Electromagnetic Probes in Heavy-Ion Collisions

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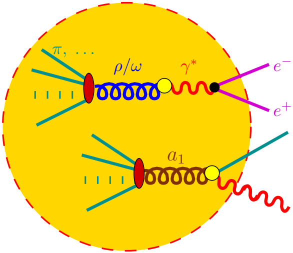
Outline

Why Electromagnetic Probes?

- $\gamma, \ell^{\pm}$: only e. m. interactions
- whole matter evolution
- probes from hot/dense inner region



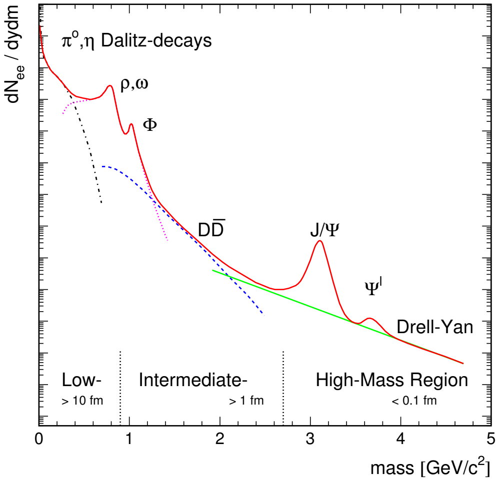


Fig. by A. Drees

[R. Rapp, J. Wambach, Adv. Nucl. Phys. **25**, 1 (2000)]

Vector Mesons and electromagnetic Probes

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

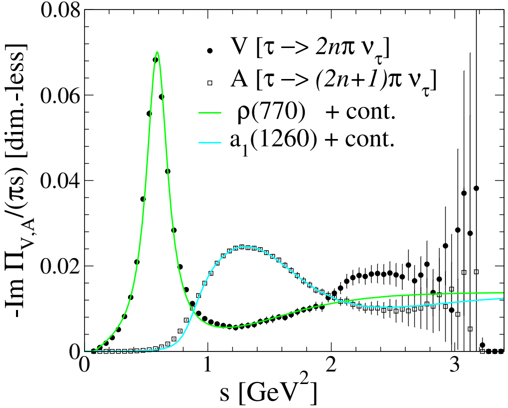
$$\Pi^{<}_{\mu\nu}(q) = \int \mathrm{d}^4 x \exp(\mathrm{i} q \cdot x) \left\langle J_\mu(0) J_\nu(x) \right\rangle_T = -2 n_B(q_0) \, \mathrm{Im} \, \Pi^{(\mathrm{ret})}_{\mu\nu}(q)$$

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

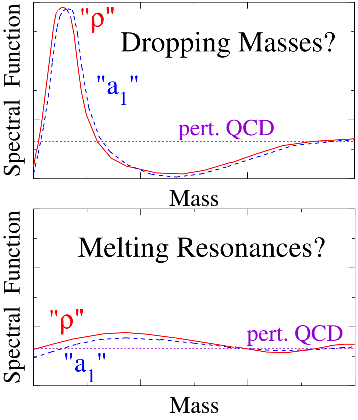
$$\frac{\mathrm{d}N_{e^+ e^-}}{\mathrm{d}^4 x \mathrm{d}^4 k} = -g^{\mu\nu} \frac{\alpha^2}{3 q^2 \pi^3} \, \mathrm{Im} \, \Pi^{(\mathrm{ret})}_{\mu\nu}(q,u) \Big|_{q^2 = M^2_{e^+ e^-}} f_B(p \cdot u)$$

- manifestly Lorentz covariant (dependent on four-velocity of fluid cell, u)
- to lowest order in α: $4\pi\alpha \Pi_{\mu\nu} \simeq \Sigma^{(\gamma)}_{\mu\nu}$
- derivable from underlying thermodynamic potential, Ω!

Vector Mesons and chiral symmetry



[R. Rapp, Pramana **60**, 675 (2003)]

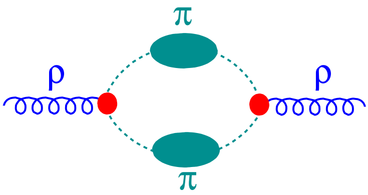


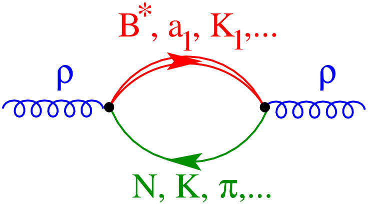
[R. Rapp, J. Phys. G **31**, S217 (2005)]

Hadronic many-body theory

- Phenomenological HMBT for vector mesons

  [R. Rapp, J. Wambach, Eur. Phys. J. A **6**, 415 (1999)]
- $\pi\pi$ interactions and baryonic excitations

