Electromagnetic Probes in a Coarse-Graining Approach

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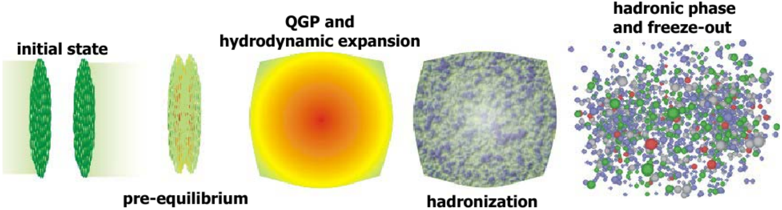
CRC-TR 211 Strong-interaction matter under extreme conditions

Outline

1. Heavy-ion collisions on one slide
2. Electromagnetic probes
   - Chiral symmetry and QCD phase diagram
   - Electromagnetic radiation from hot/dense QCD matter
   - Hadronic many-body theory
3. Bulk-medium evolution with transport and coarse graining
   - coarse-graining in UrQMD
4. Dileptons in heavy-ion collisions
   - Dielectrons (SIS/HADES)
   - Dimuons (SPS/NA60)
   - Dielectrons at RHIC
   - Dielectrons at FAIR/RHIC-BES
5. Signatures of the QCD-phase structure?
6. Conclusions and Outlook

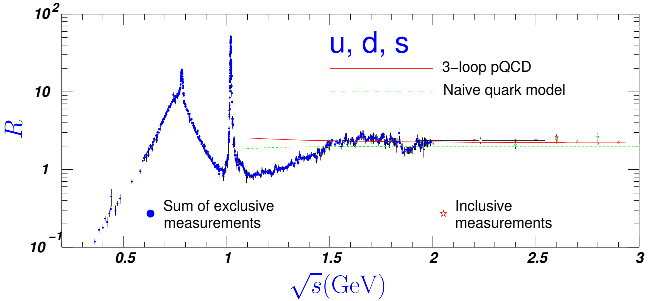
Heavy-Ion collisions in a Nutshell

- theory of strong interactions: Quantum Chromo Dynamics, QCD
- GSI SIS: pp, dp, pA, AA collisions at low energies ($E_{\text{kin}} = 1.25\text{-}3.5\,\text{GeV}$)
  Dielectrons from HADES
- CERN SPS: AA collisions with $E_{\text{kin}} = 158\,\text{GeV}$ per nucleon on a fixed target (center-mass energy: $\sqrt{s_{NN}} = 17.3\,\text{GeV}$)
  dileptons (particularly $\mu^+\mu^-$ in In-In collisions from NA60)
- BNL RHIC: Au Au collisions with center-mass energy of $\sqrt{s_{NN}} = 200\,\text{GeV}$; "beam-energy scan" $\sqrt{s_{NN}} = 7.7\text{-}39\,\text{GeV}$
  dileptons from STAR and PHENIX; direct photons from PHENIX
- CERN LHC: Pb-Pb collisions at $\sqrt{s} = 2.76\,\text{TeV}$ per nucleon
  direct photons from ALICE
- future experiments at CBM/FAIR and NICA: high μ_{B}



Electromagnetic probes
theory perspective

Vacuum Baseline: $e^+e^- \rightarrow$ hadrons

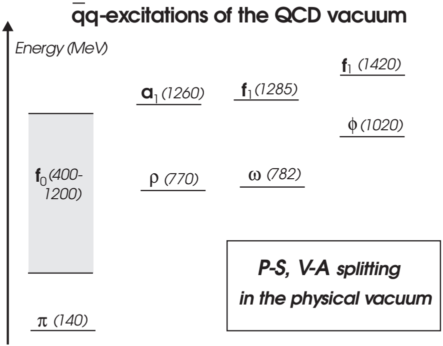


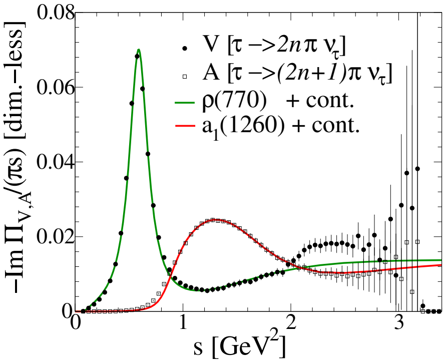
$$R := \frac{\sigma_{\mathrm{e^+e^-\rightarrow hadrons}}}{\sigma_{e^+e^-\rightarrow\mu^+\mu^-}}$$

- probes all hadrons with quantum numbers of γ^*
- $R_{\mathrm{QM}} = N_c \sum_{f=u,d,s} Q_f^2 = 3\times[(2/3)^2+(-1/3)^2+(-1/3)^2]=2$
- Our aim pp $\rightarrow \ell^+\ell^-$, pA $\rightarrow \ell^+\ell^-$, AA $\rightarrow \ell^+\ell^-$ ($\ell = \mathrm{e},\mu$)

Hadron phenomenology and chiral symmetry

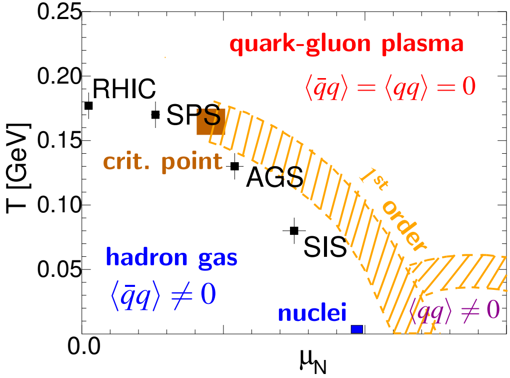
- QCD in light-quark sector (u, d, (s)): chiral symmetry
- in vacuum: Spontaneous breaking of chiral symmetry because $\langle \overline{q} q \rangle \neq 0$
- $\Rightarrow$ mass splitting of chiral partners





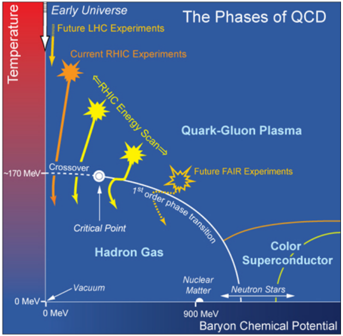
The QCD-phase diagram

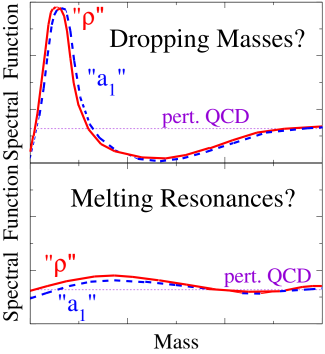
- hot and dense matter: quarks and gluons close together
- highly energetic collisions ⇒ "deconfinement"
- quarks and gluons relevant dof ⇒ quark-gluon plasma
- still strongly interacting ⇒ fast thermalization!



The QCD-phase diagram

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

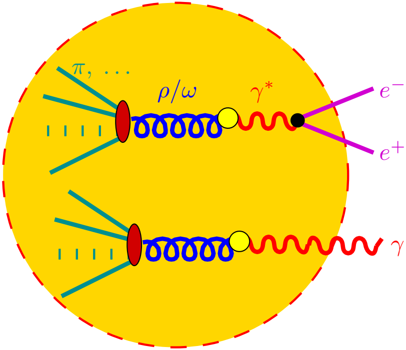




- mechanism of chiral restoration?
- two main theoretical ideas
  - “dropping masses”: $m_{\text{had}} \propto \langle \overline{\psi} \psi \rangle$
  - “melting resonances”: broadening of spectra through medium effects
  - More theoretical question: realization of chiral symmetry in nature?

