Dileptons with a coarse-grained transport approach

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Outline

1. Electromagnetic probes (theory perspective)
   - QCD and accidental symmetries
   - The QCD-phase diagram
   - motivation for electromagnetic probes
   - Electromagnetic radiation from hot/dense matter
   - the (essential) hadronic sources of em. probes
   - hadronic many-body theory

2. Bulk-medium evolution with transport and coarse graining
   - coarse-graining in UrQMD
   - Dimuons (SPS/NA60)
   - Dielectrons (SIS/HADES)

3. Conclusions and Outlook

Electromagnetic probes

theory perspective

QCD and ("accidental") symmetries

- fundamental theory of strong interactions: QCD

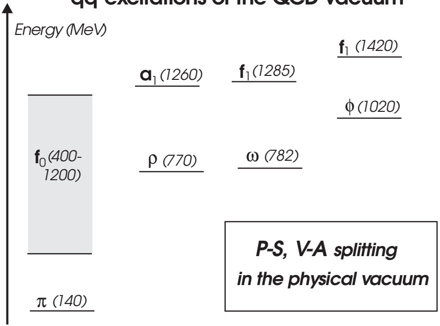
$$\mathscr{L}_{\text{QCD}} = -\frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a + \bar{\psi}(\mathrm{i}\not{D} - \hat{M})\psi$$

- particle content:
  - ψ: Quarks, including flavor- and color degrees of freedom, $\hat{M} = \text{diag}(m_u, m_d, m_s, \ldots) =$ current quark masses
  - A_μ^a: gluons, gauge bosons of $\text{SU}(3)_{\text{color}}$
- symmetries
  - fundamental building block: local $\text{SU}(3)_{\text{color}}$ symmetry
  - in light-quark sector: approximate chiral symmetry
  - chiral symmetry ⇒ connection between QCD and effective hadronic models

Phenomenology and Chiral symmetry

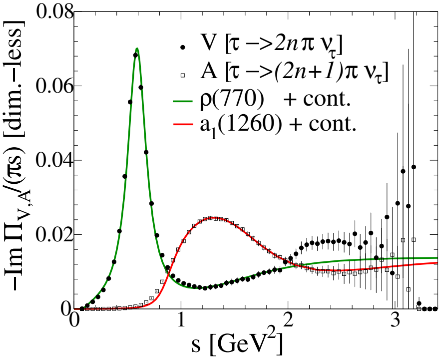
- in vacuum: Spontaneous breaking of chiral symmetry
- ⇒ mass splitting of chiral partners

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



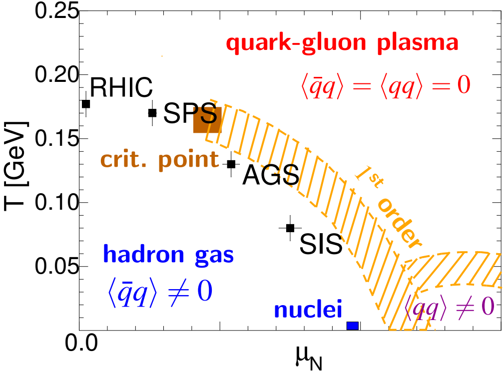
P-S, V-A splitting

in the physical vacuum



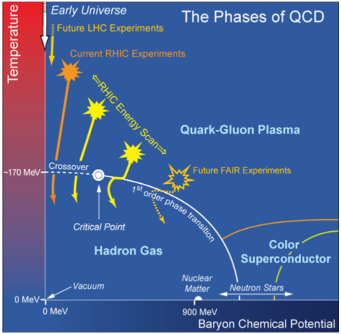
The QCD-phase diagram

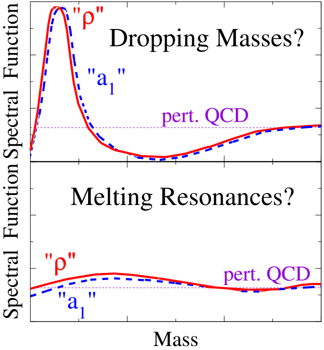
- hot and dense matter: quarks and gluons close together
- highly energetic collisions ⇒ "deconfinement"
- quarks and gluons relevant dof ⇒ quark-gluon plasma
- still strongly interacting ⇒ fast thermalization!



The QCD-phase diagram

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

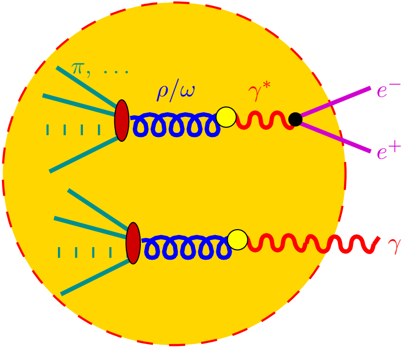




- mechanism of chiral restoration?
- two main theoretical ideas
  - “dropping masses”: $m_{\text{had}} \propto \langle \overline{\psi} \psi \rangle$
  - “melting resonances”: broadening of spectra through medium effects
  - More theoretical question: realization of chiral symmetry in nature?

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



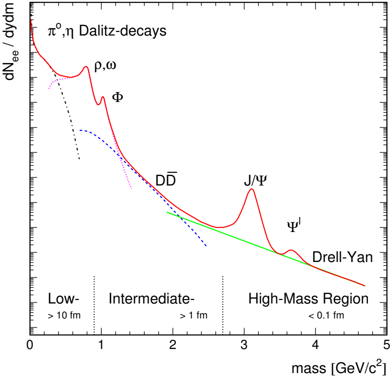


Fig. by A. Drees

Electromagnetic probes from thermal source

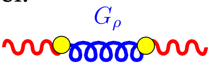
- photon and dilepton thermal emission rates given by same electromagnetic-current-correlation function ($J_\mu = \sum_f Q_f \overline{\psi_f} \gamma_\mu \psi_f$)
- McLerran-Toimela formula [MT85, GK91]

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

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

- 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

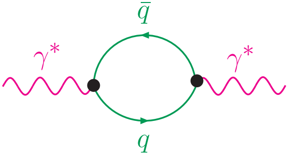
$$\frac{\mathrm{d}N^{(\mathrm{MT})}_{l^+l^-}}{\mathrm{d}^4x\,\mathrm{d}^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M^2)}{M^2} g_{\mu\nu} \mathrm{Im} \sum_i \Pi^{\mu\nu}_{\mathrm{em},i}(M,\vec{q}) f_B(q \cdot u)$$