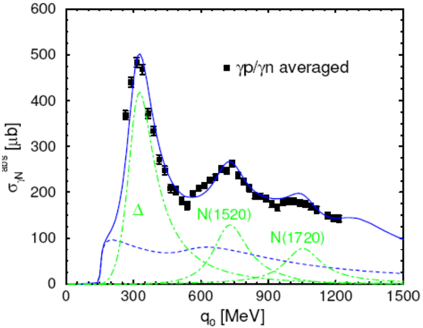


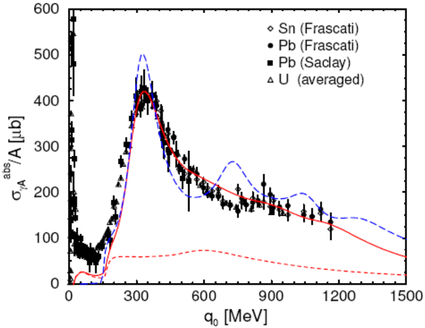


- Baryon (resonances) important, even at RHIC with low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)
- large broadening of vector-meson M spectra
- little mass shifts

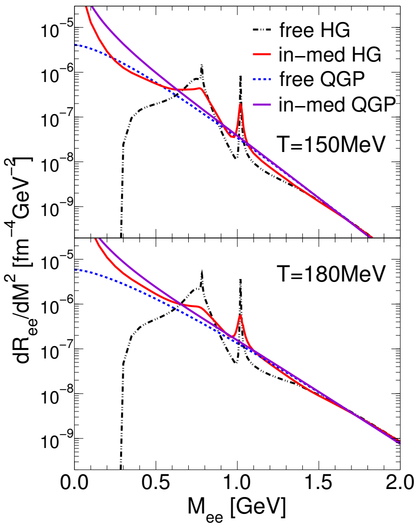
  (many attractive and repulsive resonance channels canceling)

Photoabsorption on nucleons and nuclei





Dilepton rates: Hadron gas $\leftrightarrow$ QGP



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

Dileptons at SIS

The GiBUU Model

GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- Boltzmann-Uehling-Uhlenbeck (BUU) framework for hadronic transport
- reaction types: pA, πA, γA, eA, νA, AA
- open-source modular Fortran 95/2003 code
- version control via Subversion
- publicly available realeases:
  http://gibuu.physik.uni-giessen.de
- Review: [O. Buss et al, Phys. Rept. **512**, 1 (2012)]

The Boltzmann-Uehling-Uhlenbeck Equation

- time evolution of phase-space distribution functions

$$[\partial_t + (\vec{\nabla}_p H_i) \cdot \vec{\nabla}_x - (\vec{\nabla}_x H_i) \cdot \vec{\nabla}_p] f_i(t, \vec{x}, \vec{p}) = I_{\text{coll}}[f_1, \ldots, f_i, \ldots, f_j]$$

- Hamiltonian H_i
  - selfconsistent hadronic mean fields, Coulomb potential, "off-shell potential"
- collision term I_{coll}
  - two- and three-body decays/collisions
  - multiple coupled-channel problem
  - resonances described with relativistic Breit-Wigner distribution

$$\mathscr{A}(x,p) = -\frac{1}{\pi} \frac{\operatorname{Im}\Pi}{(p^2 - M^2 - \operatorname{Re}\Pi)^2 + (\operatorname{Im}\Pi)^2}; \quad \operatorname{Im}\Pi = -\sqrt{p^2}\Gamma$$

  - off-shell propagation: test particles with off-shell potential

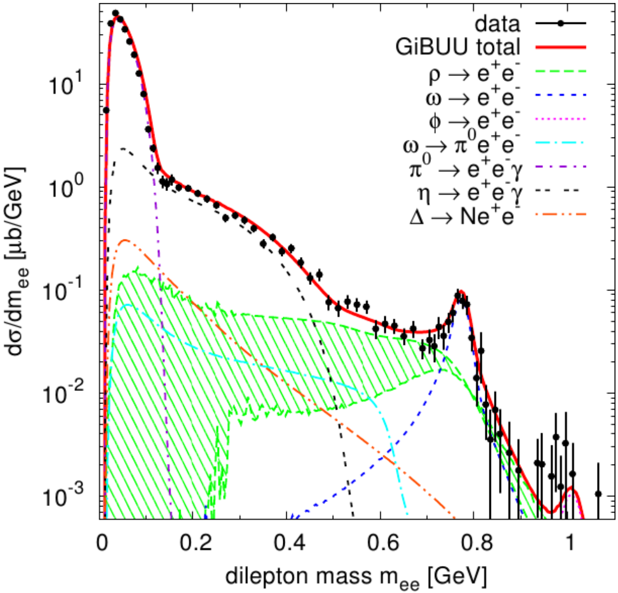
Baryon-resonance model at SIS energies

- resonances (parameters from Manley analysis)

