Electromagnetic Probes in Heavy-Ion Collisions II
Phenomenology from SIS to LHC energies

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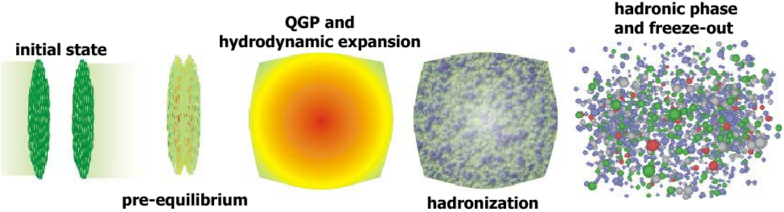
Outline

1. Heavy-ion collisions on one slide
2. QCD and ultra-hot and -dense matter
3. Electromagnetic probes in heavy-ion collisions
4. Simulations for electromagnetic probes in HICs
    - Dileptons at SIS energies (HADES)
    - Dileptons at SPS and RHIC
    - Direct photons at RHIC and LHC: “the flow puzzle”
5. Outlook: Signatures of the QCD-phase structure?
6. References

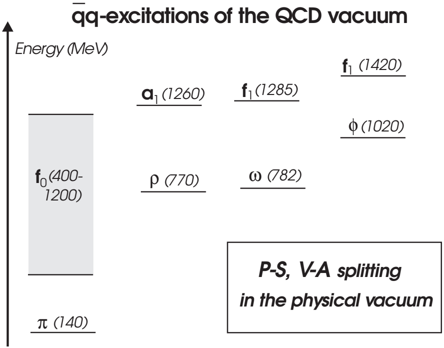
Heavy-Ion collisions in a Nutshell

- theory of strong interactions: Quantum Chromo Dynamics, QCD
- at high densities/temperatures: hadrons dissolve into a QGP
- create QGP in Heavy-Ion Collisions at RHIC (and LHC)
- 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



Phenomenology and Chiral symmetry

- in vacuum: Spontaneous breaking of chiral symmetry
- ⇒ mass splitting of chiral partners



$\bar{q}q$-excitations of the QCD vacuum

Energy (MeV)

f_1 *(1420)*

a_1 *(1260)*

f_1 *(1285)*

ϕ *(1020)*

f_0 *(400-1200)*

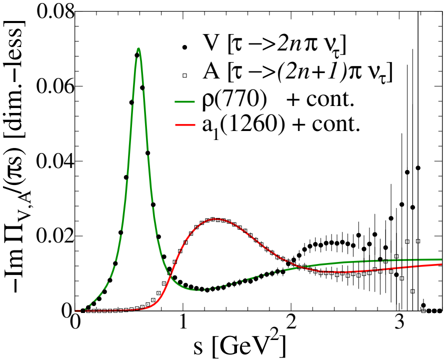
ρ *(770)*

ω *(782)*

π *(140)*

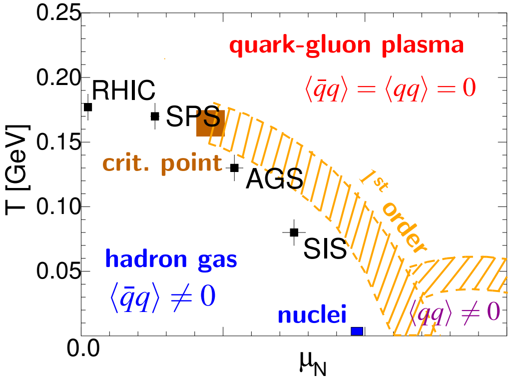
P-S, V-A splitting

in the physical vacuum



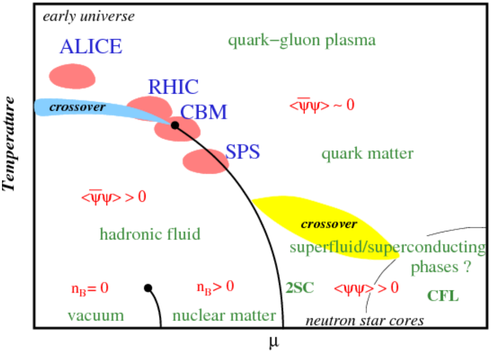
The QCD-phase diagram

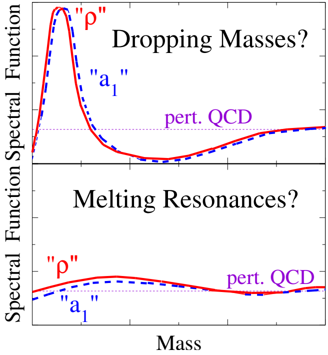
- hot and dense matter: quarks and gluons close together
- highly energetic collisions ⇒ “deconfinement”
- quarks and gluons relevant degrees of freedom ⇒ quark-gluon plasma
- still strongly interacting ⇒ fast thermalization!



The QCD-phase diagram

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

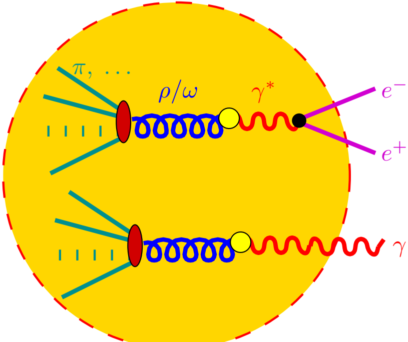




- mechanism of chiral restoration?
- two main theoretical ideas
  - "dropping masses": $m_{\text{had}} \propto \langle\overline{\psi}\psi\rangle$
  - "melting resonances": broadening of spectra through medium effects

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



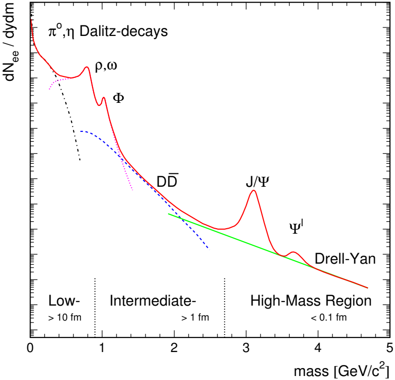


Fig. by A. Drees

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]

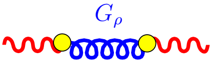
$$\Pi^{<}_{\mu\nu}(q) = \int \mathrm{d}^4 x \exp(\mathrm{i} q \cdot x) \left\langle J_\mu(0) J_\nu(x) \right\rangle_T = -2 f_{\mathrm{B}}(q \cdot u) \operatorname{Im} \Pi^{(\mathrm{ret})}_{\mu\nu}(q)$$

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

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

- manifestly 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:

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



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

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

- General: McLerran-Toimela formula

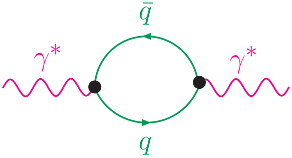
$$\frac{\mathrm{d}N_{l^+l^-}^{(\mathrm{MT})}}{\mathrm{d}^4x\,\mathrm{d}^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M^2)}{M^2} g_{\mu\nu} \mathrm{Im} \sum_i \Pi^{\mu\nu}_{\mathrm{em},i}(M,\vec{q}) f_{\mathrm{B}}(q\cdot u)$$

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

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

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

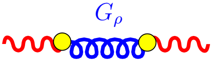
$$-\mathrm{i}\Pi_{\mathrm{em,QGP}} =$$



Radiation from thermal sources: ρ decays

- model assumption: vector-meson dominance

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

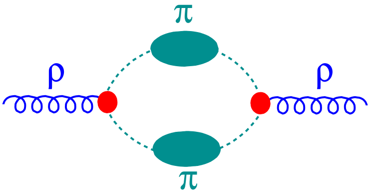


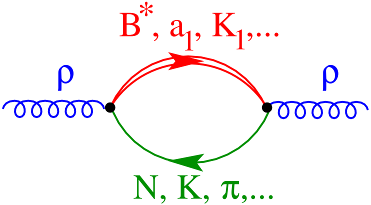
$$\frac{\mathrm{d}N^{(\mathrm{MT})}_{\rho\to l^+l^-}}{\mathrm{d}^4x\,\mathrm{d}^4q} = \frac{M}{q^0}\Gamma_{\rho\to l^+l^-}(M)\frac{\mathrm{d}N_\rho}{\mathrm{d}^3\vec{x}\,\mathrm{d}^4q}$$
$$= -\frac{\alpha^2}{3\pi^3}\frac{L(M^2)}{M^2}\frac{m_\rho^4}{g_\rho^2}g_{\mu\nu}\,\mathrm{Im}\,D_\rho^{\mu\nu}(M,\vec{q})f_{\mathrm{B}}\left(\frac{q\cdot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