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

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

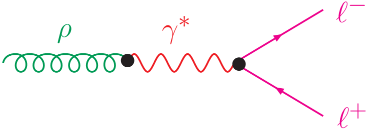
- in QGP phase: $q\bar{q}$ annihilation
- hard-thermal-loop improved em. current-current correlator

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



Radiation from thermal sources: ρ decays

- model assumption: vector-meson dominance

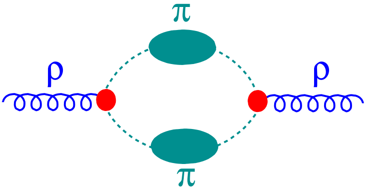


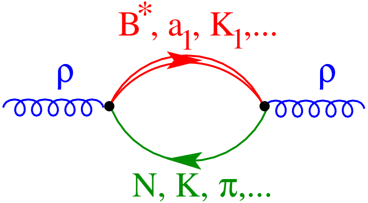
$$\frac{\mathrm{d}N^{(\mathrm{MT})}_{\rho\to l^+l^-}}{\mathrm{d}^4x\,\mathrm{d}^4q} = \frac{M}{q^0}\Gamma_{\rho\to l^+l^-}(M)\frac{\mathrm{d}N_\rho}{\mathrm{d}^3\vec{x}\,\mathrm{d}^4q}$$
$$= -\frac{\alpha^2}{3\pi^3}\frac{L(M^2)}{M^2}\frac{m_\rho^4}{g_\rho^2}g_{\mu\nu}\,\mathrm{Im}\,D_\rho^{\mu\nu}(M,\vec{q})f_B\left(\frac{q\cdot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

- 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 $T(t)$, $\mu_{\text{meson/baryon}}(t)$
- analogous for ω and ϕ

Hadronic many-body theory

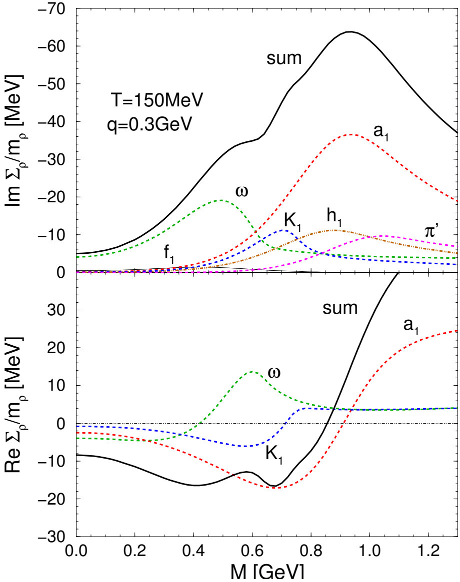
- hadronic many-body theory (HMBT) for vector mesons
  [Ko et al, Chanfray et al, Herrmann et al, Rapp et al, …]
- $\pi\pi$ interactions and baryonic excitations
- effective hadronic models, implementing symmetries
- parameters fixed from phenomenology
  (photon absorption at nucleons and nuclei, $\pi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





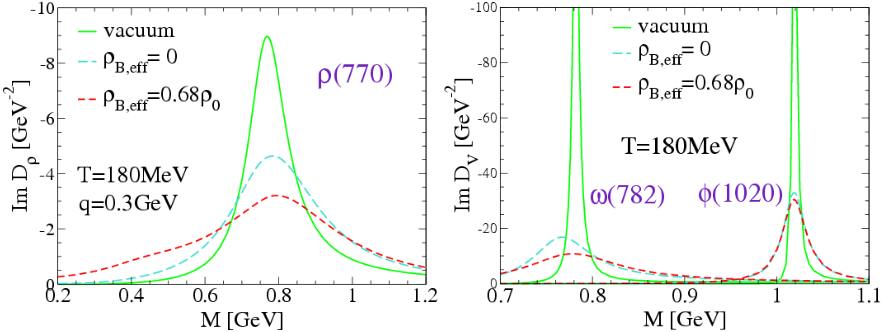
- Baryons important, even at low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

Meson contributions



[GR99]

In-medium spectral functions and baryon effects



[RW99]

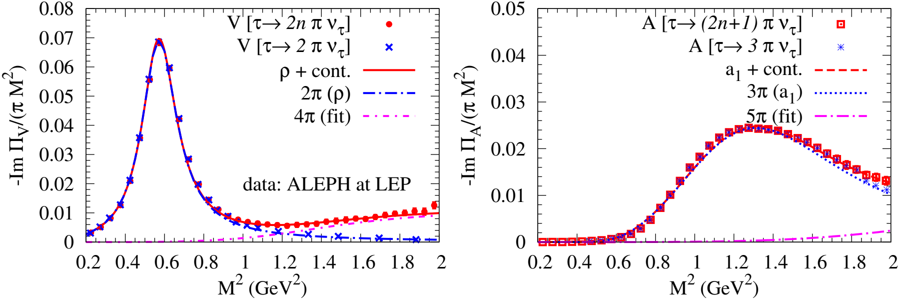
- baryon effects important
    - large contribution to broadening of the peak
    - responsible for most of the strength at small M

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: [R. Barate et al (ALEPH Collaboration) 98]

Non-thermal sources

- Drell-Yan: $q+\overline{q} \rightarrow \ell^+\ell^-$ in early hard collisions

$$\left.\frac{\mathrm{d}N_{\text{DY}}^{AA}}{\mathrm{d}M\,\mathrm{d}y}\right|_{b=0} = \frac{3}{4\pi R_0^2} A^{4/3} \frac{\mathrm{d}\sigma_{\text{DY}}^{NN}}{\mathrm{d}M\,\mathrm{d}y}$$

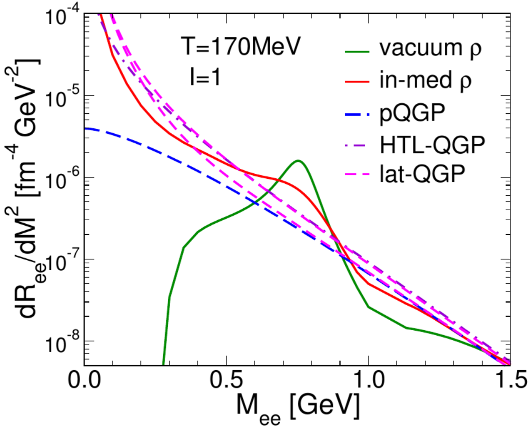
$$\frac{\mathrm{d}\sigma_{\text{DY}}^{NN}}{\mathrm{d}M\,\mathrm{d}y} = K\frac{8\pi\alpha}{9sM}\sum_{q=u,d,s} e_q^2\left[q(x_1)\bar{q}(x_2)+\bar{q}(x_1)q(x_2)\right]$$