	rating	M_0 [MeV]	Γ_0 [MeV]	$\lvert\mathcal{M}^2\rvert/16\pi$ [mb GeV^2] NR	ΔR	branching ratio in % πN	ηN	$\pi\Delta$	ρN	σN	$\pi N^*(1440)$	$\sigma\Delta$
$P_{11}(1440)$	****	1462	391	70	—	69	—	22_P	—	9	—	—
$S_{11}(1535)$	***	1534	151	8	60	51	43	—	2_S+1_D	1	2	—
$S_{11}(1650)$	****	1659	173	4	12	89	3	2_D	3_D	2	1	—
$D_{13}(1520)$	****	1524	124	4	12	59	—	5_S+15_D	21_S	—	—	—
$D_{15}(1675)$	****	1676	159	17	—	47	—	53_D	—	—	—	—
$P_{13}(1720)$	*	1717	383	4	12	13	—	—	87_P	—	—	—
$F_{15}(1680)$	****	1684	139	4	12	70	—	10_P+1_F	5_P+2_F	12	—	—
$P_{33}(1232)$	****	1232	118	OBE	210	100	—	—	—	—	—	—
$S_{31}(1620)$	**	1672	154	7	21	9	—	62_D	25_S+4_D	—	—	—
$D_{33}(1700)$	*	1762	599	7	21	14	—	74_S+4_D	8_S	—	—	—
$P_{31}(1910)$	****	1882	239	14	—	23	—	—	—	—	67	10_P
$P_{33}(1600)$	***	1706	430	14	—	12	—	68_P	—	—	20	—
$F_{35}(1905)$	***	1881	327	7	21	12	—	1_P	87_P	—	—	—
$F_{37}(1950)$	****	1945	300	14	—	38	—	18_F	—	—	—	44_F

- production channels in Teis: $NN \rightarrow N\Delta$, $NN \rightarrow NN^*, N\Delta^*$, $NN \rightarrow \Delta\Delta$
- extension to $NN \rightarrow \Delta N^*, \Delta\Delta^*$, $NN \rightarrow NN\pi$,
  $NN \rightarrow NN\rho, NN\omega, NN\pi\omega, NN\phi$,
  $NN \rightarrow BYK$ $(B = N, \Delta,\ Y = \Lambda, \Sigma)$

p p at HADES ($E_{\text{kin}} = 3.5$ GeV)



[J. Weil, HvH, U. Mosel, Eur. Phys. J. A **48**, 111 (2012)]

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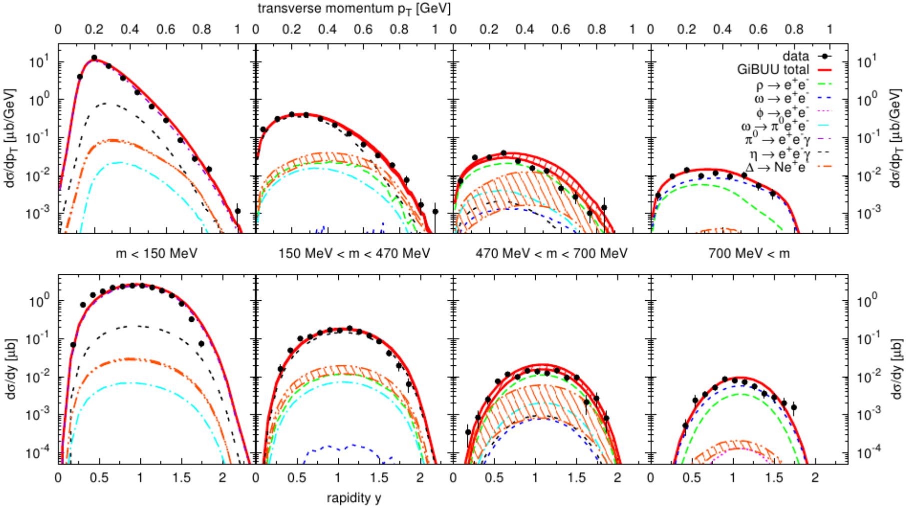
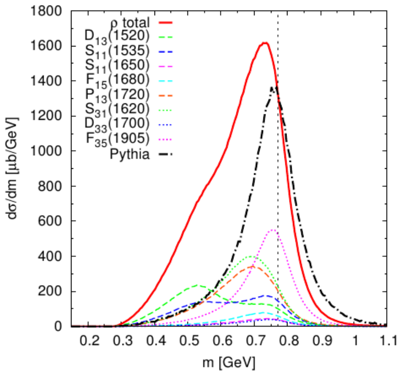
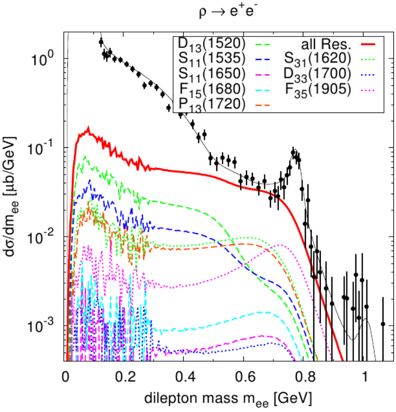


[J. Weil, HvH, U. Mosel, Eur. Phys. J. A **48**, 111 (2012)]