- 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 $T(t)$, $\mu_{\mathrm{meson/baryon}}(t)$
- $-\mathrm{Im}\,D_\rho$ in-medium ρ-meson spectral function!
- analogous for ω and ϕ

Hadronic many-body theory

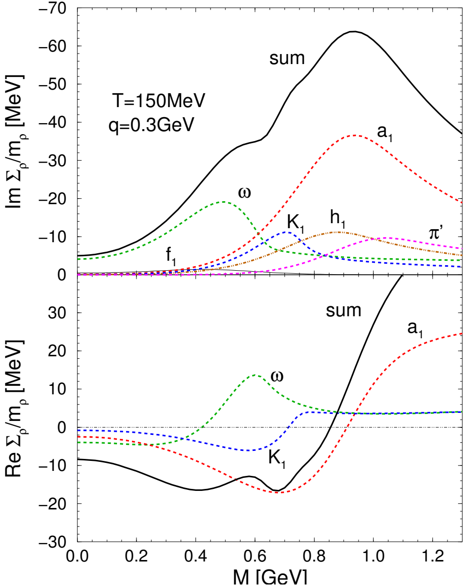
- hadronic many-body theory (HMBT) for vector mesons
  [LK95, CS92, CS93, RCW97, UBRW98, UBW02, UBRW00, Her92, HFN93, GR99, RW99, RW00]
- $\pi\pi$ interactions and baryonic excitations
- effective hadronic models, implementing symmetries
- parameters fixed from phenomenology
  (photon absorption at nucleons and nuclei, $\pi N \to \rho N$)
- evaluated at finite temperature and density
- self-energies ⇒ mass shift and broadening of particle in the medium





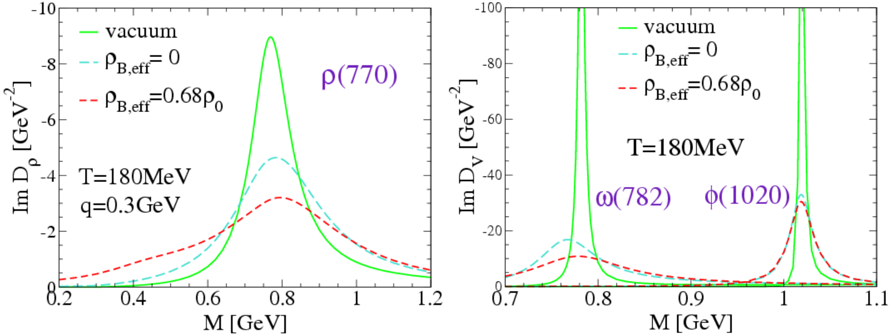
- Baryon (resonances) important, even at low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

Meson contributions



[GR99]

In-medium spectral functions and baryon effects



[RW99]

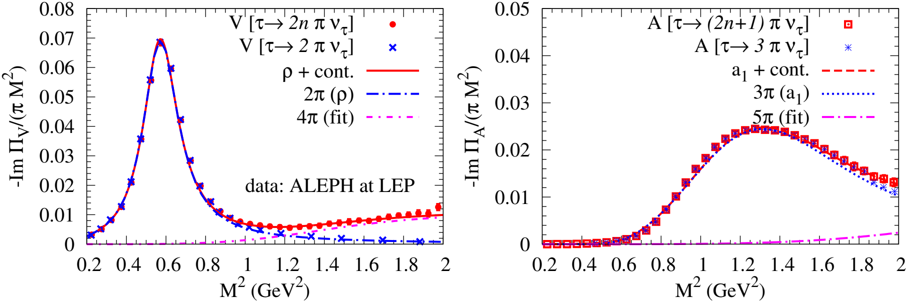
- baryon effects important
  - large contribution to broadening of the peak
  - responsible for most of the strength at small M

Radiation from thermal sources: multi-π processes

- use vector/axial-vector correlators from τ-decay data
- Dey-Eletsky-Ioffe mixing: $\hat{\varepsilon} = 1/2\varepsilon(T,\mu_\pi)/\varepsilon(T_c,0)$

$$\Pi_V = (1-\hat{\varepsilon}) z_\pi^4 \Pi_{V,4\pi}^{\text{vac}} + \frac{\hat{\varepsilon}}{2} z_\pi^3 \Pi_{A,3\pi}^{\text{vac}} + \frac{\hat{\varepsilon}}{2}(z_\pi^4 + z_\pi^5)\Pi_{A,5\pi}^{\text{vac}}$$

- avoid double counting: leave out two-pion piece and $a_1 \rightarrow \rho + \pi$ (already contained in ρ spectral function)



Data: [B+98]

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 ⇒ local thermal equilibrium
    ⇒ use equilibrium rates
  - use transport-hydro hybrid model: treat early stage with transport, then coarse grain ⇒ switch to hydro
    ⇒ switch back to transport (Cooper-Frye “particlization”)
- here: UrQMD transport for entire bulk evolution
  ⇒ use coarse graining in space-time cells ⇒ extract $T, \mu_B, \mu_\pi, \ldots$
  ⇒ use equilibrium rates locally

Simulations for em. probes in heavy-ion collisions

Coarse-grained UrQMD (CGUrQMD)

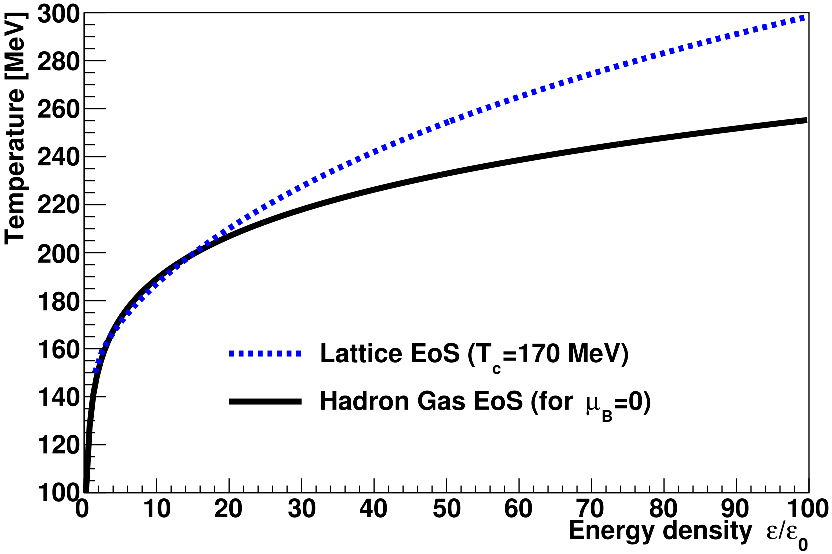
- problem with medium modifications of spectral functions/interactions
- only available in equilibrium many-body QFT models
- use “in-medium cross sections” naively: double counting?!?
- way out: map transport to local-equilibrium fluid
- use ensemble of UrQMD runs with an equation of state
- fit temperature, 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
- extrapolated lattice QGP and Rapp-Wambach hadronic many-body theory
- caveat: consistency between EoS, matter content of QFT model/UrQMD!