  - parton distribution functions: GRV94LO
  - higher-order effects
    - K factor
    - non-zero pair q_T: for IMR and HMR fitted by Gaussian spectrum (NA50 procedure)
  - extrapolation to LMR: constrained by photon point $M \rightarrow 0$
- ρ decays after thermal freeze-out: Cooper-Frye formula

$$\frac{\mathrm{d}N_{\rho\rightarrow l^+l^-}^{(\text{fo})}}{\mathrm{d}^3\vec{x}\,\mathrm{d}^4q} = \frac{\Gamma_{l^+l^-}}{\Gamma_\rho^{\text{tot}}}\frac{\mathrm{d}N_i}{\mathrm{d}^3\vec{x}\,\mathrm{d}q} = \frac{q_0}{M}\frac{1}{\Gamma_\rho^{\text{tot}}}\left[\frac{\mathrm{d}N_{\rho\rightarrow l^+l^-}^{(\text{MT})}}{\mathrm{d}^4x\,\mathrm{d}^4q}\right]_{t=t_{\text{fo}}}$$

Dilepton rates: Hadron gas ⟷ 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 ⇒ 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

Coarse-grained UrQMD (CGUrQMD)

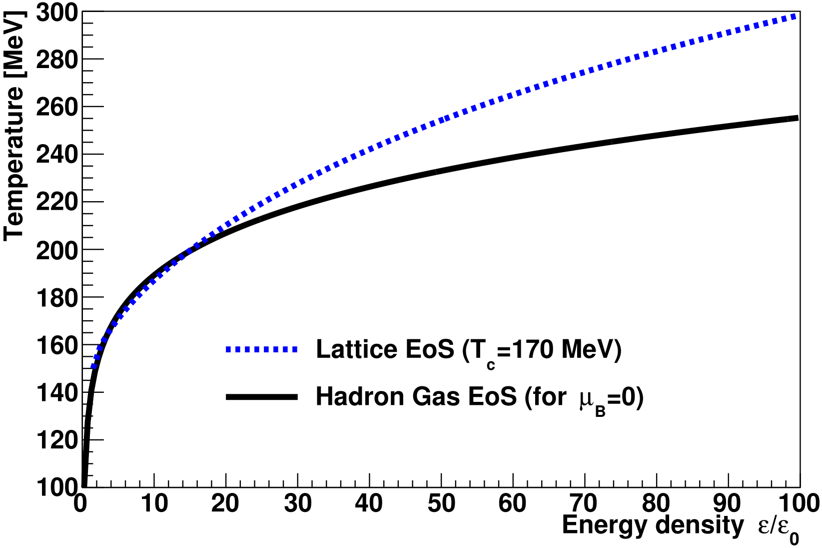
- problem with medium modifications of spectral functions/interactions
- only available in equilibrium many-body QFT models
- use “in-medium cross sections” naively: double counting?!?
- way out: map transport to local-equilibrium fluid
- use ensemble of UrQMD runs with an equation of state
- fit temperature,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

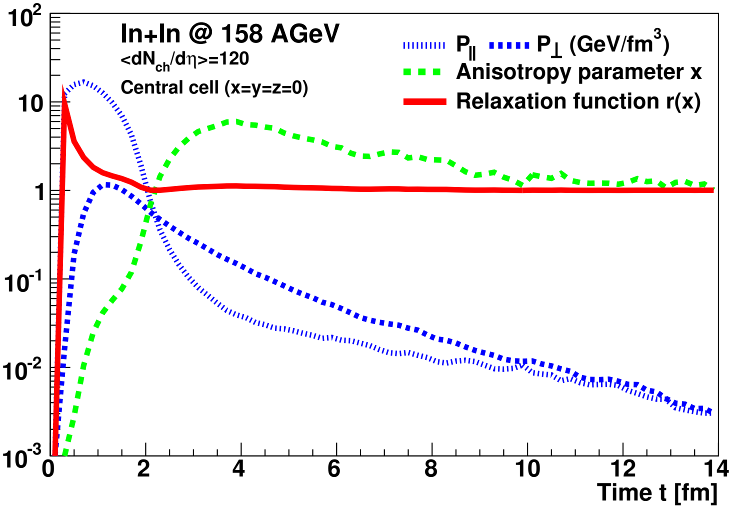
Coarse-grained UrQMD (CGUrQMD)

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



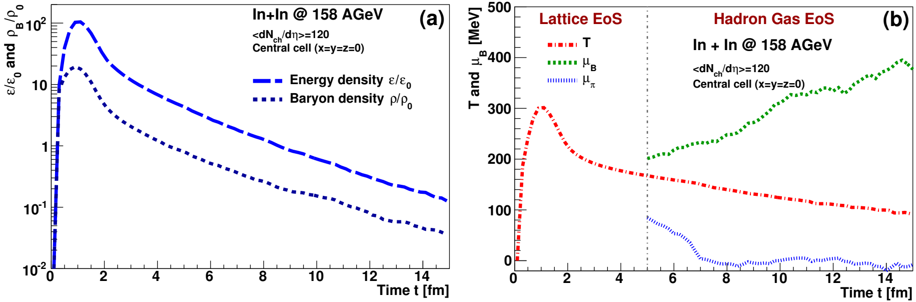
Coarse-grained UrQMD (CGUrQMD)

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



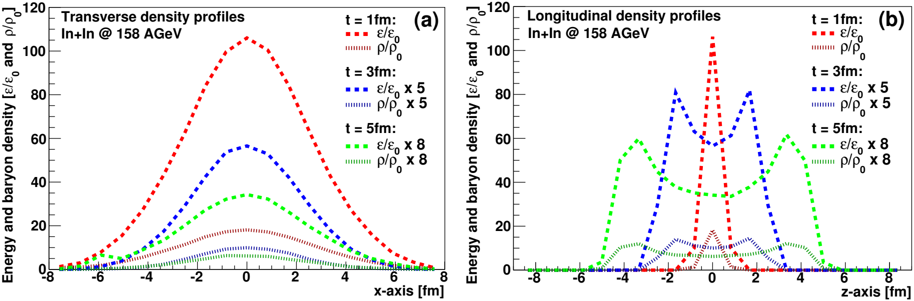
Coarse-grained UrQMD (CGUrQMD)