“ρ meson” in pp

- production through hadron resonances
  $NN \to NR \to NN\rho$, $NN \to N\Delta \to NN\pi\rho$

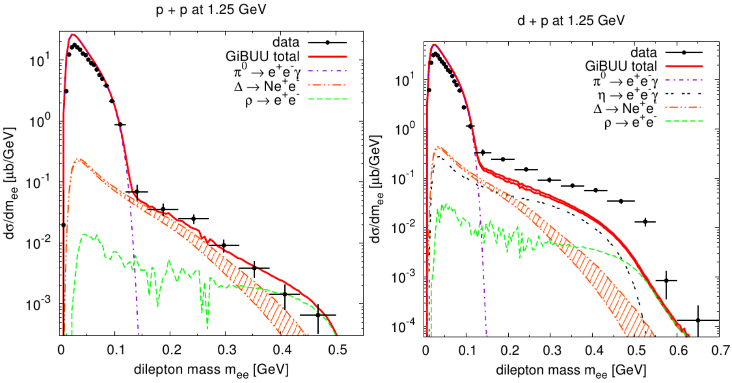




[J. Weil, HvH, U. Mosel, Eur. Phys. J. A **48**, 111 (2012)]

- “ρ”-line shape “modified” already in elementary hadronic reactions
- due to production mechanism via resonances

dp at 1.25 GeV

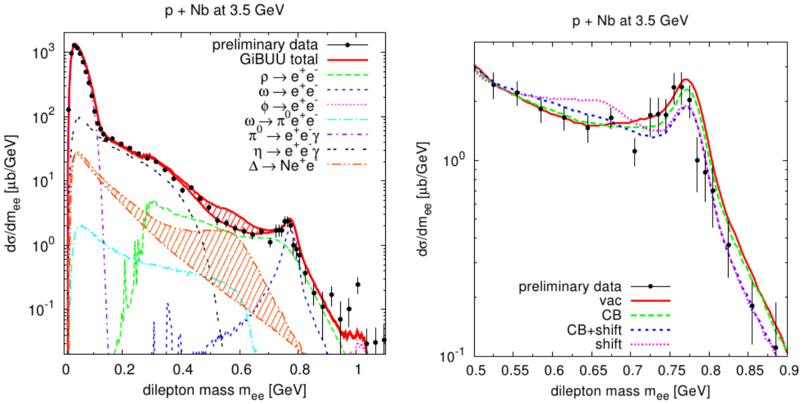


- pp quite well described at low energies
- discrepancies in np (“quasifree dp”)
- isospin effects at low energies? Further modelling/data needed!

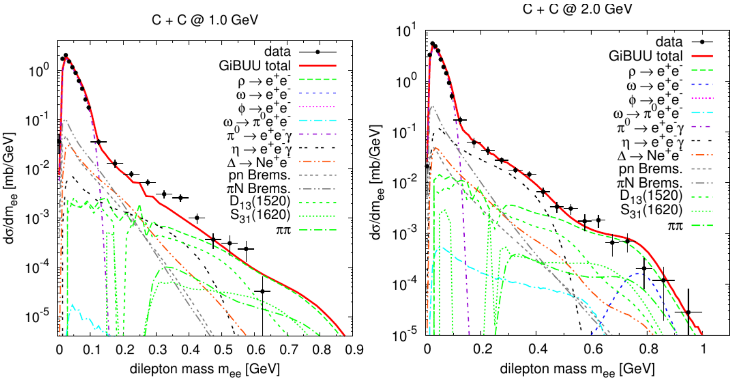
[J. Weil, HvH, U. Mosel, Eur. Phys. J. A **48**, 111 (2012)]

p Nb at HADES (3.5 GeV)

- medium effects built in transport model
  - binding effects, Fermi smearing, Pauli blocking
  - final-state interactions
  - production from secondary collisions
- sensitivity on medium effects of vector-meson spectral functions?



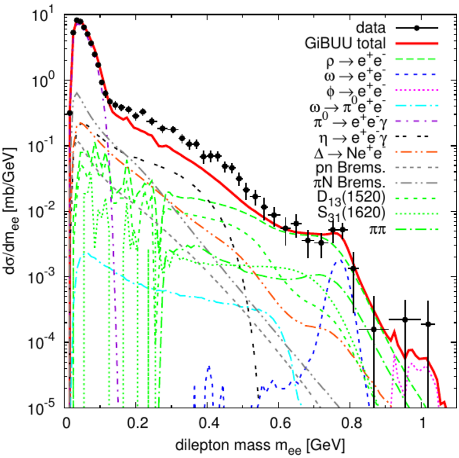
CC at 1.0 GeV and 2.0 GeV



- overall good description without medium effects (small system)
- discrepancy at 1.0 GeV ⇔ uncertainties in pn?

[J. Weil, U. Mosel, arXiv:1211.3761 [nucl-th]]

Ar KCl at 1.76 GeV



- room for medium effects!