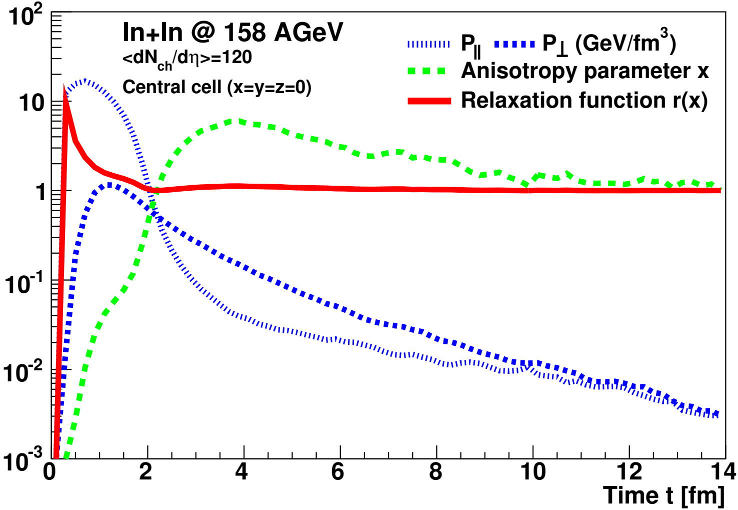
Coarse-grained UrQMD (CGUrQMD)

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



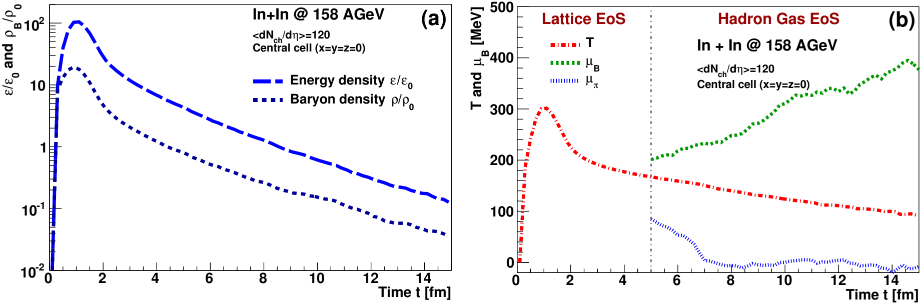
Coarse-grained UrQMD (CGUrQMD)

- pressure anisotropy (In-In collisions (NA60) at SIS)



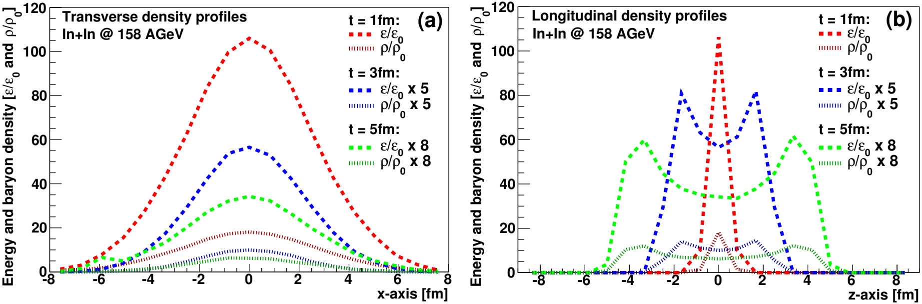
Coarse-grained UrQMD (CGUrQMD)

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



Coarse-grained UrQMD (CGUrQMD)

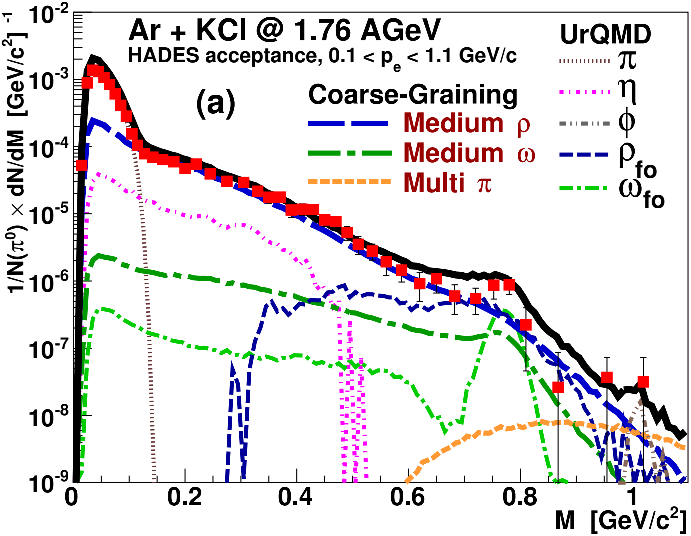
- energy (ϵ) and baryon (ρ) density profiles (for In+In@SPS; NA60)



Dielectrons (SIS/HADES)

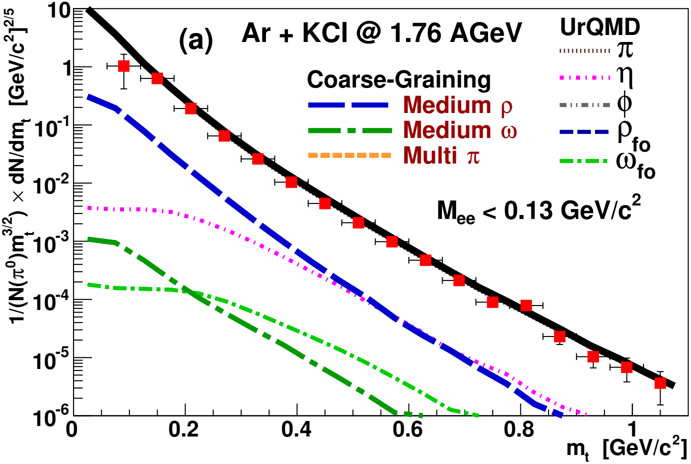
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- coarse-graining method works at low energies!
- UrQMD-medium evolution + RW-QFT rates [EHWB15b]



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 [EHWB15b]
- $M_{\mathrm{ee}} < 0.13\,\mathrm{GeV}$



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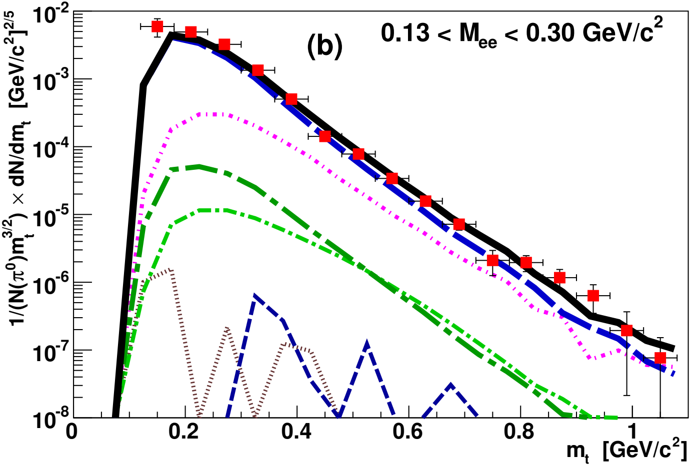
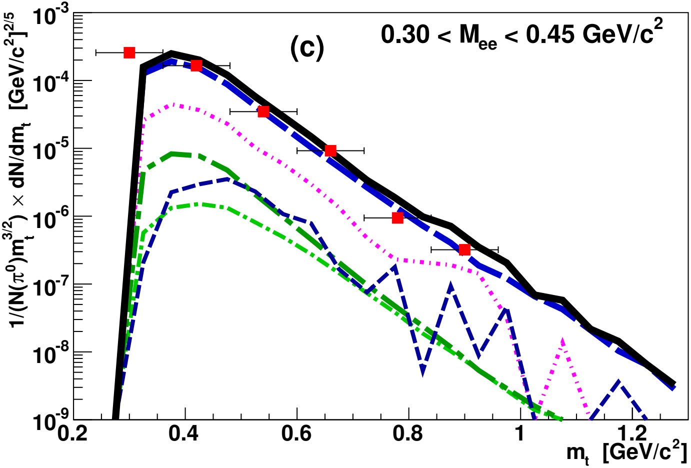
- dielectron spectra from $\mathrm{Ar}+\mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow \mathrm{e}^+\mathrm{e}^-$ (SIS/HADES)
- m_t spectra [EHWB15b]
- $0.13\,\mathrm{GeV} M_{\mathrm{ee}} < 0.3\,\mathrm{GeV}$



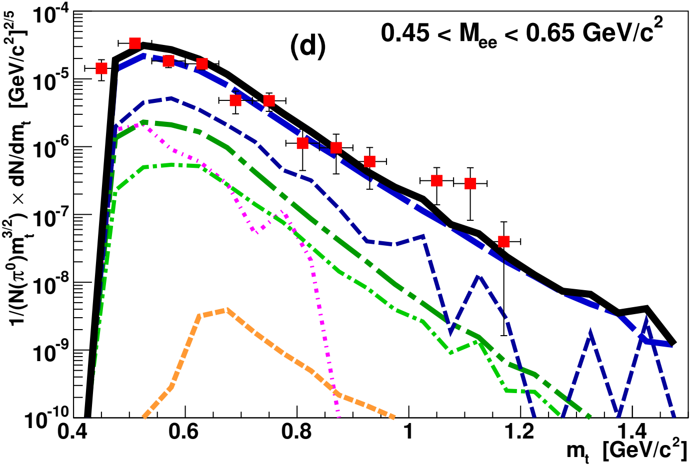
CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

- dielectron spectra from $\mathrm{Ar}+\mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow \mathrm{e}^{+}\mathrm{e}^{-}$ (SIS/HADES)
- m_t spectra [EHWB15b]
- $0.3\,\mathrm{GeV} M_{\mathrm{ee}} < 0.45\,\mathrm{GeV}$