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



Coarse-grained UrQMD (CGUrQMD)

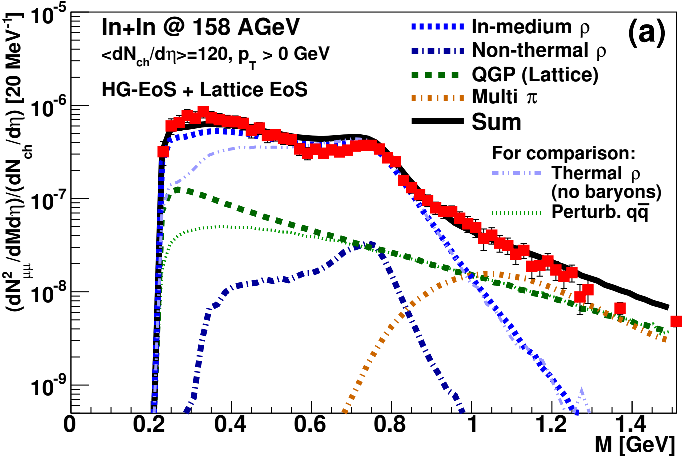
- energy (ϵ) and baryon (ρ) density profiles (for In+In@SPS; NA60)



Dimuons (SPS/NA60)

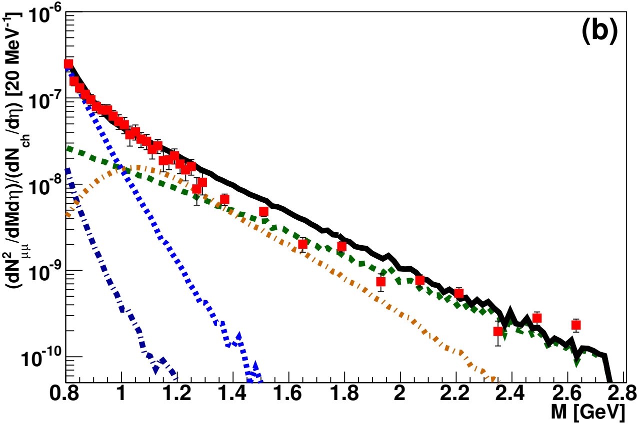
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



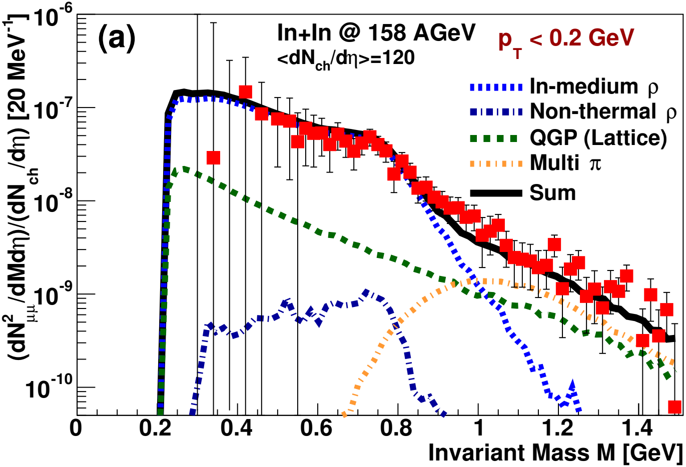
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

- dimuon spectra from In + In(158 *A*GeV) $\rightarrow \mu^+\mu^-$ (NA60)
- 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!)



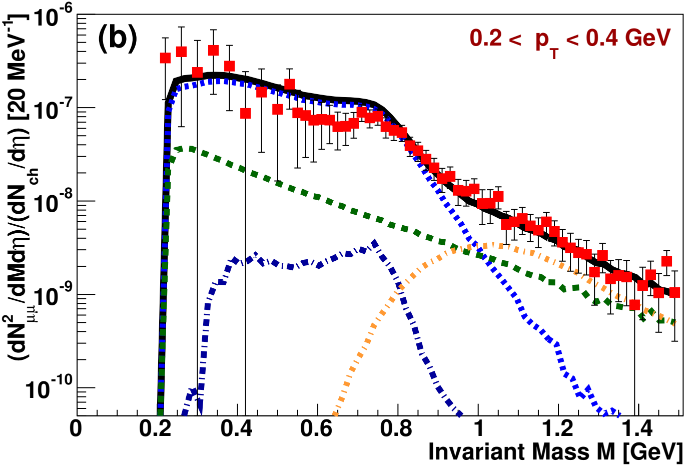
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



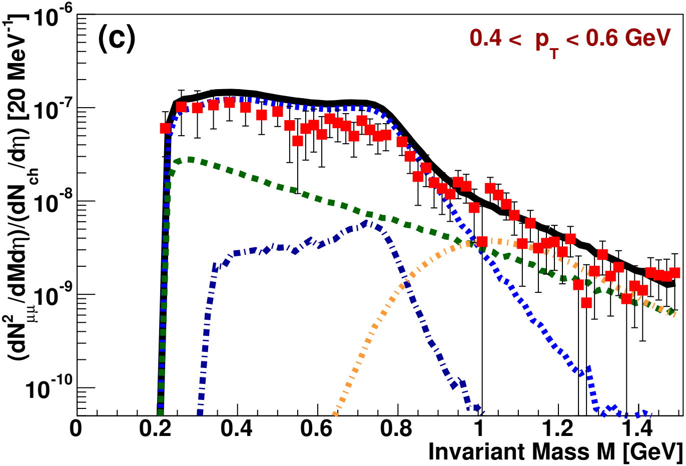
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



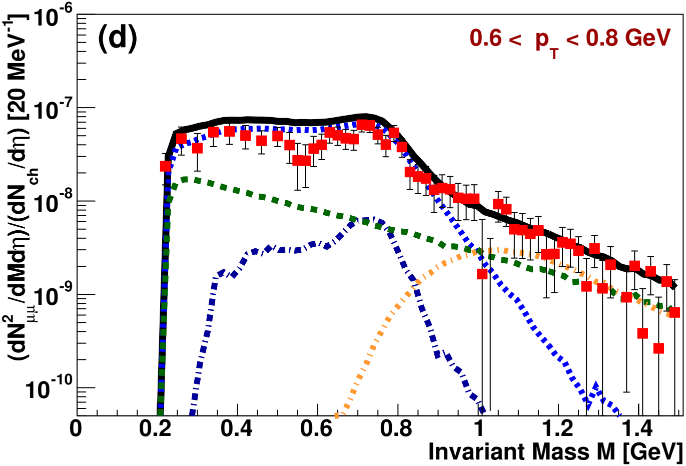
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