[J. Weil, U. Mosel, arXiv:1211.3761 [nucl-th]]

Dileptons at the SPS

Sources for dileptons at the SpS

1. "core" $\Leftrightarrow$ emission from thermal source

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

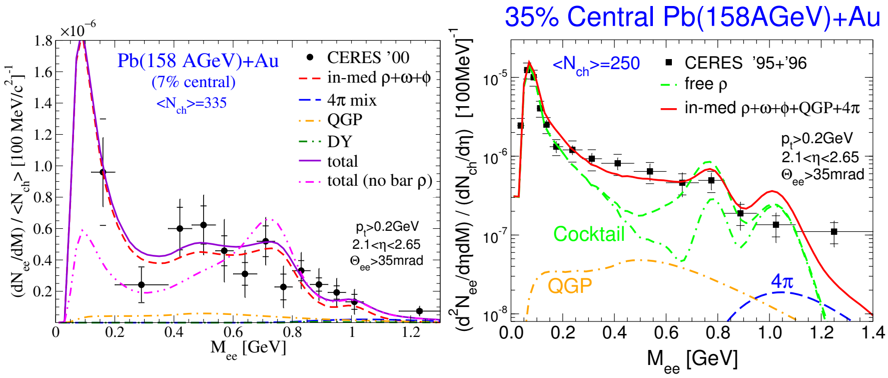
2. "corona" $\Leftrightarrow$ emission from "primordial" mesons (jet-quenching)
3. after thermal freeze-out $\Leftrightarrow$ emission from "freeze-out" mesons

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

- additional factor $\gamma = q_0/M$ compared to thermal emission
- physical reason
  - thermal source rate $\propto \tau_{\text{med}}\frac{\Gamma_{\text{meson}\to\ell^+\ell^-}}{\gamma}$
  - decay of mesons after fo: rate $\propto \frac{\Gamma_{\text{meson}\to\ell^+\ell^-}}{\Gamma_{\text{meson}}}$
- initial hard processes: Drell Yan

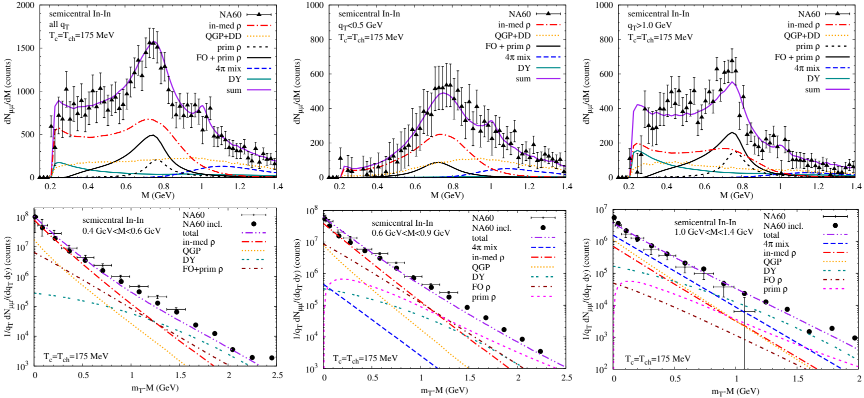
CERES/NA45 dielectron spectra

- 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

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

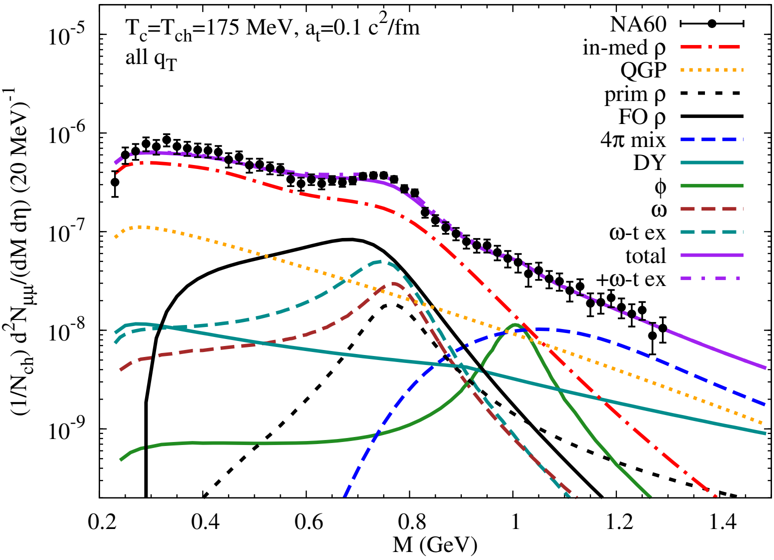


- M spectra

[HvH, R. Rapp, Nucl. Phys. A **806**, 339 (2008)]

  - 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

M spectra (in p_T slices)