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



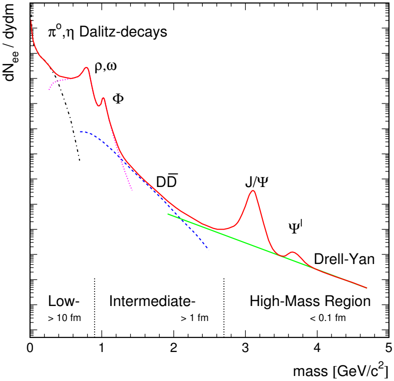


Fig. by A. Drees

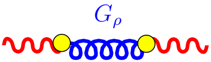
Electromagnetic probes from thermal source

- 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 [MT85, GK91]

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

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

- Lorentz covariant (dependent on four-velocity of fluid cell, u)
- $q \cdot u = E_{\mathrm{cm}}$: Doppler blue shift of q_T spectra!
- to lowest order in α: $4\pi\alpha\Pi_{\mu\nu} \simeq \Sigma^{(\gamma)}_{\mu\nu}$
- vector-meson dominance model:

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

- $\ell^+\ell^-$-inv.-mass spectra
  $\Rightarrow$ in-med. spectral functions of vector mesons (ρ, ω, ϕ)!

Radiation from thermal QGP: $q\bar{q}$ annihilation

- General: McLerran-Toimela formula

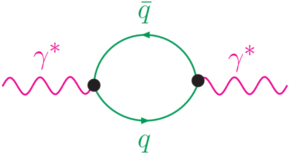
$$\frac{\mathrm{d}N^{(\mathrm{MT})}_{l^+l^-}}{\mathrm{d}^4 x \, \mathrm{d}^4 q} = -\frac{\alpha^2}{3\pi^3} \frac{L(M^2)}{M^2} g_{\mu\nu} \mathrm{Im} \sum_i \Pi^{\mu\nu}_{\mathrm{em},i}(M,\vec{q}) f_B(q \cdot u)$$

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

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

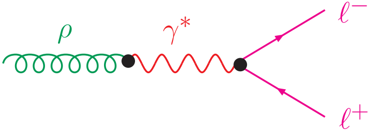
- in QGP phase: $q\bar{q}$ annihilation
- hard-thermal-loop improved em. current-current correlator

$$-\mathrm{i}\Pi_{\mathrm{em,QGP}} =$$



Radiation from thermal sources: ρ decays

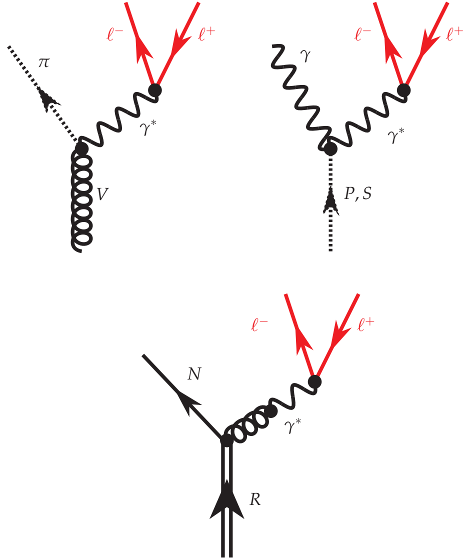
- model assumption: vector-meson dominance



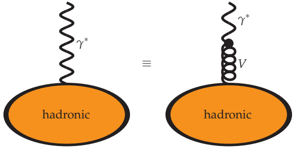
$$\frac{\mathrm{d}N^{(\mathrm{MT})}_{\rho\to l^+l^-}}{\mathrm{d}^4x\,\mathrm{d}^4q} = \frac{M}{q^0}\Gamma_{\rho\to l^+l^-}(M)\frac{\mathrm{d}N_\rho}{\mathrm{d}^3\vec{x}\,\mathrm{d}^4q}$$
$$= -\frac{\alpha^2}{3\pi^3}\frac{L(M^2)}{M^2}\frac{m_\rho^4}{g_\rho^2}g_{\mu\nu}\,\mathrm{Im}\,D_\rho^{\mu\nu}(M,\vec{q})f_B\left(\frac{q\cdot u-2\mu_\pi(t)}{T(t)}\right)$$

- 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

Transition form factors: “ρ mesons” via VMD

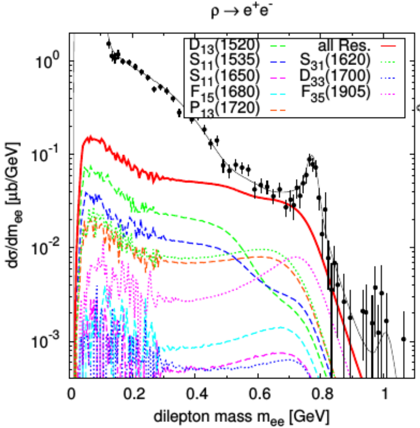


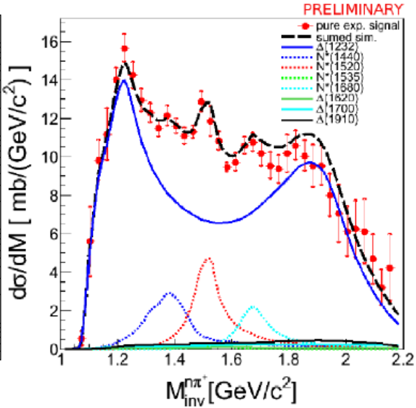
- vector mesons have “vacuum spectral shapes”
- propagated as “on-shell particles” of finite lifetime and variable mass
- Dalitz decay:
  1 particle $\rightarrow$ 3 particles
- V: $\omega \rightarrow \pi + \gamma^* \rightarrow \pi + \ell^+ + \ell^-$
- P, S: $\pi, \eta \rightarrow \gamma + \gamma^* \rightarrow \gamma + \ell^+ + \ell^-$
- R: Baryon resonances
  $\Delta, N^* \rightarrow N + V \rightarrow N + \gamma^* \rightarrow N + \ell^+ + \ell^-$
- vector-meson dominance
- model for hadron em. trans. FF



GiBUU: “ρ meson” in pp

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

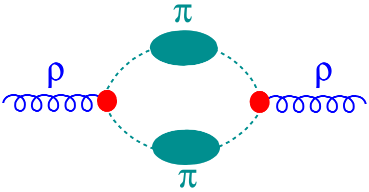


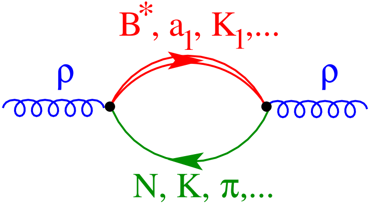


- plots: J. Weil et al [WHM12, ABB+14]
- VMD model ⇔ em. transition form factors of baryon resonances!
- “ρ”-line shape “modified” already in elementary hadronic reactions
- due to production mechanism via resonances

Hadronic many-body theory

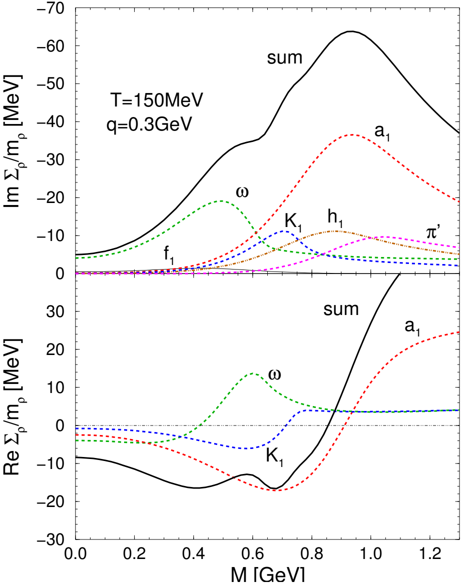
- hadronic many-body theory (HMBT) for vector mesons
  [Ko et al, Chanfray et al, Herrmann et al, Rapp et al, …]
- $\pi\pi$ interactions and baryonic excitations
- effective hadronic models, implementing symmetries
- parameters fixed from phenomenology
  (photon absorption at nucleons and nuclei, $\pi N \to \rho N$)
- evaluated at finite temperature and density
- self-energies $\Rightarrow$ mass shift and broadening in the medium