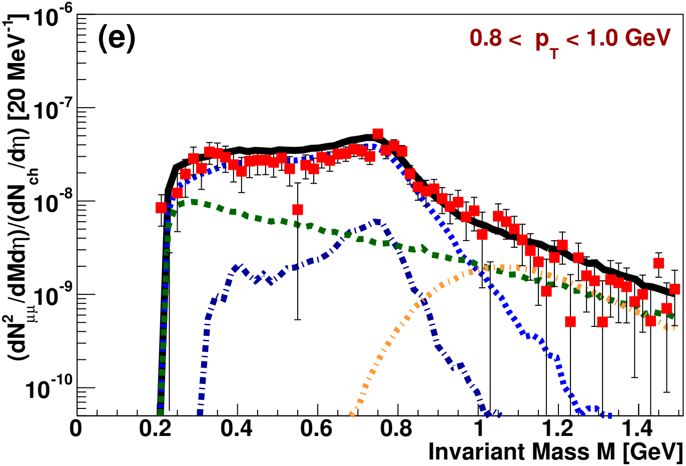
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



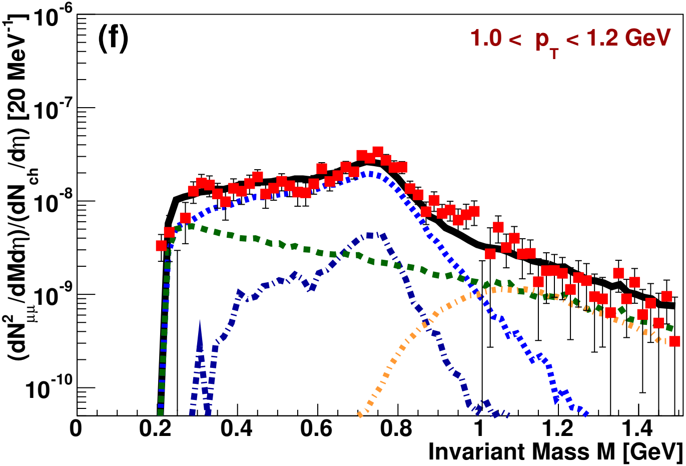
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



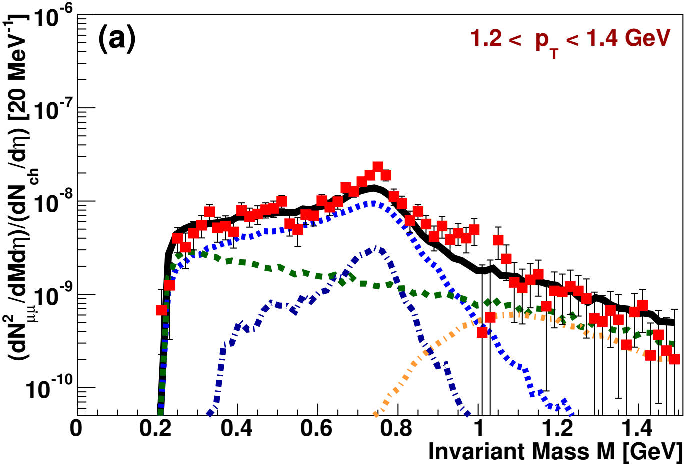
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



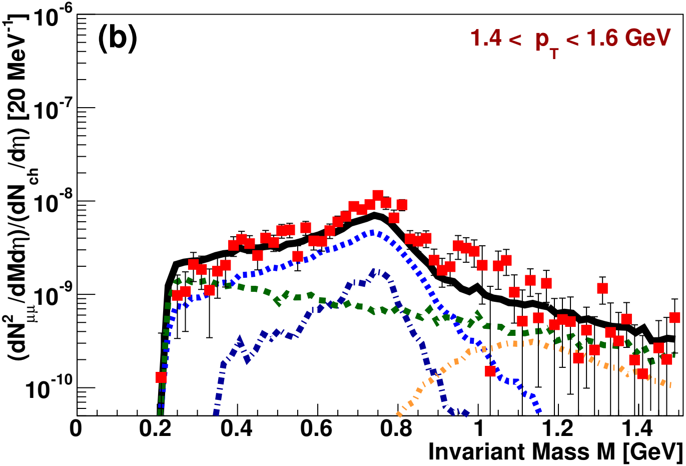
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



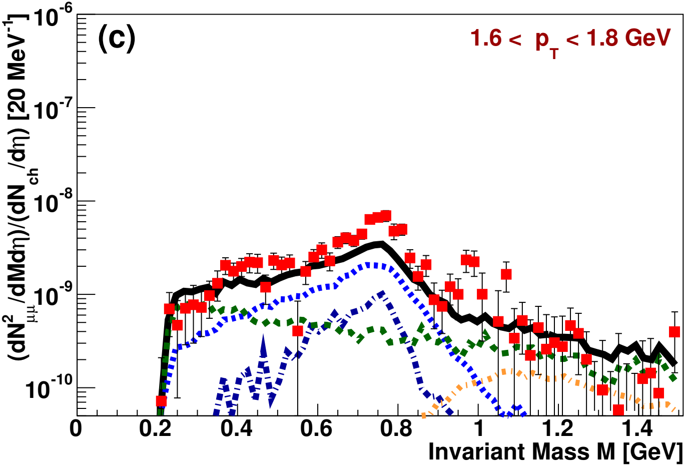
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



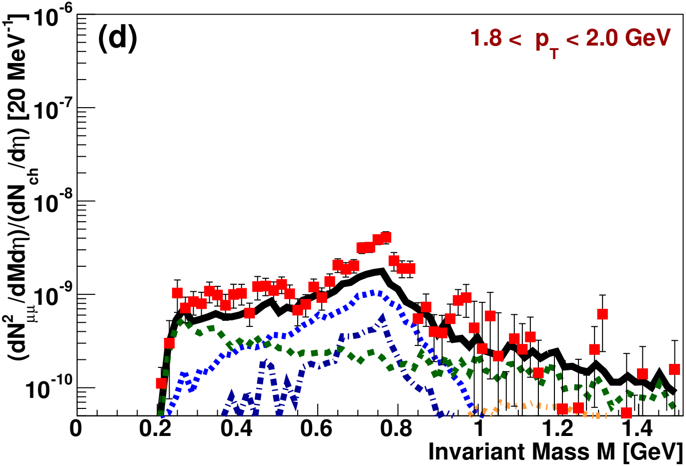
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