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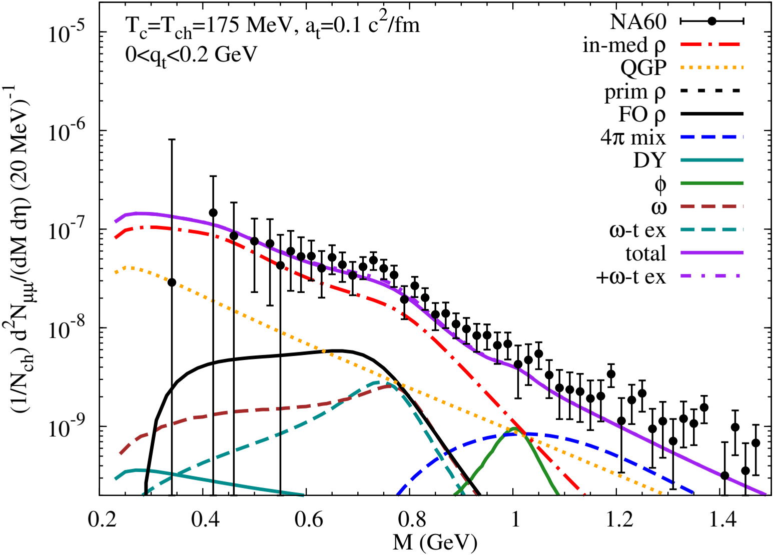

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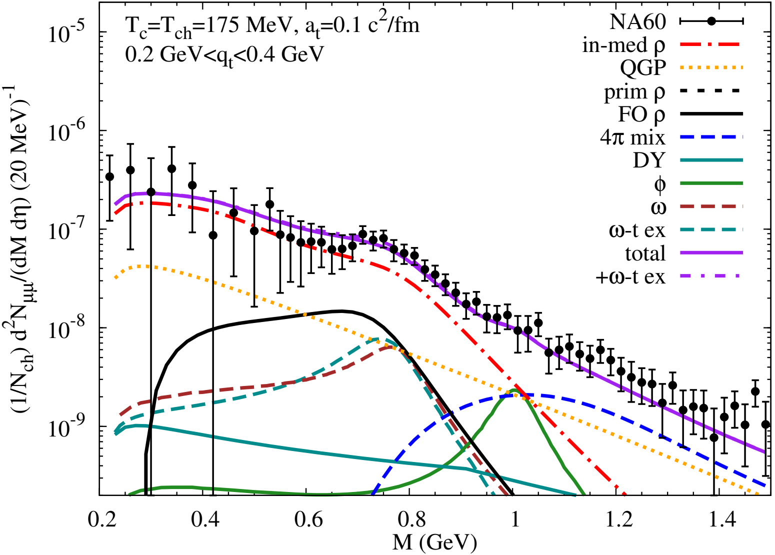

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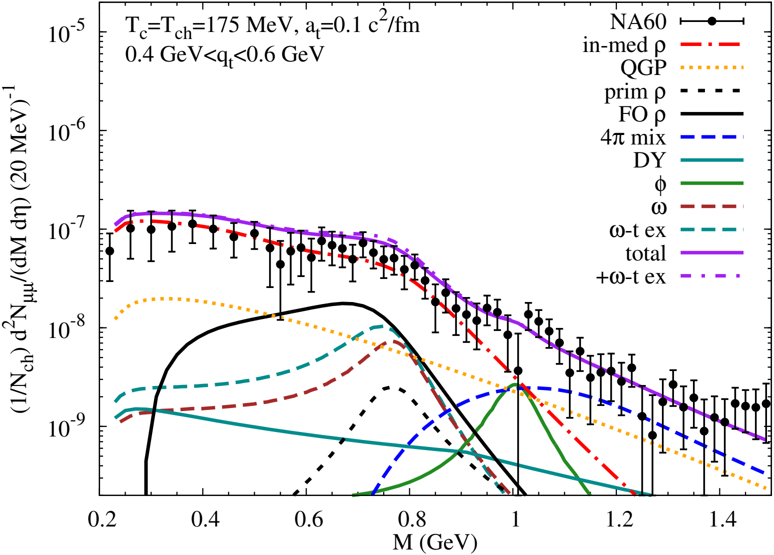

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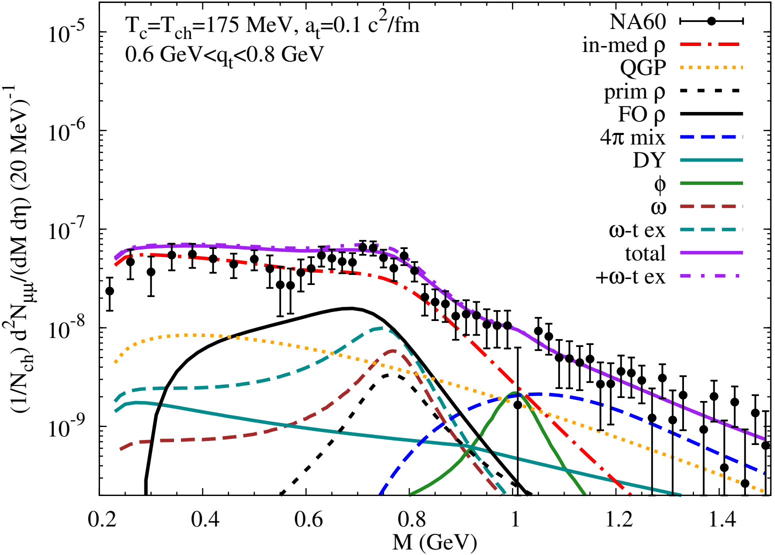