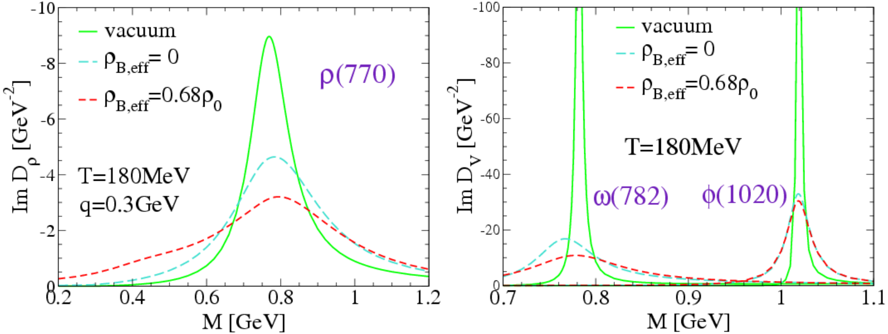
- Baryons important, even at low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

Meson contributions



[RG99]

In-medium spectral functions and baryon effects

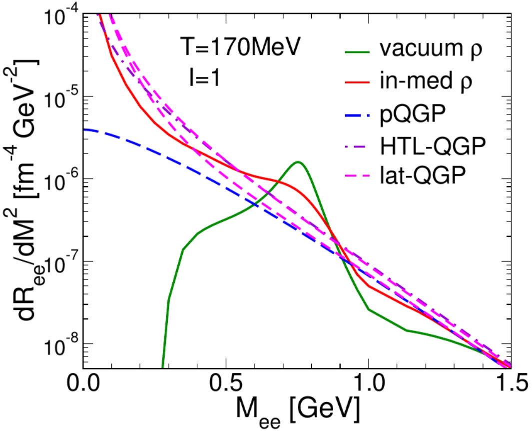


[RW99]

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

Dilepton rates: Hadron gas $\longleftrightarrow$ QGP

- in-medium hadron gas matches with QGP
- similar results also for γ rates
- "quark-hadron duality"?



[Rap13]

Bulk-medium evolution

Bulk evolution with transport and coarse graining

- established transport models for bulk evolution
  - e.g., UrQMD, GiBUU, BAMPS, (p)HSD,...
  - solve Boltzmann equation for hadrons and/or partons
- dilemma: need medium-modified dilepton/photon emission rates
- usually available only in equilibrium QFT calculations
- ways out:
  - use (ideal) hydrodynamics $\Rightarrow$ local thermal equilibrium
    $\Rightarrow$ use equilibrium rates
  - use transport-hydro hybrid model: treat early stage with transport, then coarse grain $\Rightarrow$ switch to hydro
    $\Rightarrow$ switch back to transport (Cooper-Frye "particlization")
- here: UrQMD transport for entire bulk evolution
  $\Rightarrow$ use coarse graining in space-time cells $\Rightarrow$ extract $T, \mu_B, \mu_\pi, \ldots$
  $\Rightarrow$ use equilibrium rates locally

Coarse-grained UrQMD (CGUrQMD)

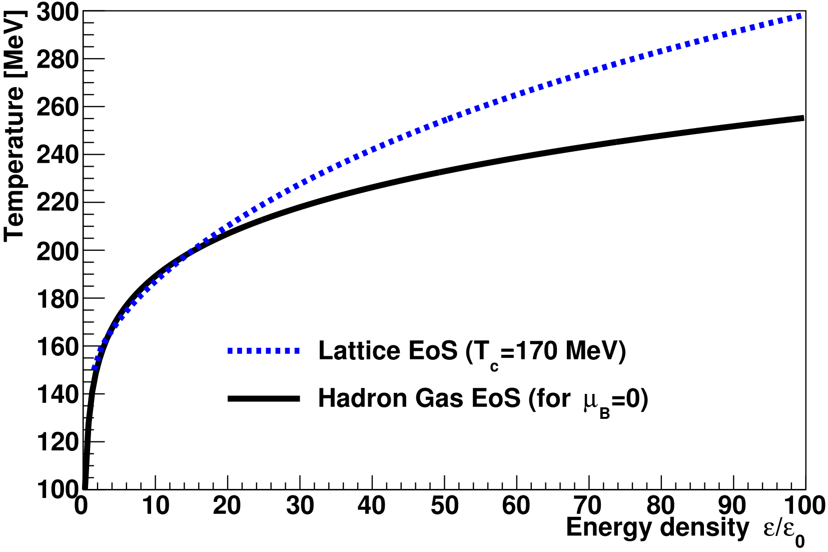
- problem with medium modifications of spectral functions/interactions
- only available in equilibrium many-body QFT models
- use "in-medium cross sections" naively: double counting?!?
- way out: map transport to local-equilibrium fluid
- use ensemble of UrQMD runs with an equation of state
- space-time grid with $\Delta t = 0.2\,\text{fm}/c$, $\Delta x = 0.8\,\text{fm}$
- fit temperature, chemical potentials, flow-velocity field from anisotropic energy-momentum tensor [FMRS13]

$$T^{\mu\nu} = (\epsilon + P_\perp) u^\mu u^\nu - P_\perp g^{\mu\nu} - (P_\parallel - P_\perp) V^\mu V^\nu$$

- thermal rates from partonic/hadronic QFT become applicable
- here: extrapolated lattice QGP and Rapp-Wambach HMBT
- caveat: consistency between EoS, matter content of QFT model/UrQMD!

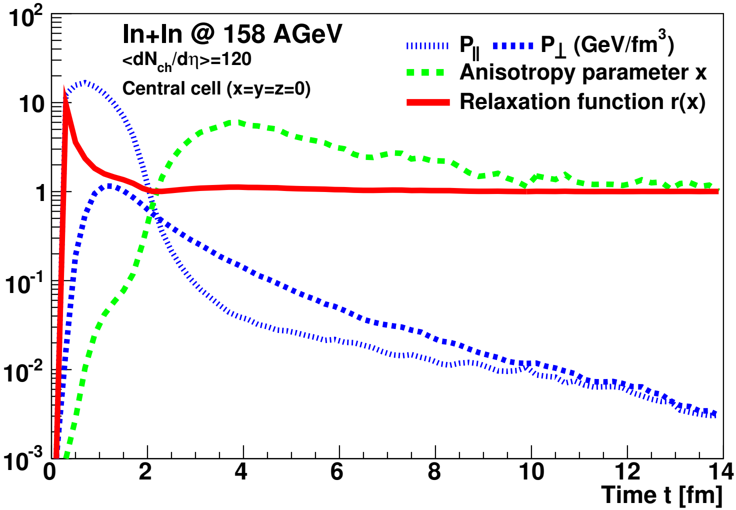
Coarse-grained UrQMD (CGUrQMD)

- $T_c = 170$ MeV; $T > T_c \Rightarrow$ lattice EoS; $T < T_c \Rightarrow$ HRG EoS



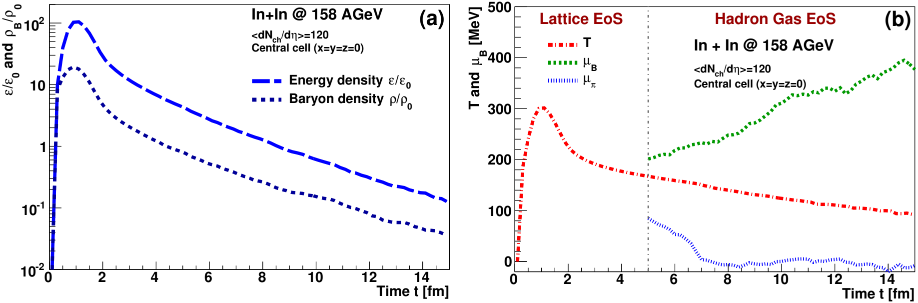
Coarse-grained UrQMD (CGUrQMD)

- pressure anisotropy (for In+In @ SPS; NA60)



Coarse-grained UrQMD (CGUrQMD)

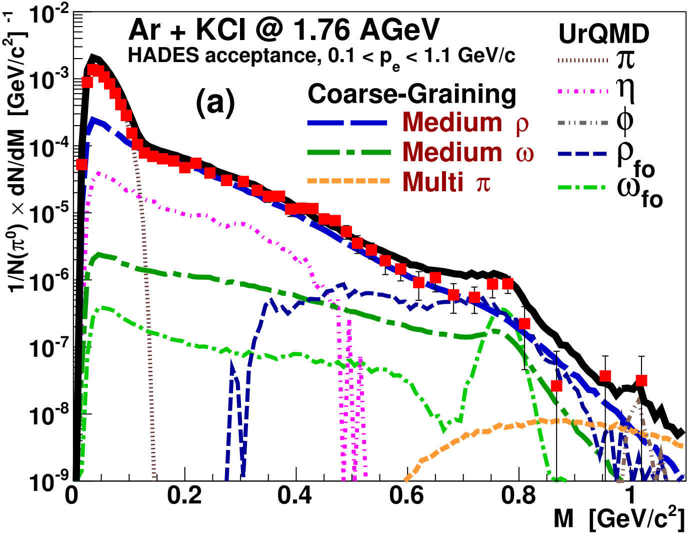
- energy/baryon density ⇒ T, μ_B (for In+In @ SPS; NA60)
- central “fluid” cell!