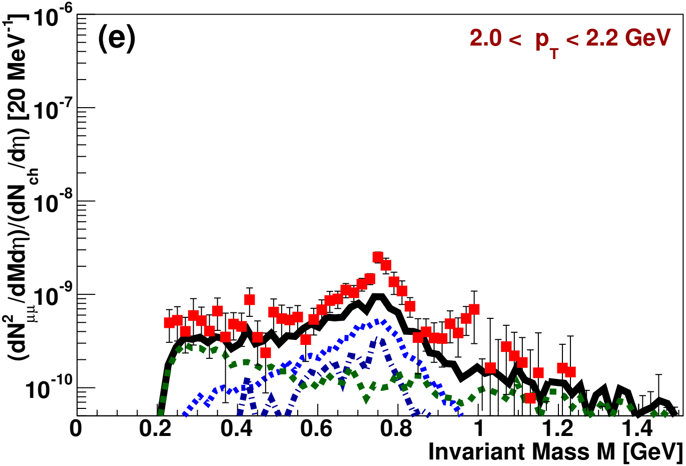
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



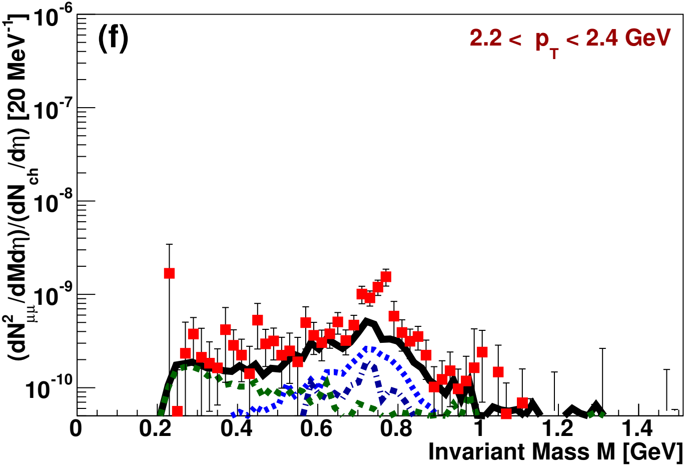
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



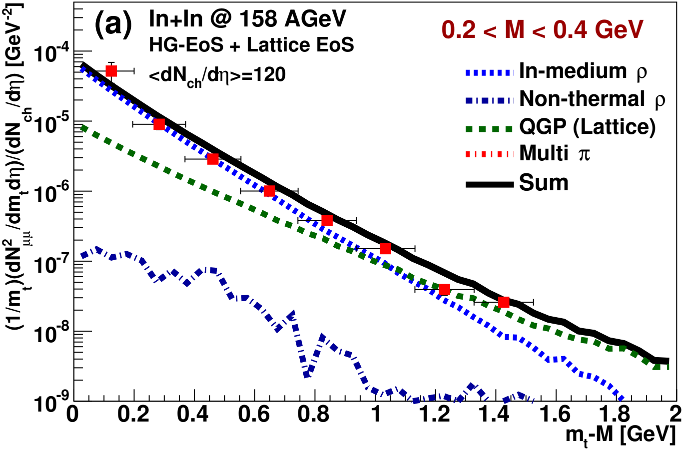
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



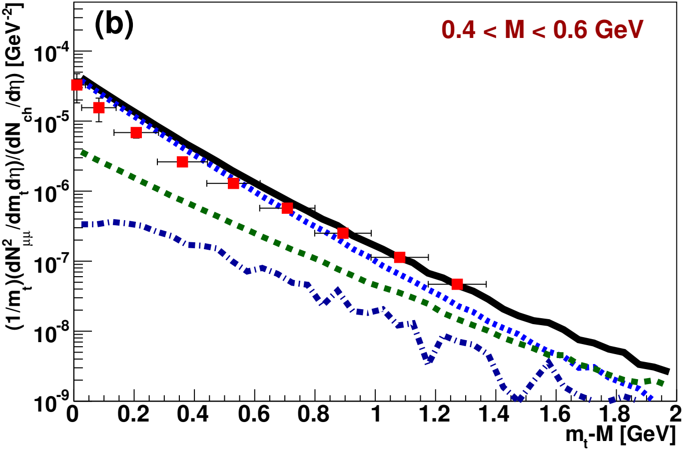
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



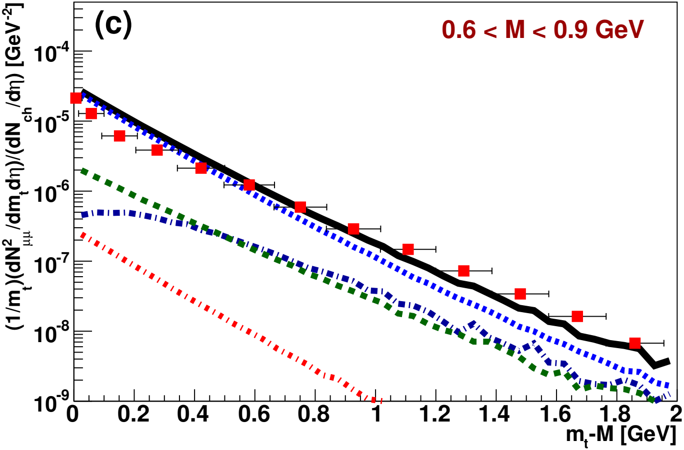
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



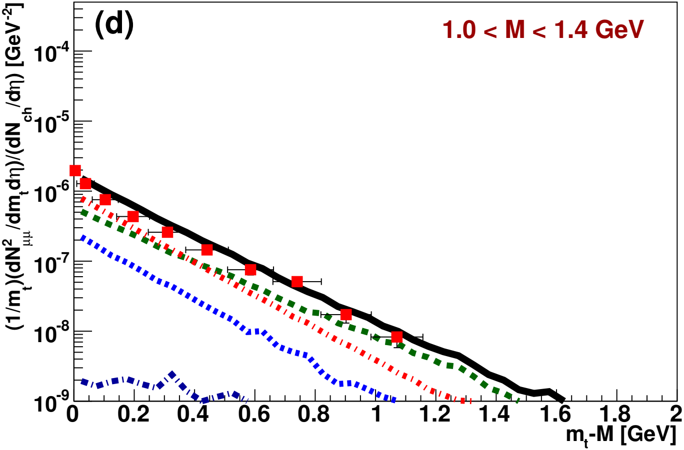
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