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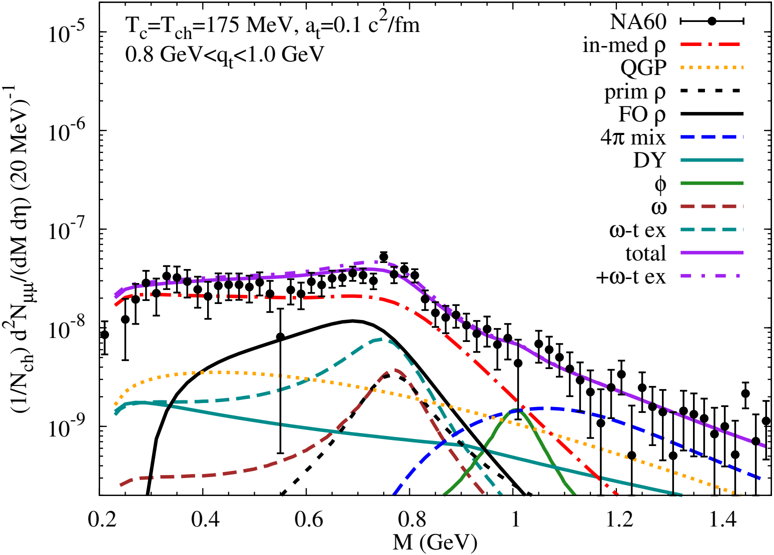

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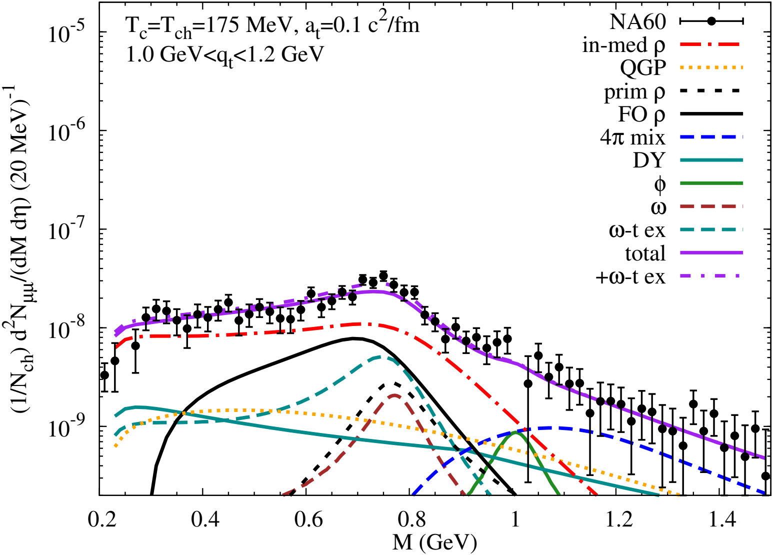

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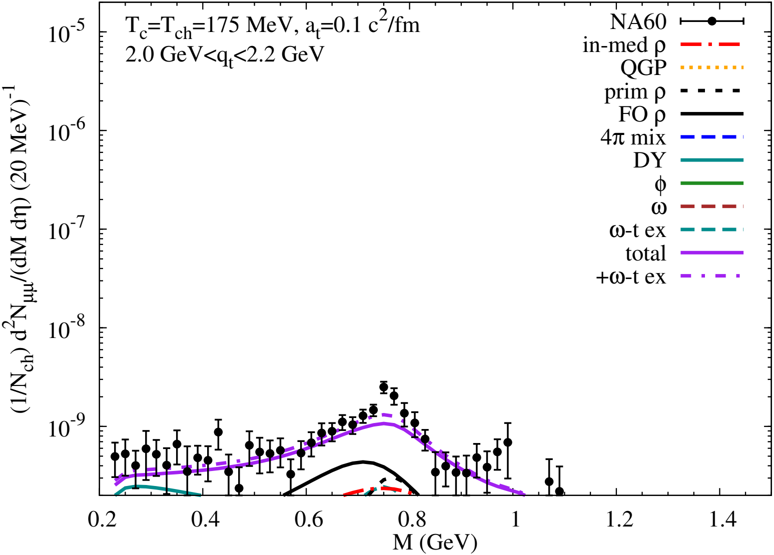

