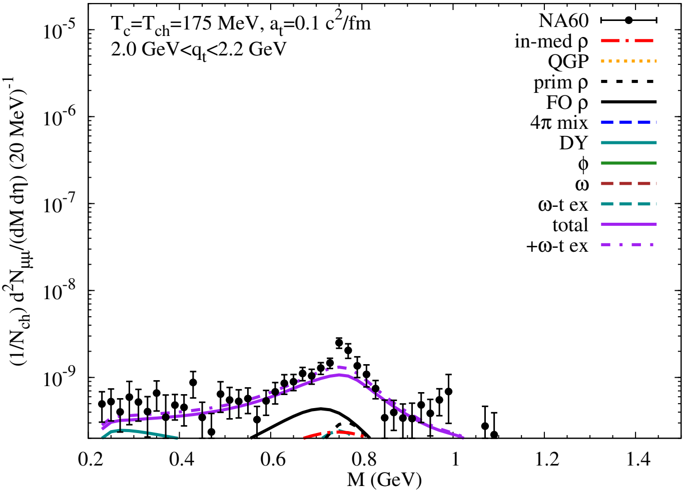

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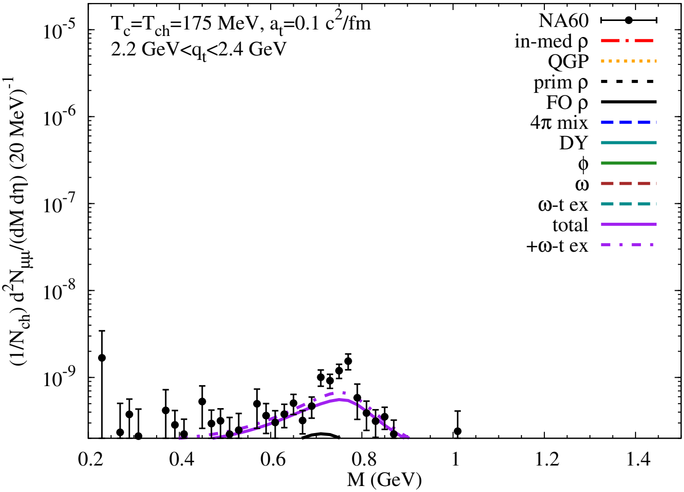
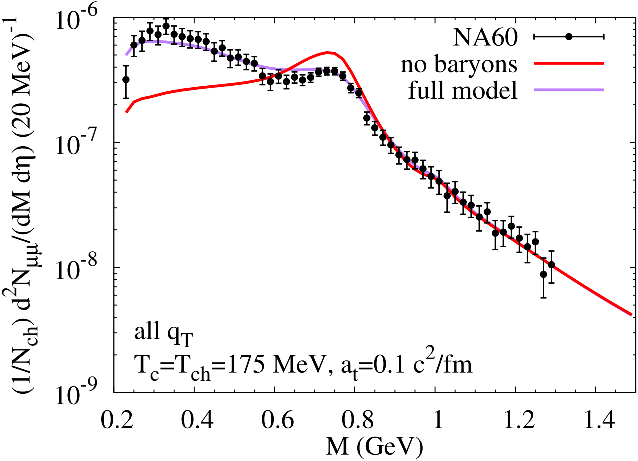
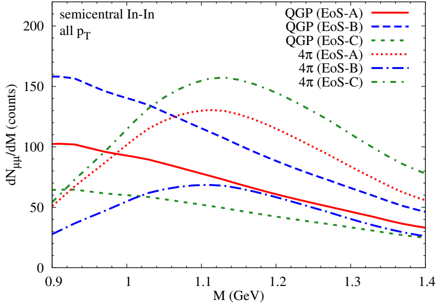


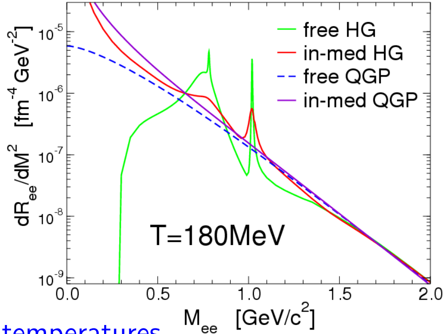
Importance of baryon effects

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



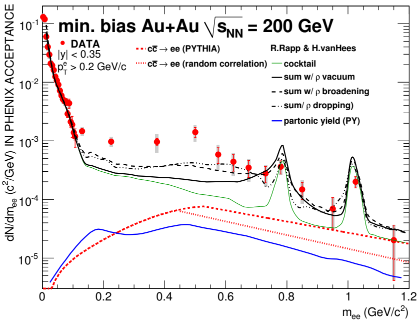
IMR: QGP vs. multi-pion radiation





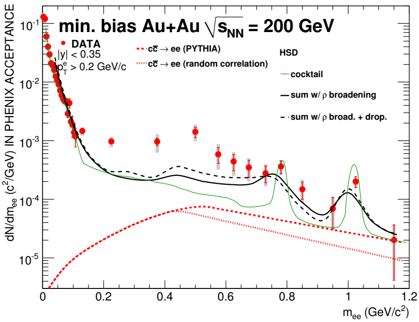
- different critical and freeze-out temperatures
  $T_c = 160 \ldots 190$ MeV, $T_{\text{chem}} = 160 \ldots 175$ MeV
- M- and p_T spectra comparably well described!
- reason: T vs. volume $\Rightarrow$ maximal l^+l^- emission for
  $T = T_{\max} = M/5.5$
- hadronic and partonic radiation "dual" for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

- huge enhancement in the LMR unexplained yet!



model: Rapp, HvH

[A. Adare et al (PHENIX), arXiv:0912.0244 [nucl-ex]]



model: HSD Bratkovskaya, Cassing

[A. Adare et al (PHENIX), arXiv:0912.0244 [nucl-ex]]

Conclusions and Outlook

- dilepton spectra ⇔ in-medium em. current correlator
- SIS energies
  - dominated by bremsstrahlung and Dalitz decays
  - puzzle in OBE models: pp vs. pn bremsstrahlung
- SPS and RHIC energies
  - excess yield dominated by radiation from thermal sources
  - baryons essential for in-medium properties of vector mesons
  - melting vector mesons with little mass shift
  - IMR well described by scenarios with radiation dominated either by QGP or multi-pion processes (depending on EoS)
  - "quark-hadron duality" of $\ell^+\ell^-$ rates around T_c
  - compatible with chiral symmetry restoration!
  - new puzzle @ RHIC?!?
  - recent review:
    R. Rapp, J. Wambach, HvH, Landolt-Börnstein, 1-23A
    arXiv: 0901.3289 [hep-ph]