Dielectrons (SIS/HADES)

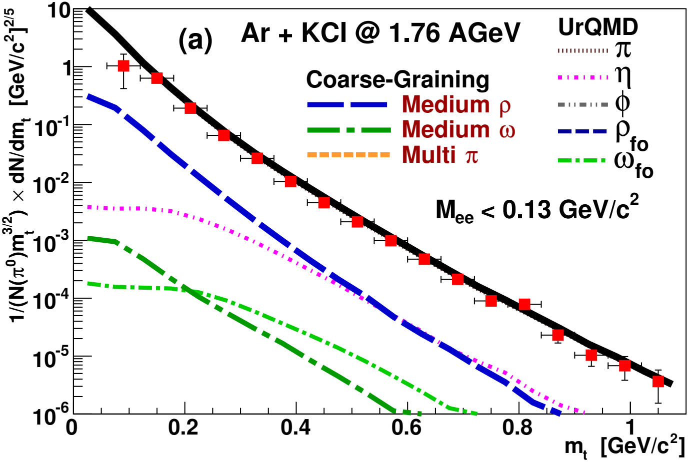
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- coarse-graining method works at low energies!
- UrQMD-medium evolution + RW-QFT rates



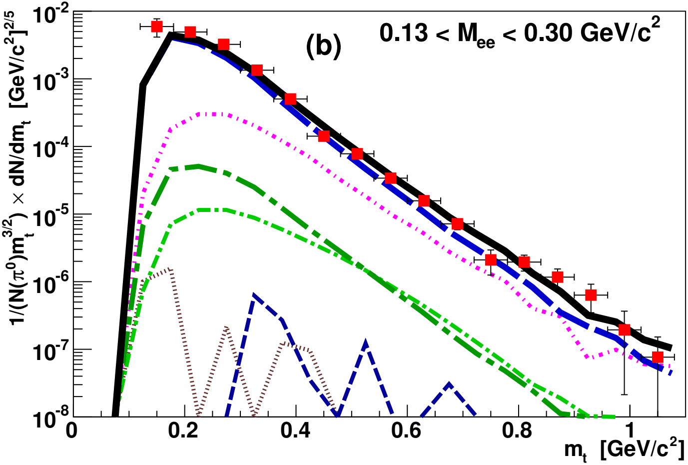
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- dielectron spectra from $\mathrm{Ar}+\mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow \mathrm{e^+e^-}$ (SIS/HADES)
- m_t spectra
- $M_{\mathrm{ee}} < 0.13$ GeV



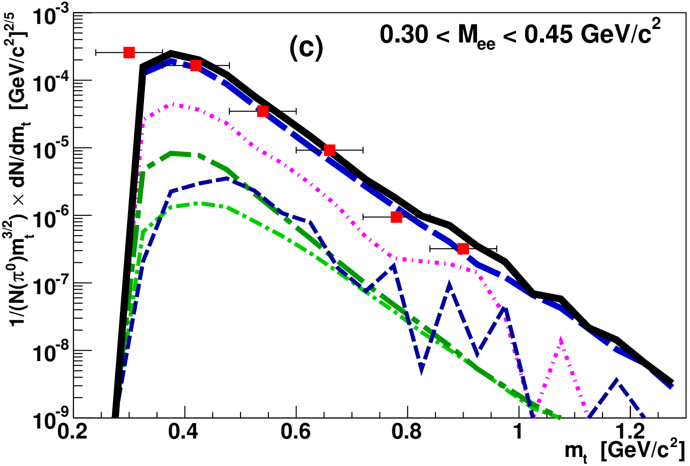
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- dielectron spectra from $\mathrm{Ar}+\mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow \mathrm{e}^{+}\mathrm{e}^{-}$ (SIS/HADES)
- m_t spectra
- $0.13\,\mathrm{GeV} M_{\mathrm{ee}} < 0.3\,\mathrm{GeV}$



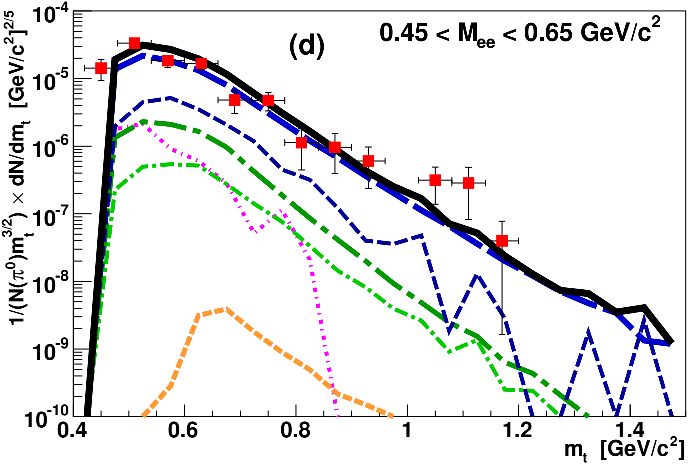
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- dielectron spectra from $\mathrm{Ar} + \mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow e^+e^-$ (SIS/HADES)
- m_t spectra
- $0.3\,\mathrm{GeV}\,M_{ee} < 0.45\,\mathrm{GeV}$



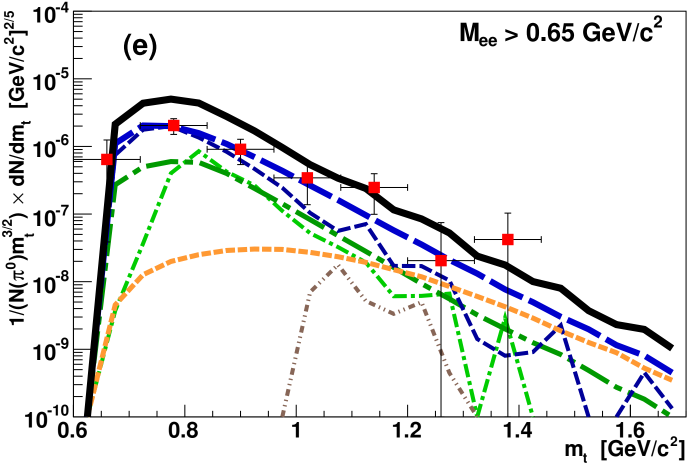
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- dielectron spectra from $\mathrm{Ar}+\mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow \mathrm{e}^+\mathrm{e}^-$ (SIS/HADES)
- m_t spectra
- $0.45\,\mathrm{GeV} M_{\mathrm{ee}} < 0.65\,\mathrm{GeV}$



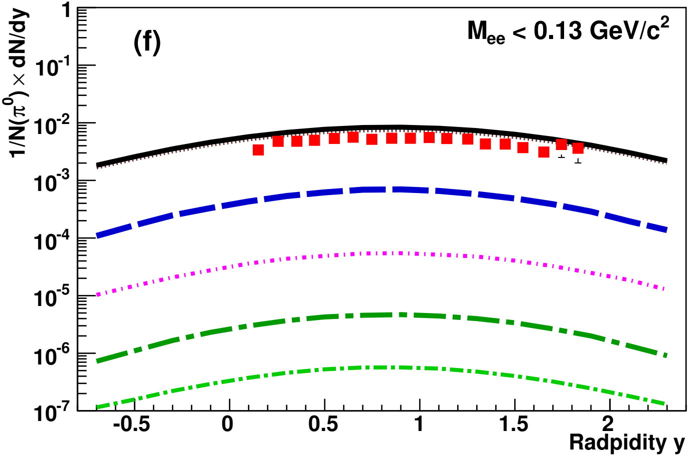
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- dielectron spectra from $\mathrm{Ar} + \mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow e^{+}e^{-}$ (SIS/HADES)
- m_t spectra
- $M_{\mathrm{ee}} > 0.65\,\mathrm{GeV}$