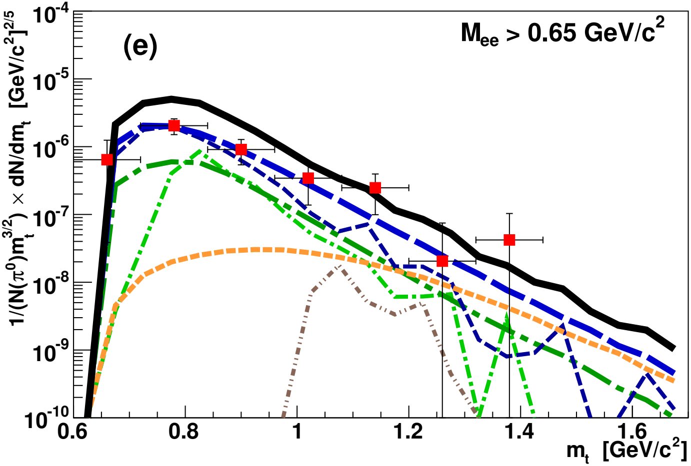
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- dielectron spectra from $\mathrm{Ar} + \mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow \mathrm{e}^+\mathrm{e}^-$ (SIS/HADES)
- m_t spectra [EHWB15b]
- $0.45\,\mathrm{GeV} M_{\mathrm{ee}} < 0.65\,\mathrm{GeV}$



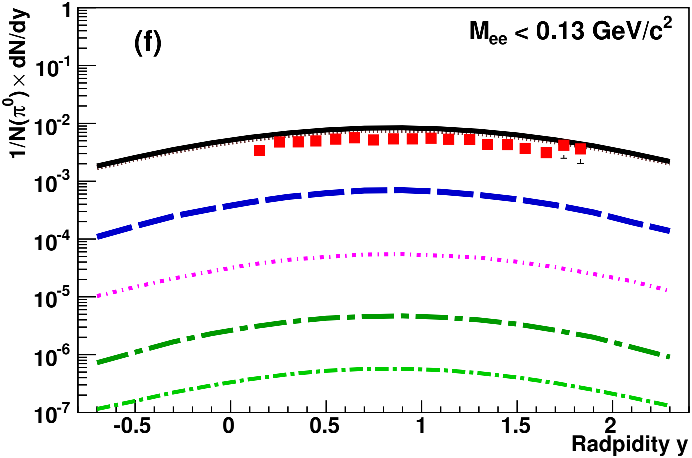
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- dielectron spectra from $\mathrm{Ar}+\mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow \mathrm{e}^+\mathrm{e}^-$ (SIS/HADES)
- m_t spectra [EHWB15b]
- $M_{\mathrm{ee}} > 0.65\,\mathrm{GeV}$

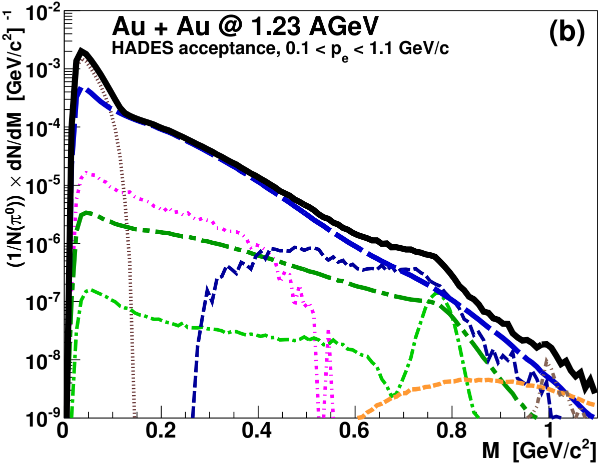


CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- dielectron spectra from $\mathrm{Ar}+\mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow \mathrm{e}^{+}\mathrm{e}^{-}$ (SIS/HADES)
- m_t spectra [EHWB15b]
- rapidity spectrum ($M_{\mathrm{ee}} < 0.13$ GeV)



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



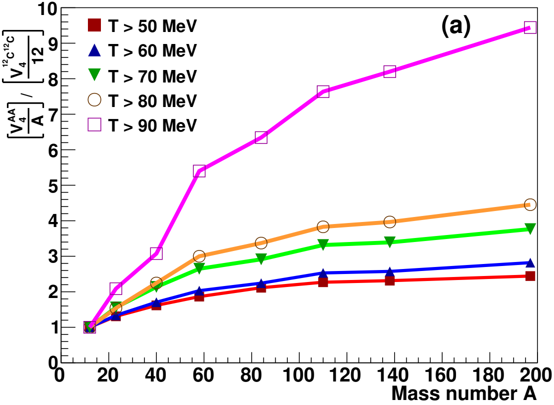
- caveat: pp/np acceptance filter with single-e cut, $p_t < 100$ MeV
- correct filter urgently needed!
- excellent agreement with preliminary HADES data (data points not shown here on request of the HADES collaboration)

What to learn about the “bulk dynamics”?

- 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 ⇒ “four-volume of the fireball”
- use CGUrQMD to study system-size dependence
- study AA collisions for different A
- hard to quantify “life time” of the “thermal” medium in transport
- here: use time, for which the central cell has $T \geq 50$ MeV

Four Volume

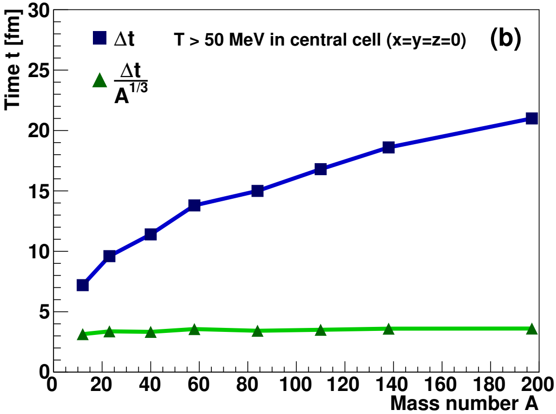
- $\frac{V_{AA}^{(4)}/A}{V_{\text{CC}}^{(4)}/12}$ of cells larger than various T



- how to explain “scaling behavior”?

Lifetime of the central cell

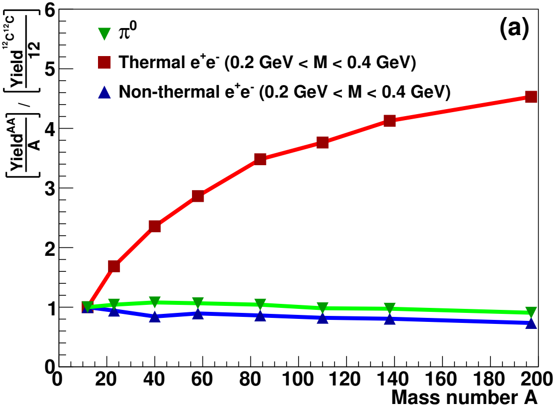
- consider central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76\, A\text{GeV}$



- $\Delta t \propto A^{1/3}$
- $A \propto V^{(3)}$ of nuclei $\Rightarrow A^{1/3} \propto d_{\text{nucl}}$
- fireball lifetime $\propto$ time of nuclei to traverse each other

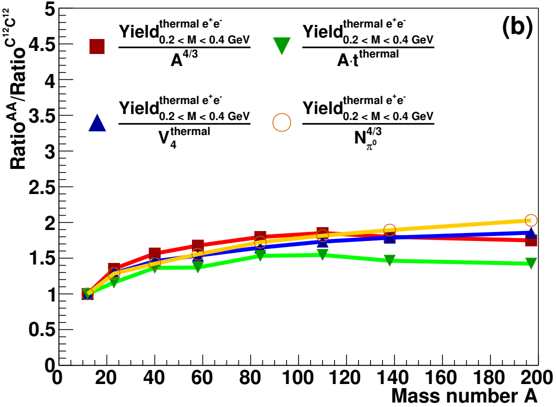
Lifetime of the central cell

- $\frac{\text{yield}_{AA}/A}{\text{yield}_{\text{CC}}/12}$



- $\text{yield}_{\text{had}} \propto A \propto V_{\text{fo}}^{(3)}$
- $\text{yield}_{\text{non-thermal ee}} \propto A \propto V_{\text{fo}}^{(3)}$
  $\Rightarrow$ hadronic decays after kinetic freeze-out