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

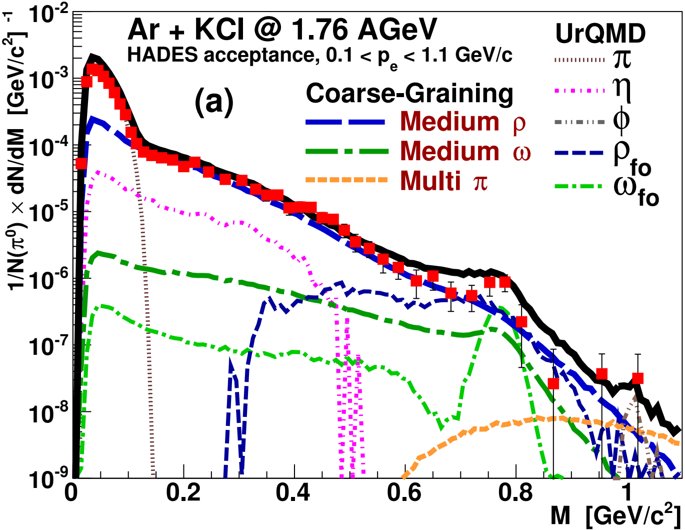
- dimuon spectra from $\text{In}+\text{In}(158\,A\text{GeV}) \rightarrow \mu^+\mu^-$ (NA60)
- min-bias data $(\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120)$



Dielectrons (SIS/HADES)

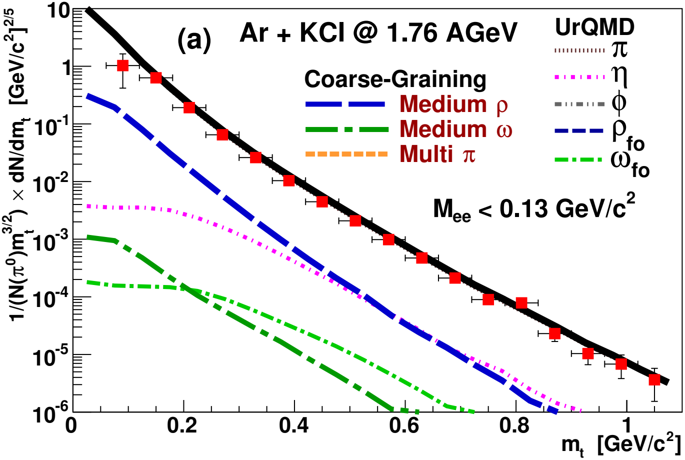
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



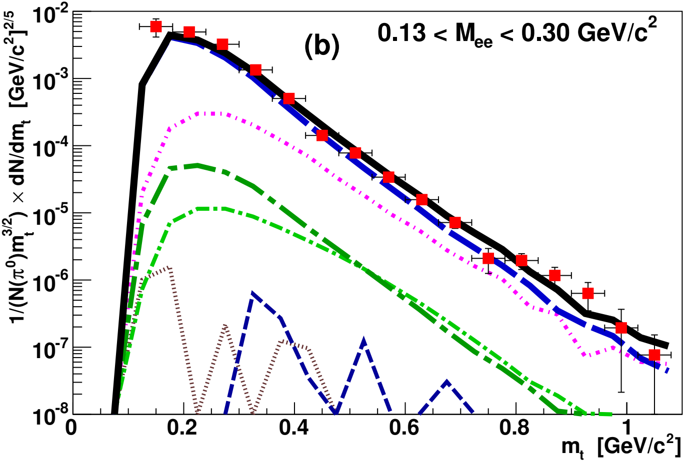
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



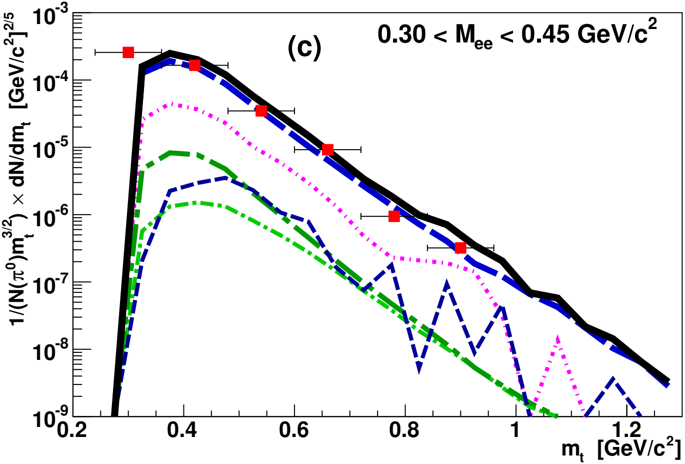
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



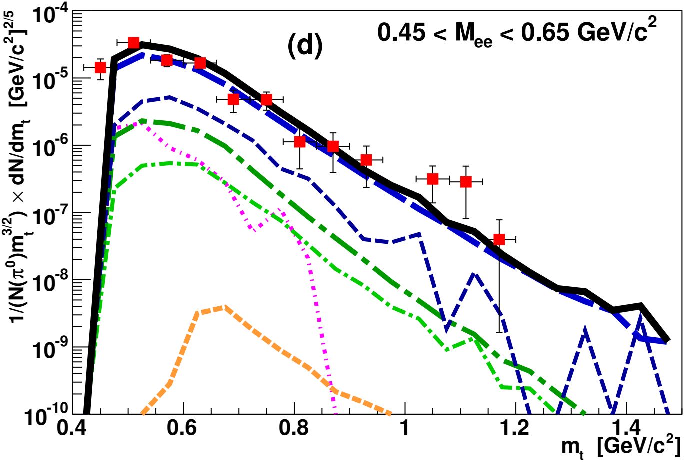
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



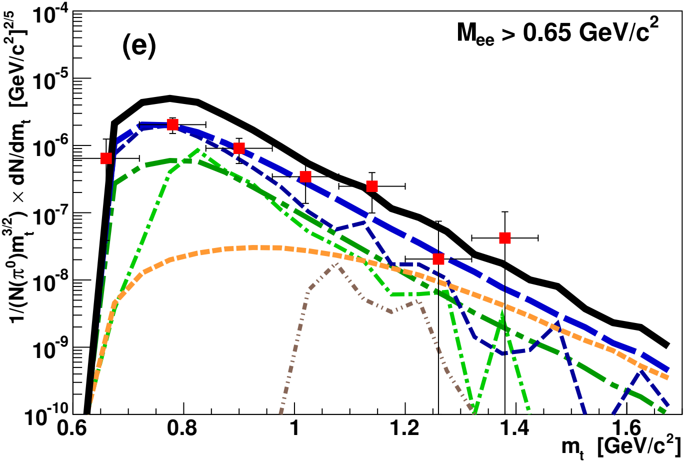
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