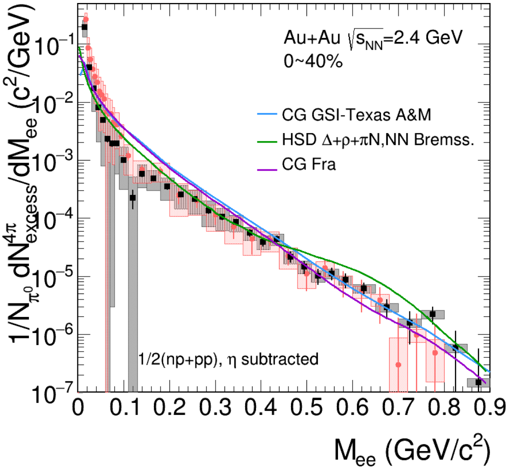


CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

- dielectron spectra from $\mathrm{Ar}+\mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow \mathrm{e}^+\mathrm{e}^-$ (SIS/HADES)
- m_t spectra
- rapidity spectrum ($M_{\mathrm{ee}} < 0.13$ GeV)



CGUrQMD: Au+Au (1.23 *A*GeV) (SIS/HADES)



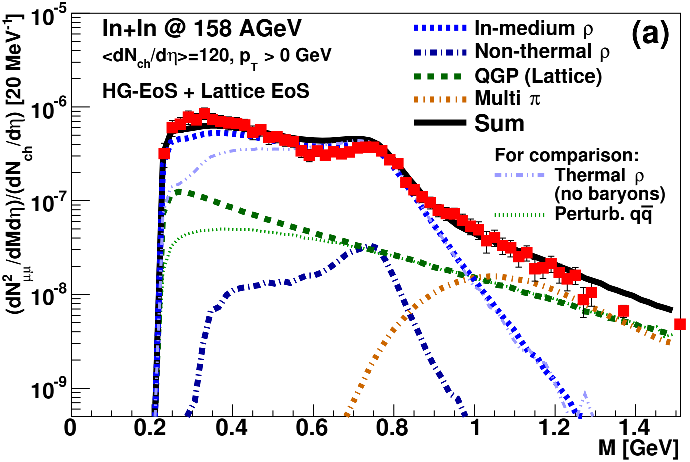
[T. Galtyuk, Quark Matter 2017 talk]

- good agreement between models and data
- consistency between two independent coarse-grained-UrQMD simulations
- based on same Rapp-Wambach in-medium rates

Dimuons (SPS/NA60)

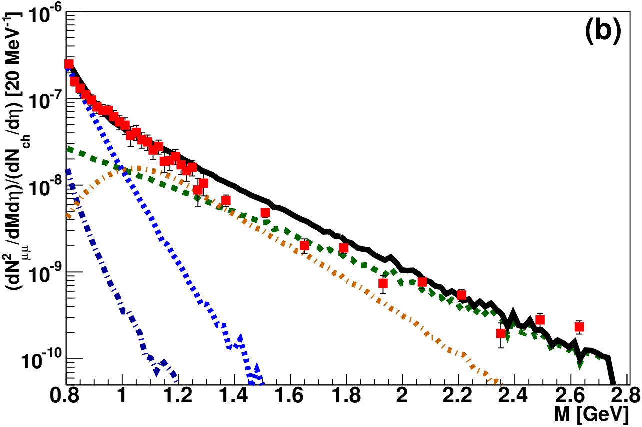
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)



CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- higher IMR: provides averaged true temperature
  $\langle T \rangle_{1.5\,\mathrm{GeV} \lesssim M \lesssim 2.4\,\mathrm{GeV}} = 205\text{-}230\,\mathrm{MeV}$
- clearly above $T_c \simeq 150\text{-}160\,\mathrm{MeV}$
  (no blueshifts in the invariant-mass spectra!)



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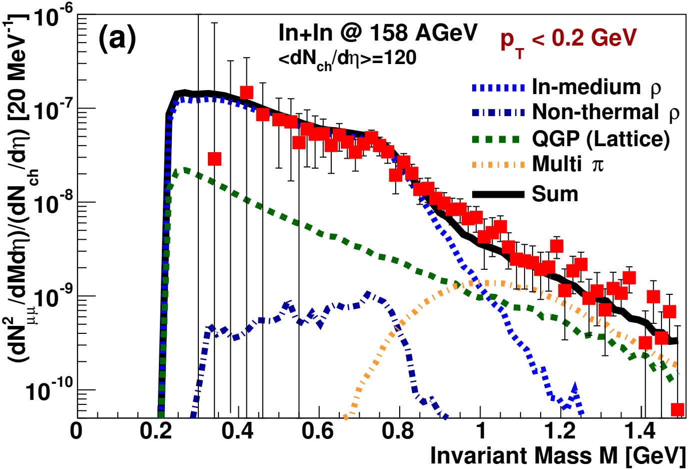
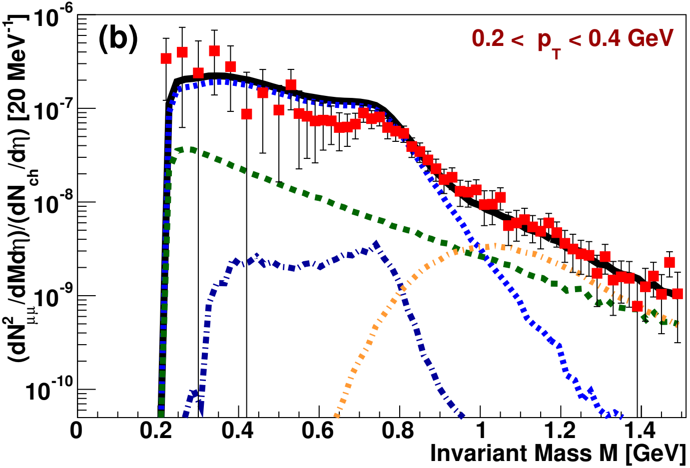
- dimuon spectra from $\text{In}+\text{In}(158\,A\text{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120$)
- $p_T < 0.2$ GeV

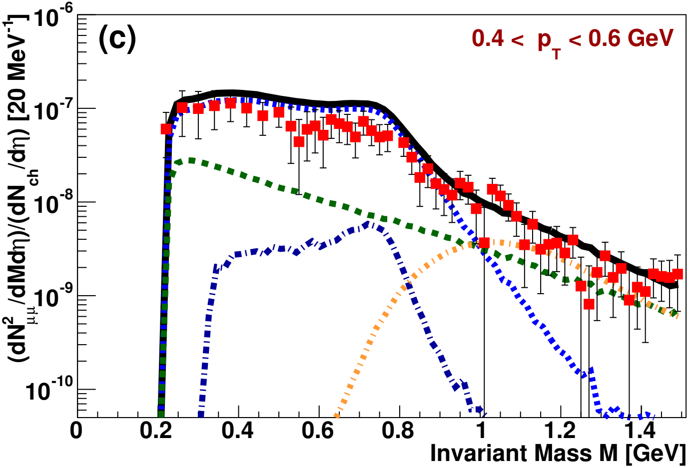


CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In} + \mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $0.2\,\mathrm{GeV} < p_T < 0.4\,\mathrm{GeV}$