Scaling behavior of thermal-dilepton yield



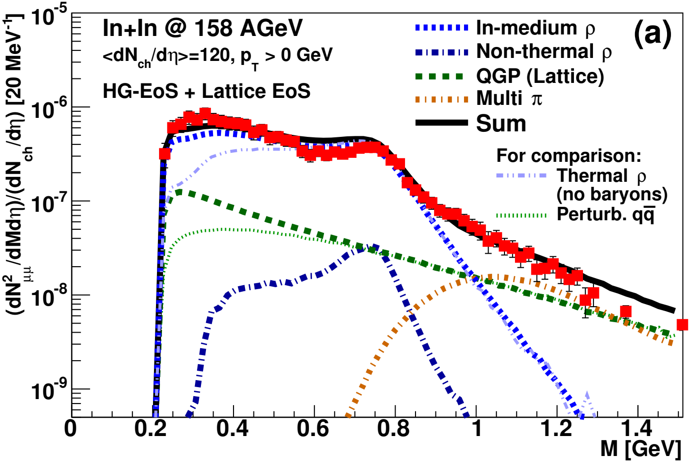
- thermal-dilepton yield roughly $\propto V_{\text{therm}}^{(4)} \propto A^{4/3} \propto A t_{\text{therm}} \propto N_{\pi^0}^{4/3}$

Dimuons (SPS/NA60)

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

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60)

  [EHWB15a]
- min-bias data $(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120)$
- note the importance of baryon effects!



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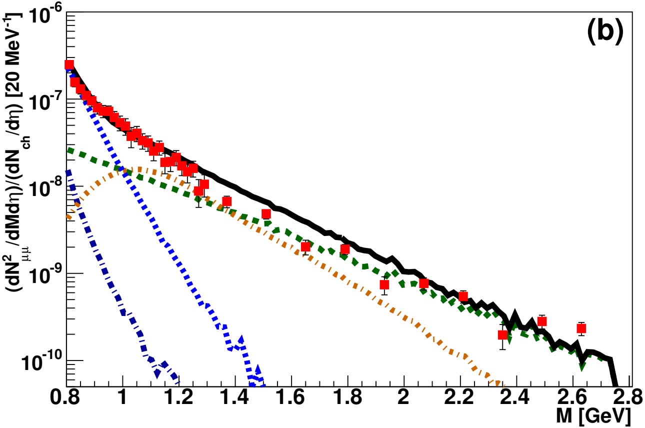
  [EHWB15a]

- min-bias data $(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120)$
- higher IMR: provides averaged true temperature

  (no blueshifts in the invariant-mass spectra!)

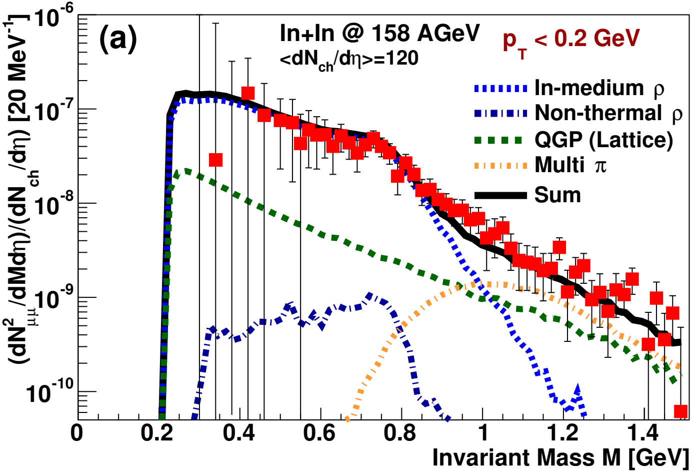


CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60)

  [EHWB15a]

- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $p_T < 0.2$ GeV

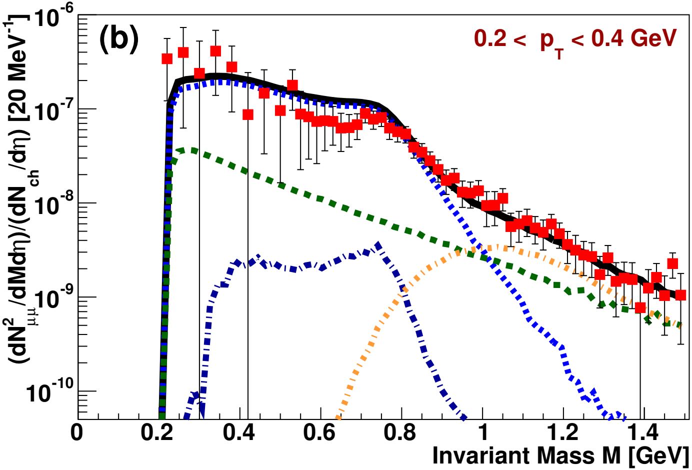


CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60)

  [EHWB15a]

- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $0.2\,\mathrm{GeV} < p_T < 0.4\,\mathrm{GeV}$

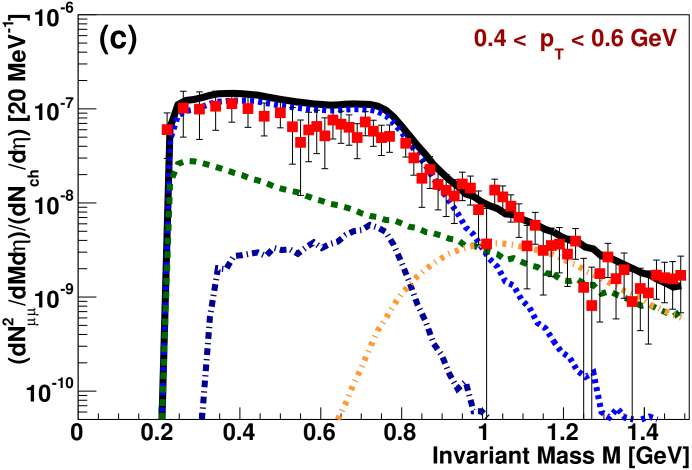


CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In} + \mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60)

  [EHWB15a]

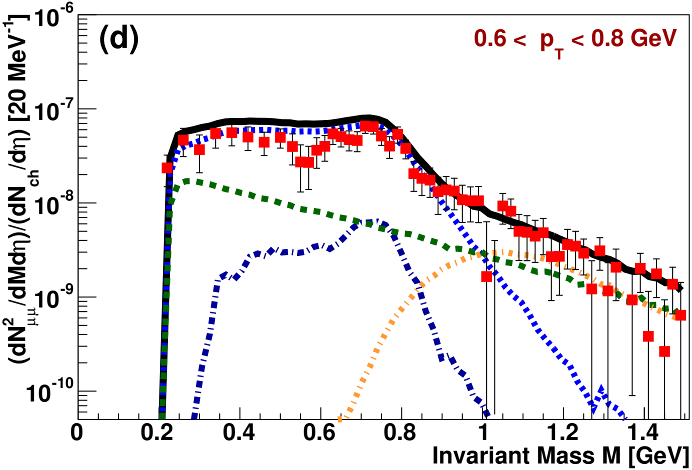
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $0.4\,\mathrm{GeV} < p_T < 0.6\,\mathrm{GeV}$



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

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60)

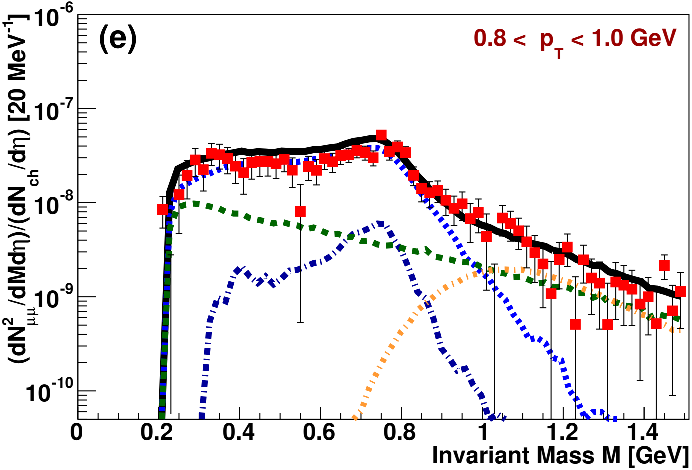
  [EHWB15a]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $0.6\,\mathrm{GeV} < p_T < 0.8\,\mathrm{GeV}$



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

- dimuon spectra from $\text{In} + \text{In}(158\,A\text{GeV}) \rightarrow \mu^+\mu^-$ (NA60)