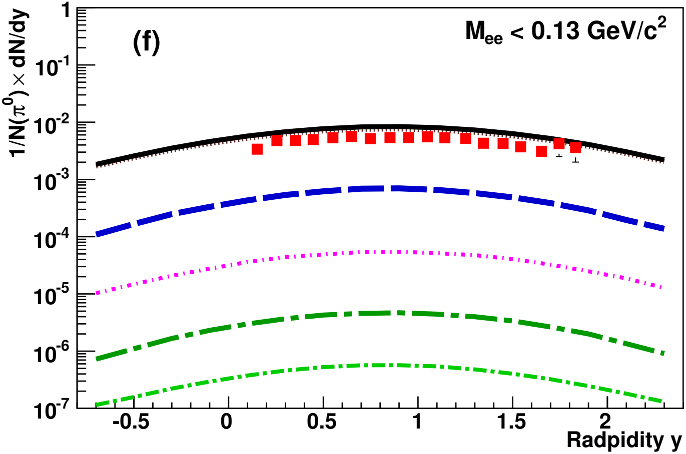
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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

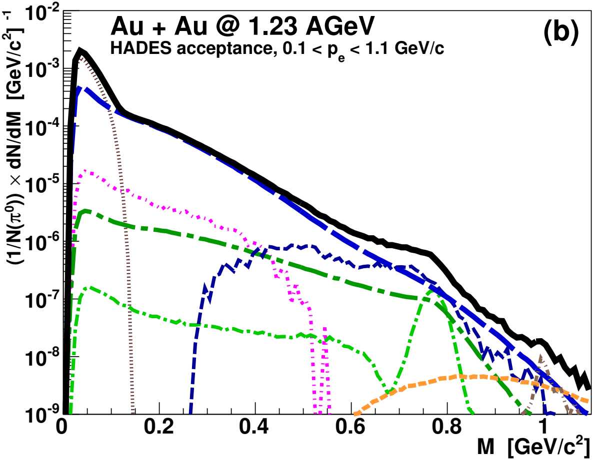


CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



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



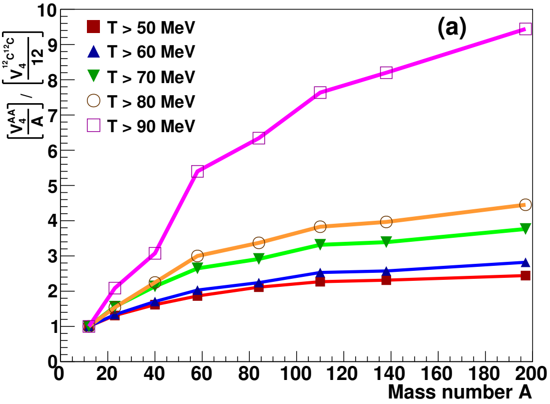
- caveat: pp/np acceptance filter with single-e cut, $p_t < 100$ MeV
- correct filter urgently needed!
- excellent agreement with preliminary HADES data (data points not shown here on request of the HADES collaboration)

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

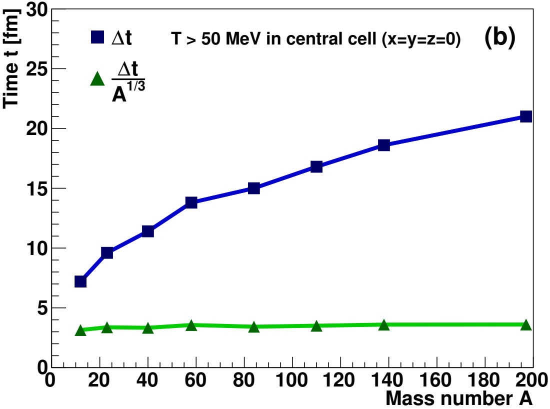
- $\frac{V_{AA}^{(4)}/A}{V_{\mathrm{CC}}^{(4)}/12}$ of cells larger than various T



- how to explain “scaling behavior”?

Lifetime of the central cell

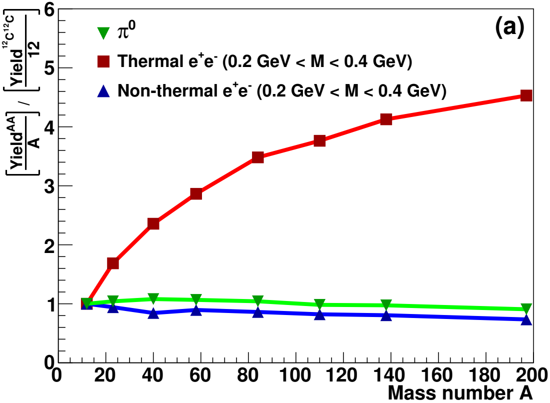
- consider central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76\,A\text{GeV}$



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

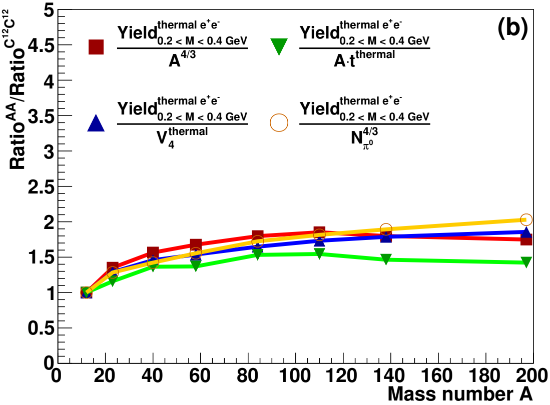
Lifetime of the central cell

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



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

Scaling behavior of thermal-dilepton yield



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

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!)

Conclusions and Outlook

- General ideas
  - em. probes ⇔ 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 at SIS, SPS energies
  - consistent description of M and m_T spectra!
  - effective slope of M spectra in higher IMR ($1.5\,\text{GeV} < M < M_{J/\psi}$) provides $\langle T \rangle$
- Outlook
  - check at available RHIC data
  - beam-energy scan at RHIC and FAIR ⇒ signature of phase transition?
  - signature of cross-over vs. 1st order (or even critical endpoint)???
- for details see [BESH15, EHWB13, EHB13, EHWB15a, EHWB14, EHWB15b, HWEB15, WEH$^+$14a, WEH$^+$14b]

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