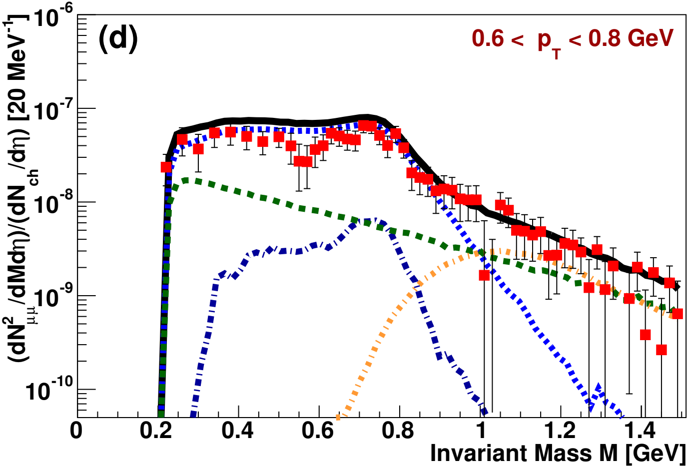


- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $0.4\,\mathrm{GeV} < p_T < 0.6\,\mathrm{GeV}$



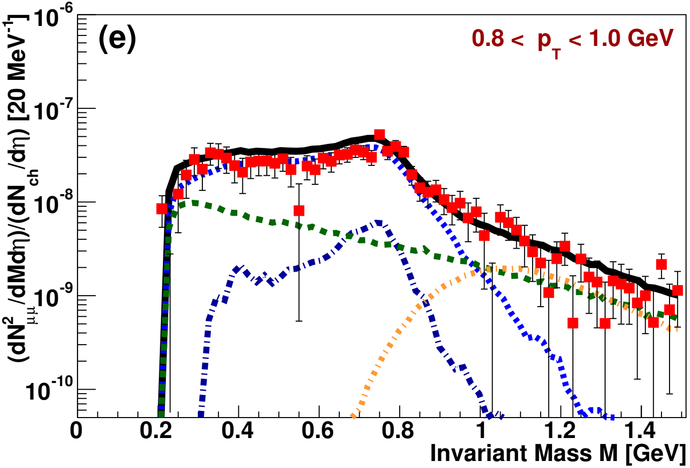
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \to \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $0.6\,\mathrm{GeV} < p_T < 0.8\,\mathrm{GeV}$



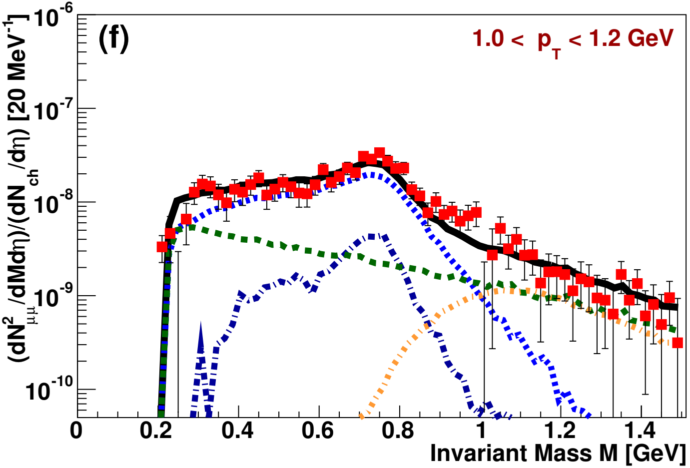
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $0.8\,\mathrm{GeV} < p_T < 1.0\,\mathrm{GeV}$



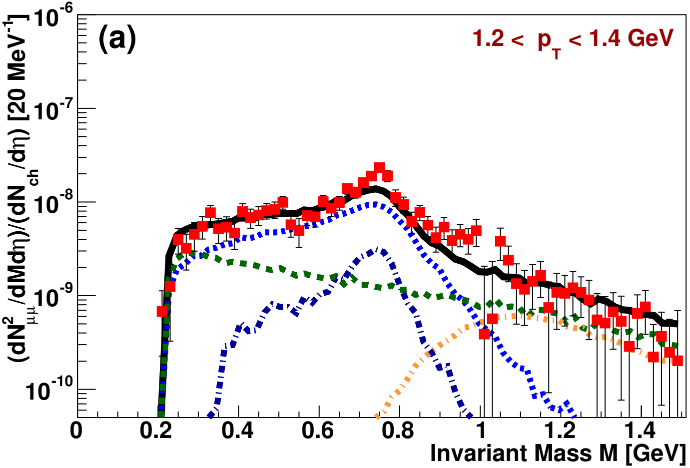
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\text{In} + \text{In}(158\,A\text{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120$)
- $1.0\,\text{GeV} < p_T < 1.2\,\text{GeV}$



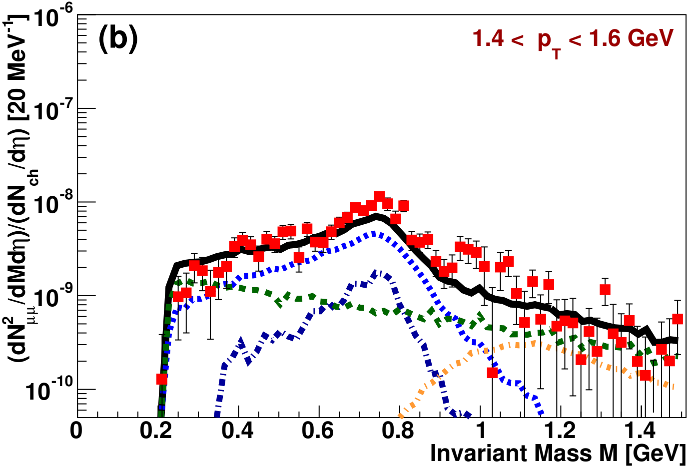
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $1.2\,\mathrm{GeV} < p_T < 1.4\,\mathrm{GeV}$



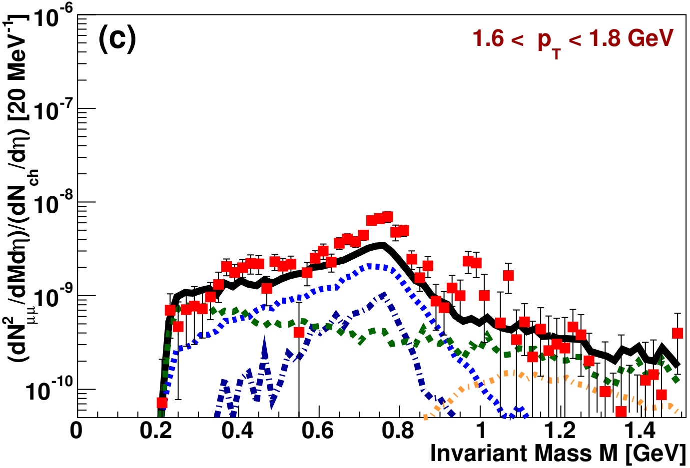
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $1.4\,\mathrm{GeV} < p_T < 1.6\,\mathrm{GeV}$

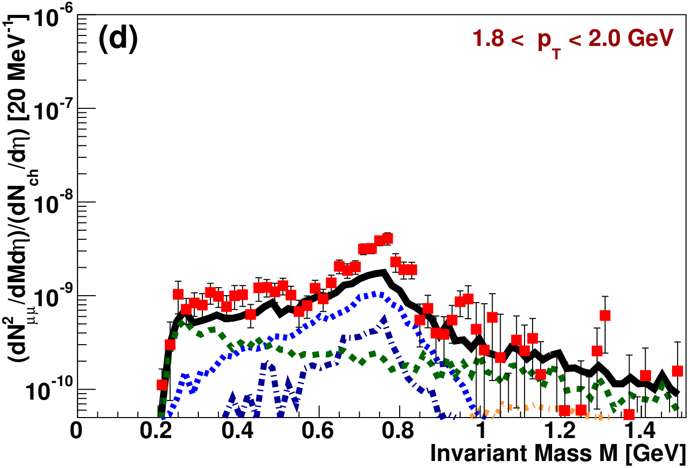


CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $1.6\,\mathrm{GeV} < p_T < 1.8\,\mathrm{GeV}$