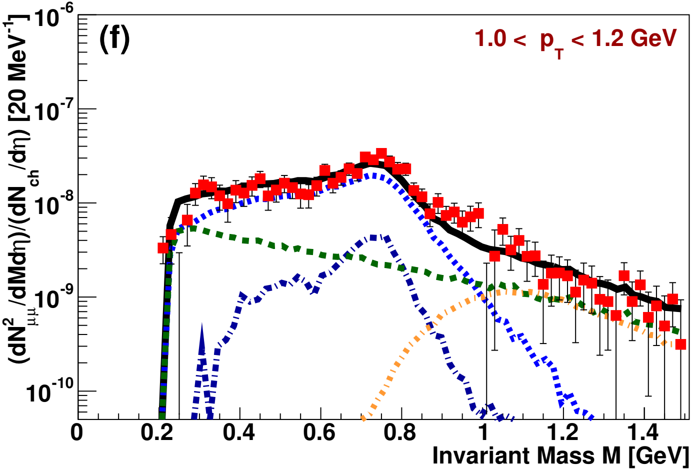
  [EHWB15a]
- min-bias data ($\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120$)
- $0.8\,\text{GeV} < p_T < 1.0\,\text{GeV}$



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

- dimuon spectra from $\mathrm{In} + \mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60)

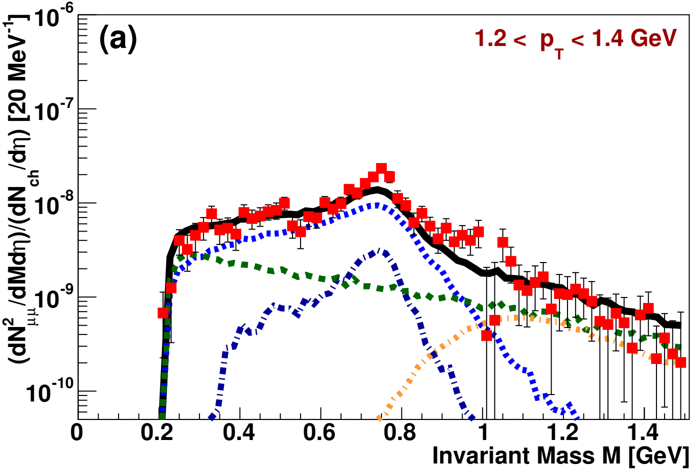
  [EHWB15a]
- min-bias data $(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120)$
- $1.0\,\mathrm{GeV} < p_T < 1.2\,\mathrm{GeV}$



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

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60)

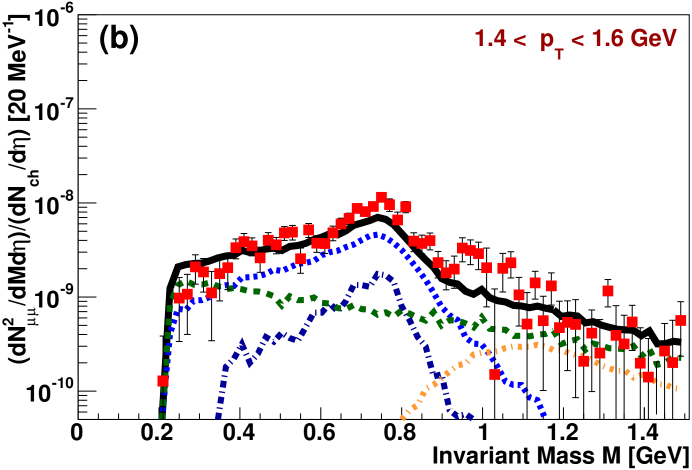
  [EHWB15a]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $1.2\,\mathrm{GeV} < p_T < 1.4\,\mathrm{GeV}$



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

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60)

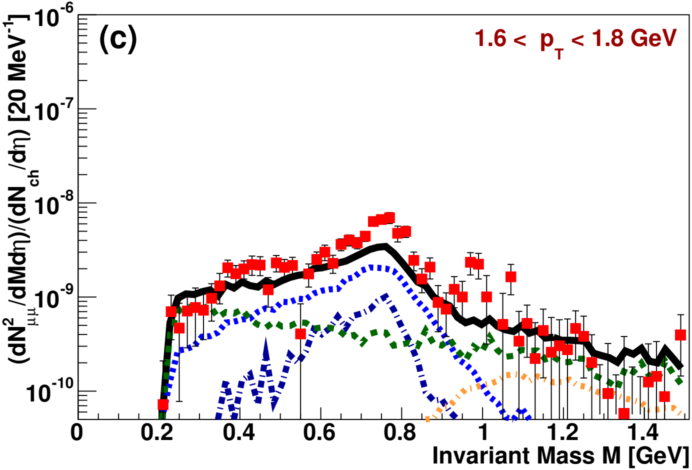
  [EHWB15a]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $1.4\,\mathrm{GeV} < p_T < 1.6\,\mathrm{GeV}$



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

- dimuon spectra from $\text{In} + \text{In}(158\,A\text{GeV}) \rightarrow \mu^+\mu^-$ (NA60)

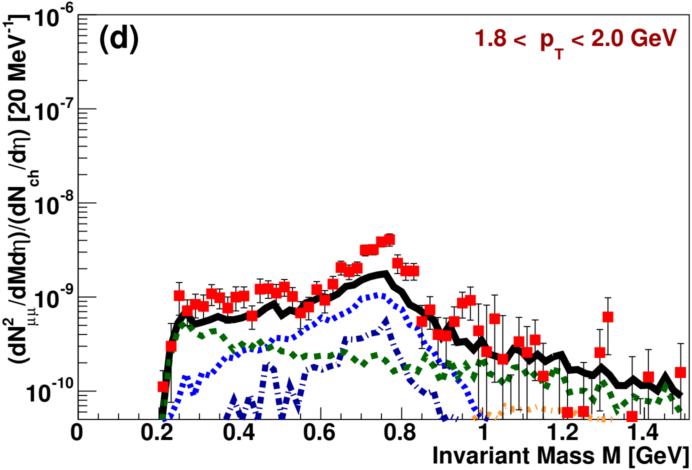
  [EHWB15a]
- min-bias data $(\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120)$
- $1.6\,\text{GeV} < p_T < 1.8\,\text{GeV}$



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

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60)

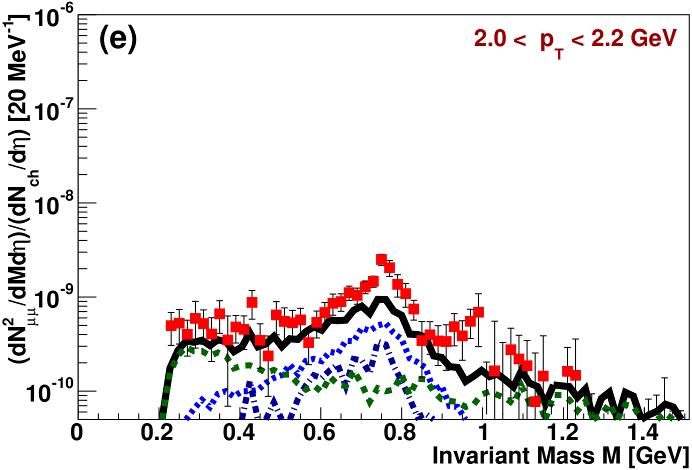
  [EHWB15a]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $1.8\,\mathrm{GeV} < p_T < 2.0\,\mathrm{GeV}$



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

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60)

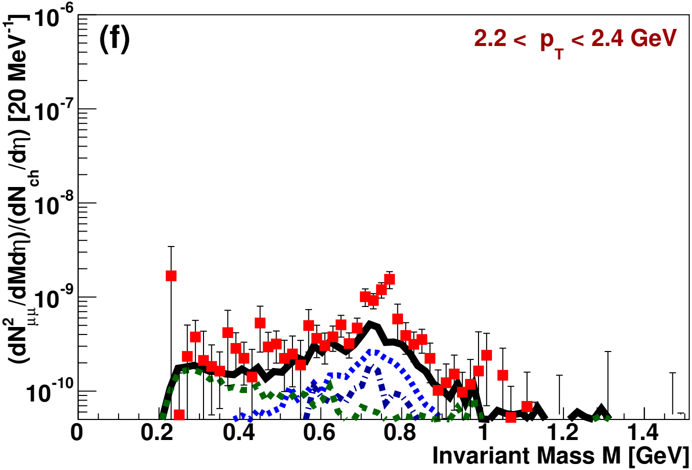
  [EHWB15a]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $2.0\,\mathrm{GeV} < p_T < 2.2\,\mathrm{GeV}$