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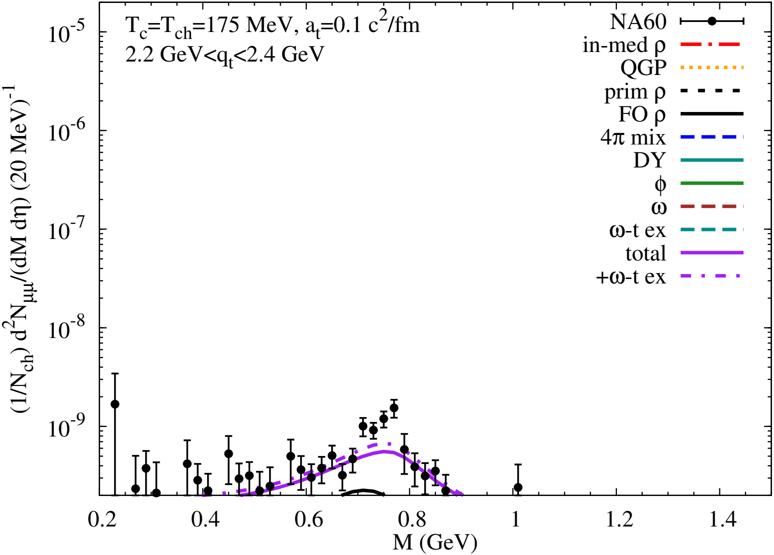
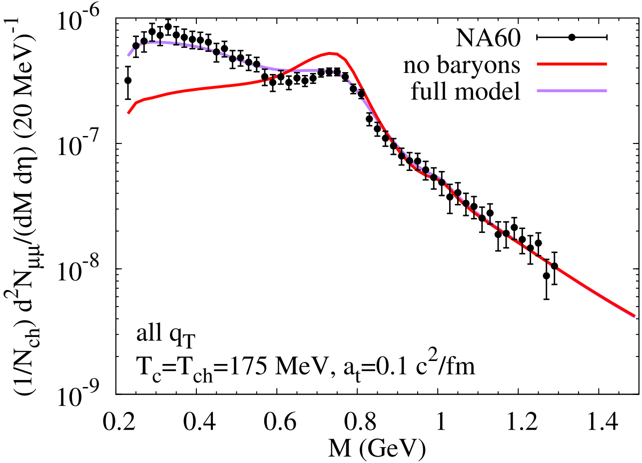


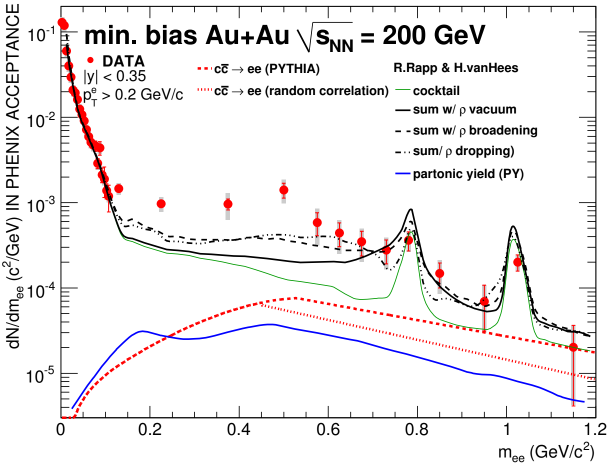
Importance of baryon effects

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



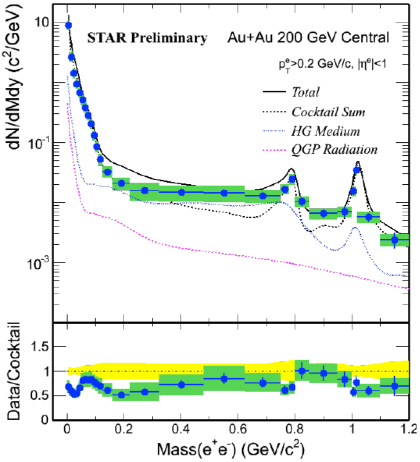
Dileptons at RHIC

- huge enhancement in the LMR unexplained yet!



model: Rapp, HvH [A. Adare et al, Phys. Rev. C **81**, 034911 (2010)]

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
- Dileptons at SIS
  - (offshell) transport models (here GiBUU, also UrQMD study in progress)
  - at low energies: ρ production via baryon resonances
  - $\ell^+\ell^-$ via vector-meson dominance
  - rates vs. M show modified shape compared to vacuum ρ already in pp!
  - room for medium effects in Ar-KCl data
  - work in progress (with UrQMD): coarse-grained hadronic medium + thermal HMBT rates
- Dileptons at SPS and RHIC
  - radiation from thermal sources: QGP, ρ, ω, ϕ, 4π...
  - excess yield dominated by radiation from thermal sources
  - "non-thermal sources" important
  - baryons essential for in-medium properties of vector mesons
  - melting ρ with little mass shift robust signal!
  - dimuons in In-In (NA60), Pb-Au (CERES/NA45)
  - also γ in Pb-Pb! (WA98)
  - huge enhancement in LMR at PHENIX: still open question; recent data from STAR: compatible with model successful already at SPS