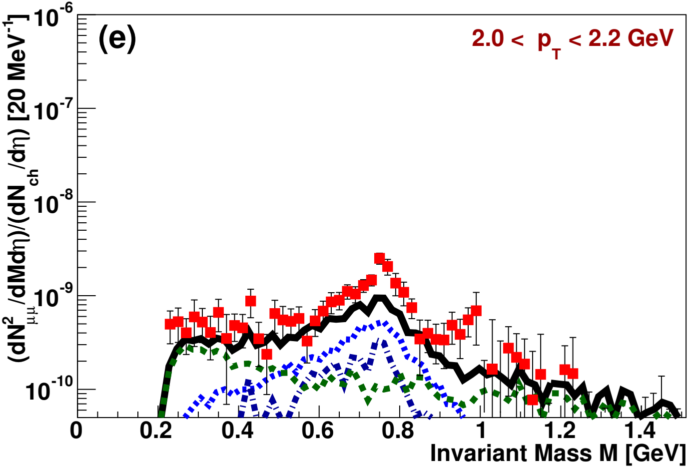


- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $1.8\,\mathrm{GeV} < p_T < 2.0\,\mathrm{GeV}$



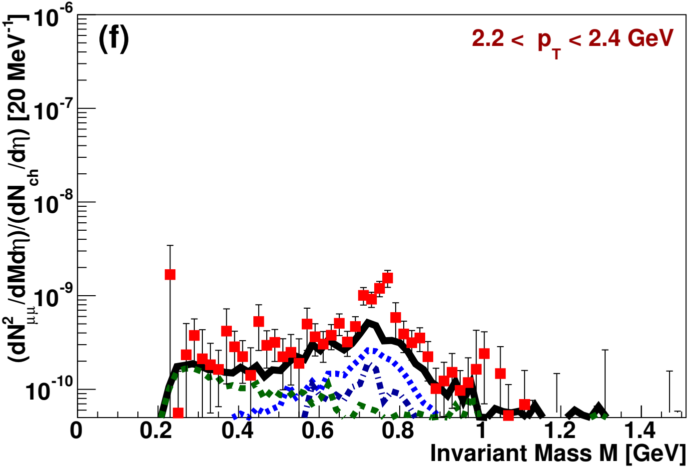
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\text{In}+\text{In}(158\,A\text{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120$)
- $2.0\,\text{GeV} < p_T < 2.2\,\text{GeV}$



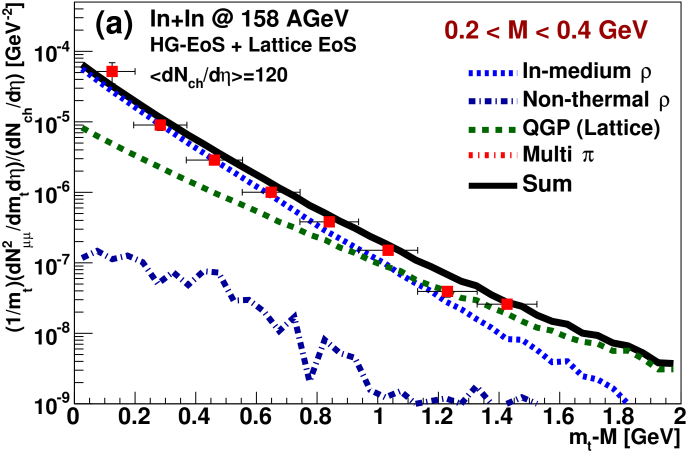
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $2.2\,\mathrm{GeV} < p_T < 2.4\,\mathrm{GeV}$



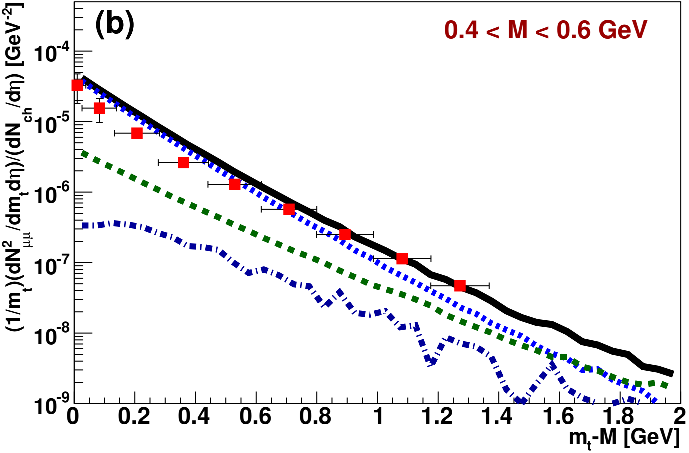
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)



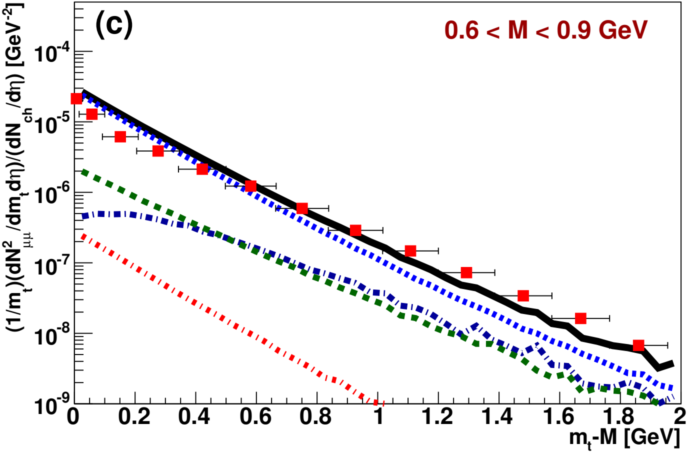
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data $(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120)$



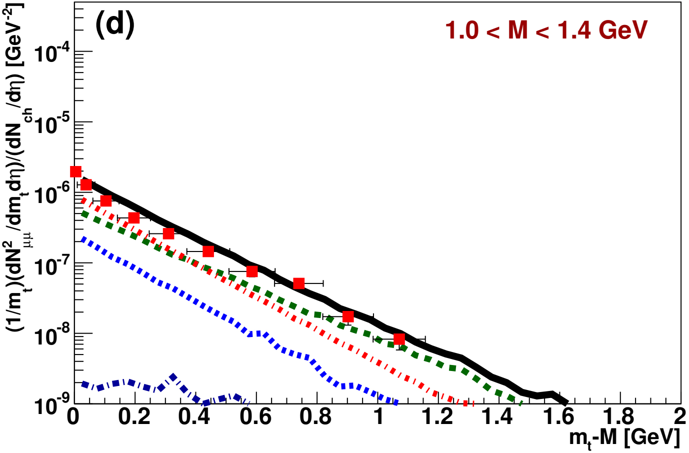
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)



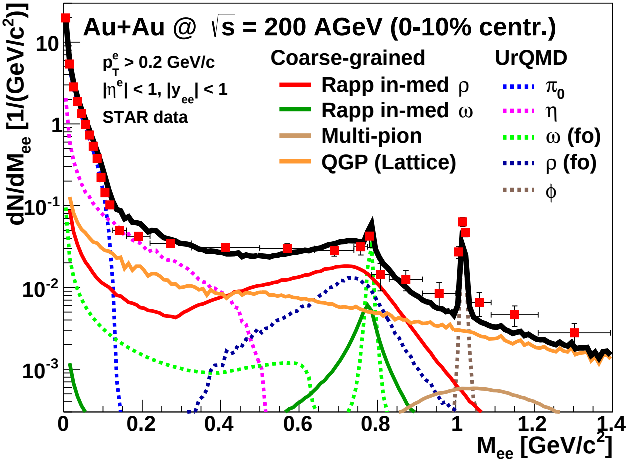
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\text{In}+\text{In}(158\,A\text{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data $(\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120)$

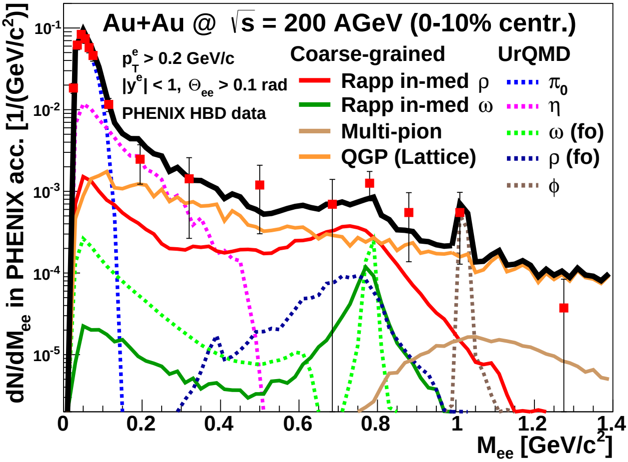


Dielectrons at RHIC

CGUrQMD: Au+Au ($\sqrt{s_{NN}} = 200\,\text{GeV}$) (RHIC/STAR)