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

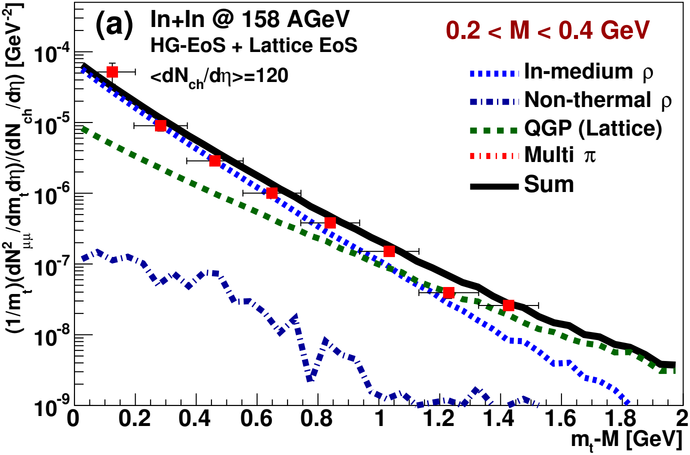
- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60)

  [EHWB15a]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $2.2\,\mathrm{GeV} < p_T < 2.4\,\mathrm{GeV}$



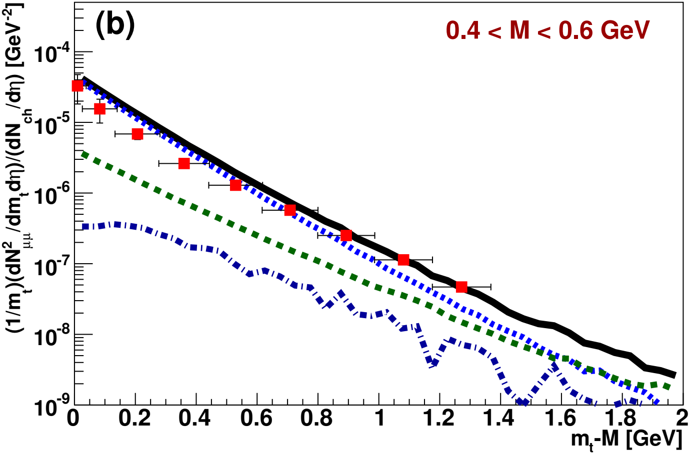
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

- dimuon spectra from In + In(158 *A*GeV) $\rightarrow \mu^+\mu^-$ (NA60) [EHWB15a]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)



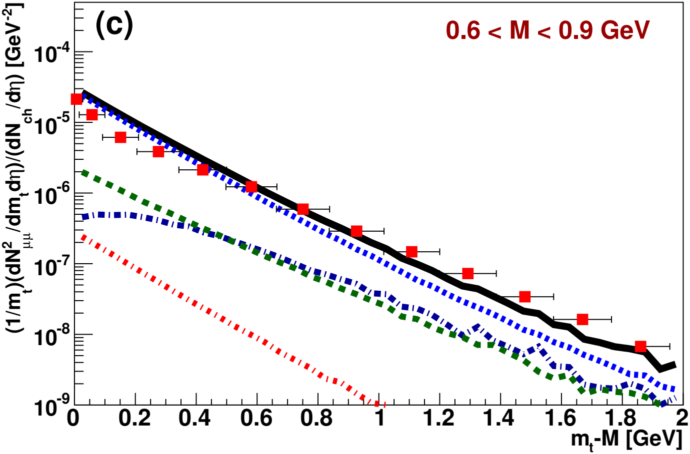
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15a]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)



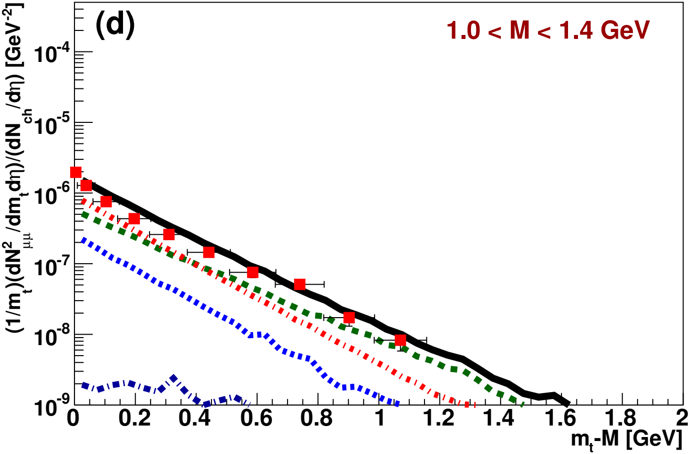
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15a]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)



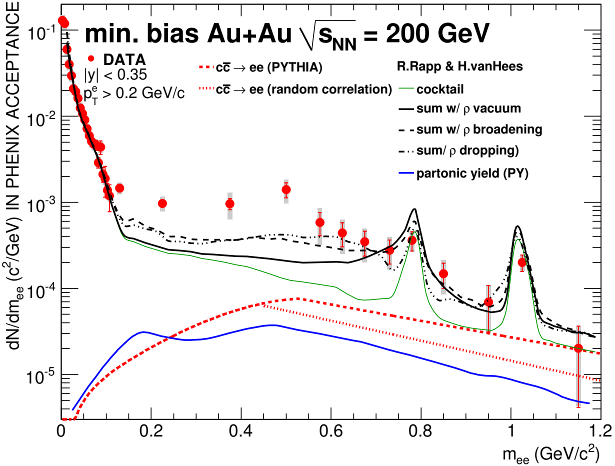
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15a]
- min-bias data $(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120)$



Dielectrons at RHIC

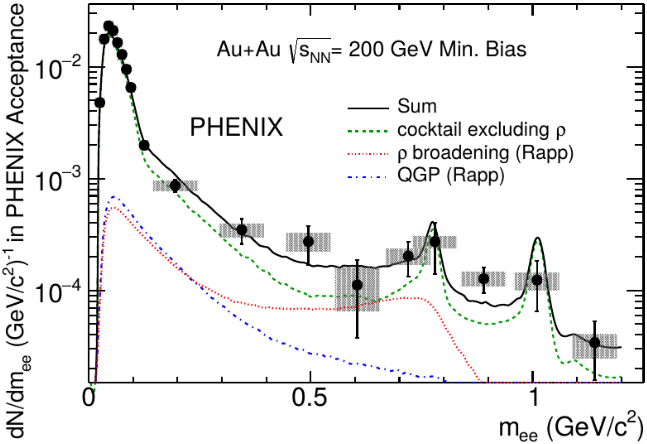
Dileptons@RHIC: PHENIX (2007)



model: Rapp, HvH, data [A+10]

- here: thermal-fireball evolution instead of CGUrQMD (work in progress)
- huge enhancement in the LMR explained by new PHENIX results from Sep/2015

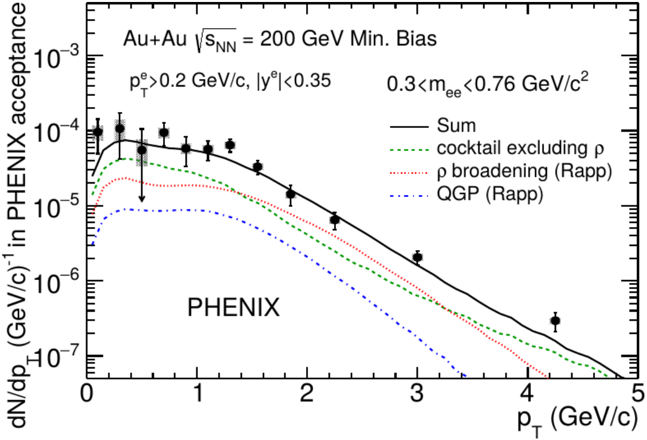
Dileptons@RHIC: PHENIX (2015)



model: Rapp, HvH, data [A+15]

- here: thermal-fireball evolution instead of CGUrQMD (work in progress)

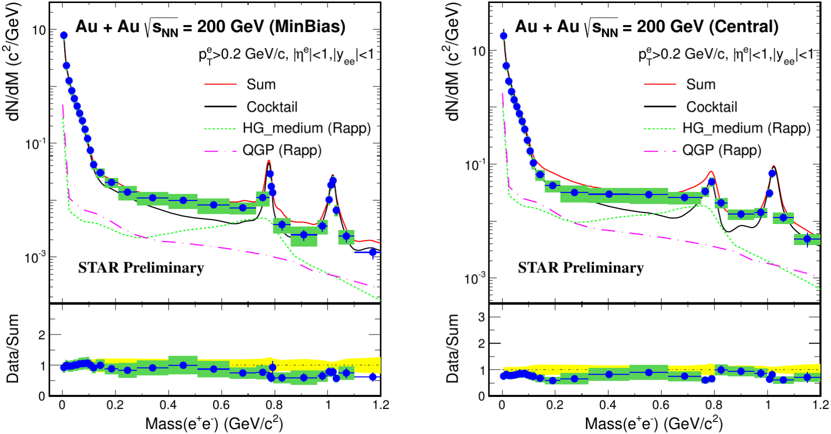
Dileptons@RHIC: PHENIX (2015)



model: Rapp, HvH, data [A+15]

- here: thermal-fireball evolution instead of CGUrQMD (work in progress)

Dileptons@RHIC: STAR (QM 2012)



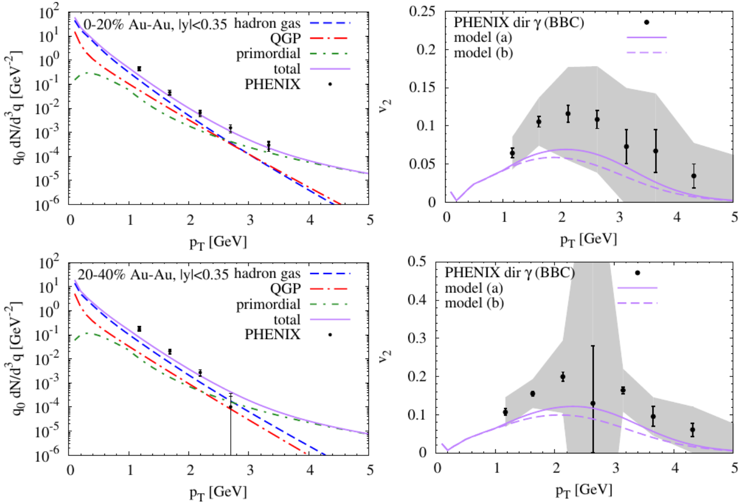
[Rap13], data: [Zha11]

- compatible with medium modifications in model calculation

Direct photons (RHIC/LHC)

Direct Photons at RHIC

- same model [TRG04] for rates as for dileptons
- fireball parametrization with elliptic flow v_2
- photons inherit v_2 from hadronic sources

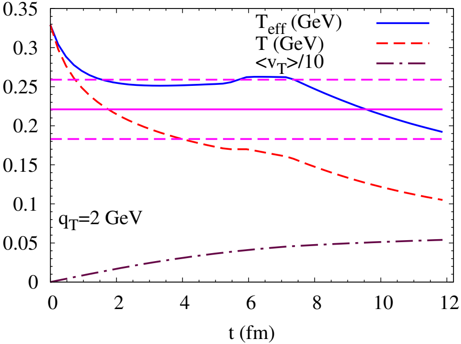


[HGR11, RHH14, HHR15]

Effective slopes vs. temperatures

- effective slopes of photon p_T spectra are NOT temperatures!
- emission from a flowing medium ⇒ Doppler effect

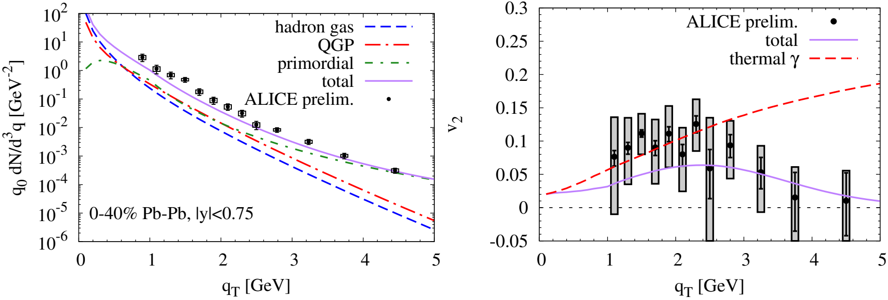
$$T_{\text{eff}} \simeq \sqrt{\frac{1+\langle v_T \rangle}{1-\langle v_T \rangle}}\, T$$



[RHH14]

Direct Photons at the LHC

same model, fireball adapted to hadron data from ALICE [HHR15]



- large direct-photon v_2
- early buildup of v_2; here developed already at end of QGP phase
- emission mostly around T_c (dual rates!) ⇒
- ⇒ source has already developed radial flow and v_2
- large effective slopes include blueshift from radial flow!
- still additional (hadronic?) sources (bremsstrahlung?) missing?!?

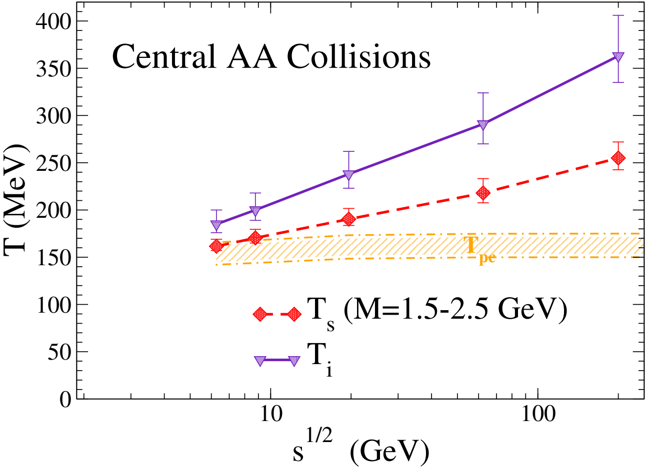
Signatures of the QCD-phase structure?

Possible signatures of QCD-phase structure?

- measurement of thermal-dilepton spectra/yields a la NA60
- scaling behavior at low energies studied with one HRG EoS
- beam-energy scan like at RHIC ⇒ deviations from naive scaling behavior?
- possible variations in fireball lifetime due to different phase transitions
- cross over at higher RHIC and LHC energies [RH14]
- deviations in regions of larger μ_B?
- possible signature of 1^{st}-order line?
- possible signature of critical point through "anomalies in fireball lifetime" due to critical slowing-down???
- NB: $\ell^+\ell^-$ also "thermometer" from invariant-mass slopes in IMR (needs a good handle on correlated $\mathrm{D}\overline{D}$ decays a la NA60!)

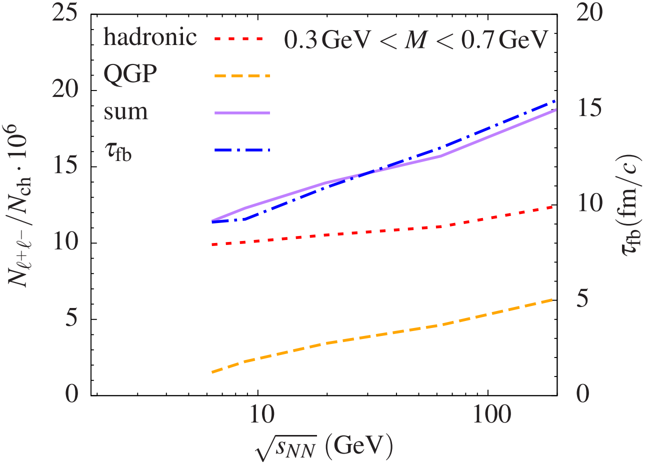
Dilepton systematics in the beam-energy scan

- beam-energy scan at RHIC and lower energies at future FAIR and NICA accelerators
- 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

- beam-energy scan at RHIC and lower energies at future FAIR and NICA accelerators
- dilepton yield as fireball-lifetime clock



[RH14]

Summary

- em. probes, $\ell^+\ell^-$ and γ: neglible final-state interactions
- probe in-medium electromagnetic current-current correlator
  over entire history of fireball evolution
- provide insight into fundamental properties of QCD matter
- needs models for electromagnetic radiation from QGP and hadron gas
- medium effects on vector mesons in hot and dense matter
- hint at chiral-symmetry restoration
  ⇒ melting resonances rather than dropping mass
- insight into fireball dynamics (temperature, lifetime)
- possible hints of QCD-phase structure (equation of state)?
- for more details, see website of the HQM Lecture Week spring 2014
  http://fias.uni-frankfurt.de/~hees/hqm-lectweek14/index.html

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