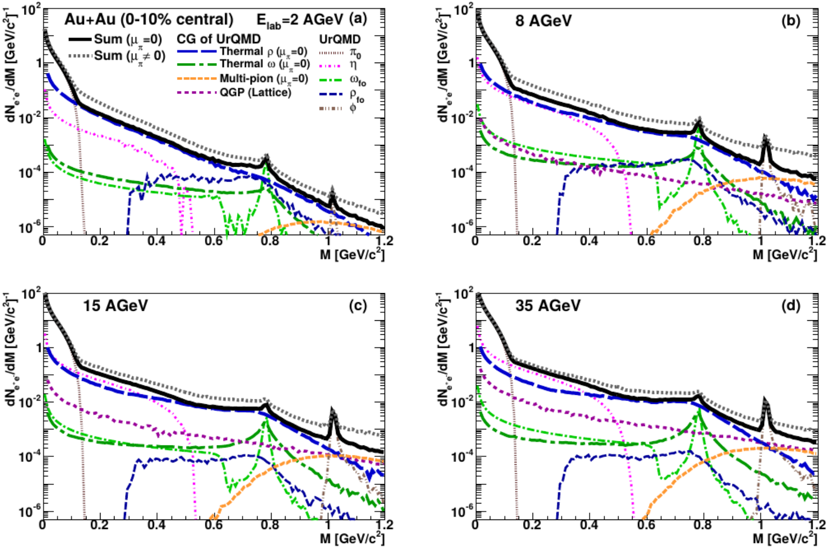


CGUrQMD: Au+Au ($\sqrt{s_{NN}} = 200\,\text{GeV}$) (RHIC/PHENIX)



Dielectrons at RHIC-BES/FAIR/NICA

CGUrQMD: Au+Au ($E_{\mathrm{lab}} = 2$-$35\,A$GeV)



NB: also photon spectra [EHB16b]

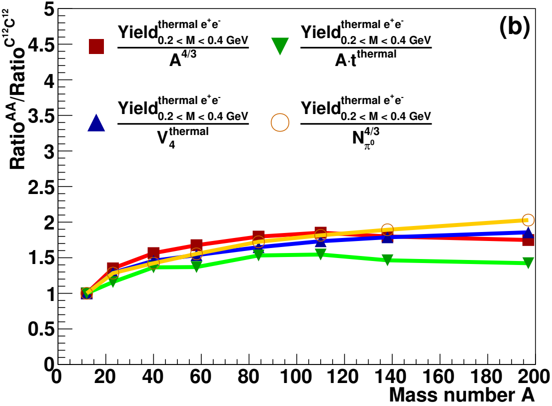
Signatures of the QCD-phase structure?

QCD phase structure from em. probes?

- hadronic observables like p_T spectra:
  "snapshot" of the stage after kinetic freezeout
- particle abundancies: chemical freezeout
- em. probes: emitted during the whole medium evolution
  life time of the medium $\Rightarrow$ "four-volume of the fireball"
- use CGUrQMD to study system-size dependence
- study AA collisions for different A [EHWB15]
- "excitation functions":
  systematics of $\ell^+\ell^-$ (and γ) emission vs. beam energy [EHB16b, RH16]
  similar study in [GHR$^+$16]
- caveat: phase transition not really implemented!!!

Scaling behavior of thermal-dilepton yield

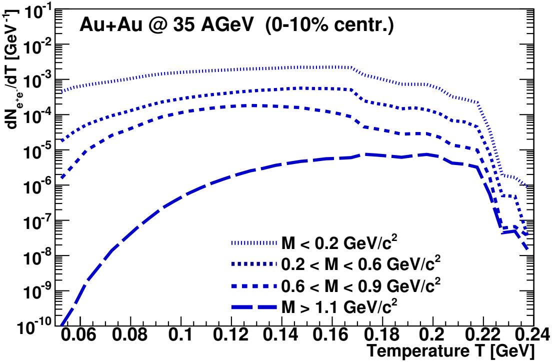
- central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76\,A\text{GeV}$



- thermal-dilepton yield roughly $\propto V_{\text{therm}}^{(4)} \propto A^{4/3} \propto A t_{\text{therm}} \propto N_{\pi^0}^{4/3}$
- at low(est) beam energies:
  lifetime of "medium" $\hat{=}$ time nuclei pass through each other

Mass-temperature relation in dilepton emission

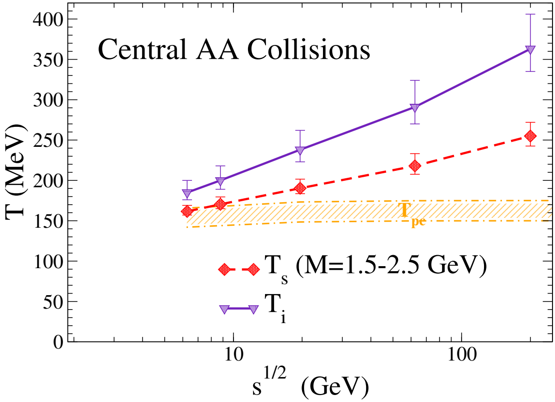
- interplay between increasing volume and decreasing temperature of fireball
- in IMR ($T < m_\phi < M_{\ell^+\ell^-} < m_{J/\psi}$) biased towards early hot stages
- only “background”: correlated $D\overline{D}$ decays, some Drell-Yan
- otherwise emission from thermal QGP and hadronic sources
- invariant-mass slope $\Leftrightarrow$ true invariant space-time averaged temperature
- no blueshift due to radial flow as in p_t spectra (e.g., photons)



[EHB16b, EHB16a]

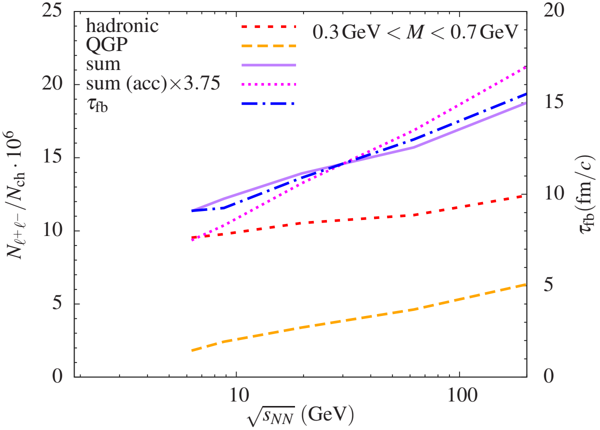
Dilepton systematics in the beam-energy scan

- thermal-fireball model [RH16, EHB16a]
- invariant-mass slope in IMR ⇒ true temperature!
- no blue shift from radial flow as in p_T/m_T spectra



Dilepton systematics in the beam-energy scan

- thermal-fireball model [RH16]
- beam-energy scan at RHIC and lower energies at FAIR and
- dilepton yield as fireball-lifetime clock



Conclusions and Outlook

- General ideas
  - em. probes $\Leftrightarrow$ in-medium em. current-correlation function
  - dual rates around T_c (compatible with χ symmetry restoration)
  - medium modifications of ρ, ω, ϕ
  - importance of baryon-resonance interactions
- Application to dileptons in HICs
  - coarse-grained transport (here: CGUrQMD)
  - allows use of thermal-QFT spectral VM functions
  - applicable also at low collision energies
  - allows use of thermal-QFT models for dilepton rates
  - successful description from SIS to RHIC energies
  - consistent description of M and m_T spectra!
  - effective slope of M spectra ($1.5\,\text{GeV} < M < M_{J/\psi}$) provides $\langle T \rangle$
  - beam-energy scan at RHIC and FAIR $\Rightarrow$ signature of phase transition?
- Outlook
  - signature of cross-over vs. 1st order (or even critical endpoint)???
  - challenge: phase transition in (coarse-grained) transport???

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