Dileptons with a coarse-grained transport approach

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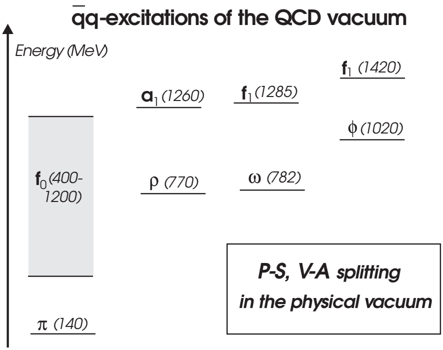
Outline

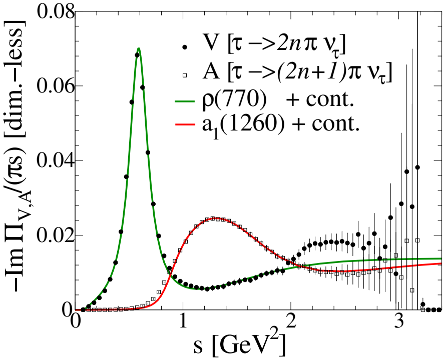
1. Electromagnetic probes
   - Chiral symmetry and QCD phase diagram
   - Electromagnetic radiation from hot/dense QCD matter
   - Hadronic many-body theory
2. Bulk-medium evolution with transport and coarse graining
   - coarse-graining in transport models
3. Dileptons in heavy-ion collisions
   - Dielectrons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

Electromagnetic probes
theory perspective

Hadron phenomenology and chiral symmetry

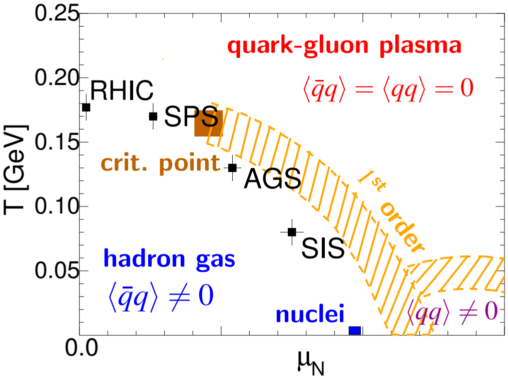
- in vacuum: Spontaneous breaking of chiral symmetry
- ⇒ mass splitting of chiral partners





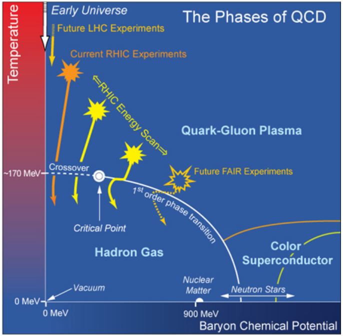
The QCD-phase diagram

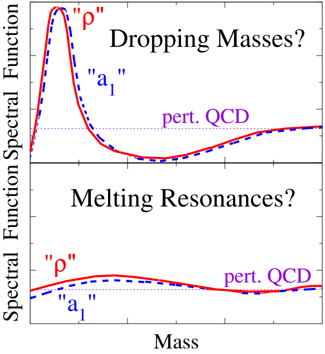
- hot and dense matter: quarks and gluons close together
- highly energetic collisions ⇒ "deconfinement"
- quarks and gluons relevant dof ⇒ quark-gluon plasma
- still strongly interacting ⇒ fast thermalization!



The QCD-phase diagram

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

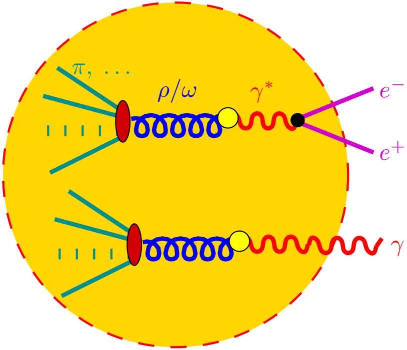




- mechanism of chiral restoration?
- two main theoretical ideas
  - "dropping masses": $m_{\text{had}} \propto \langle \overline{\psi} \psi \rangle$
  - "melting resonances": broadening of spectra through medium effects
  - More theoretical question: realization of chiral symmetry in nature?

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



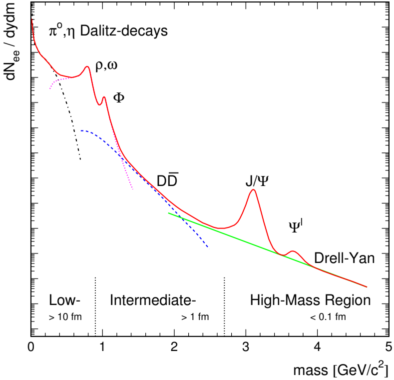


Fig. by A. Drees

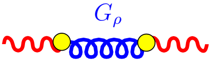
Electromagnetic probes from thermal source

- 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]

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

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

- 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

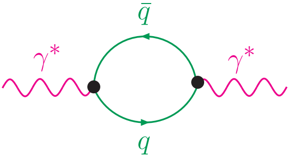
$$\frac{\mathrm{d}N^{(\mathrm{MT})}_{l^+l^-}}{\mathrm{d}^4x\,\mathrm{d}^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M^2)}{M^2} g_{\mu\nu} \mathrm{Im} \sum_i \Pi^{\mu\nu}_{\mathrm{em},i}(M,\vec{q}) f_B(q\cdot u)$$

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

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

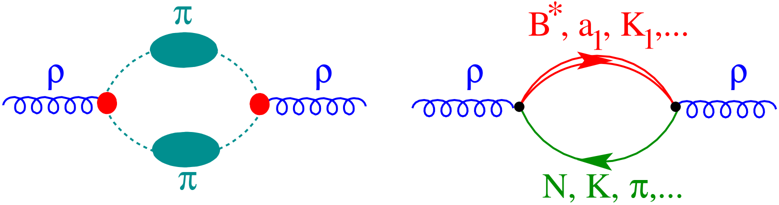
- in QGP phase: $q\bar{q}$ annihilation
- hard-thermal-loop improved em. current-current correlator

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



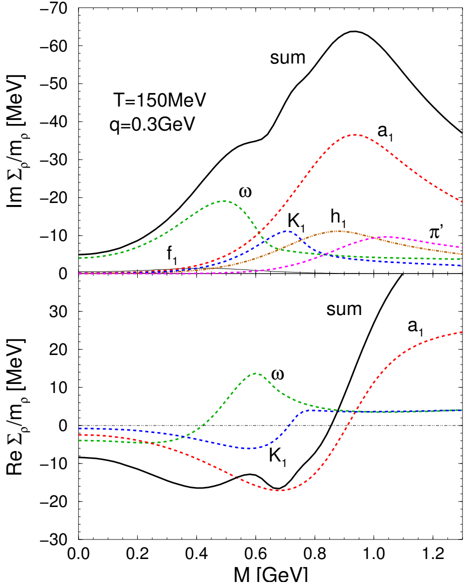
Hadronic many-body theory

- 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 ⇒ mass shift and broadening in the medium



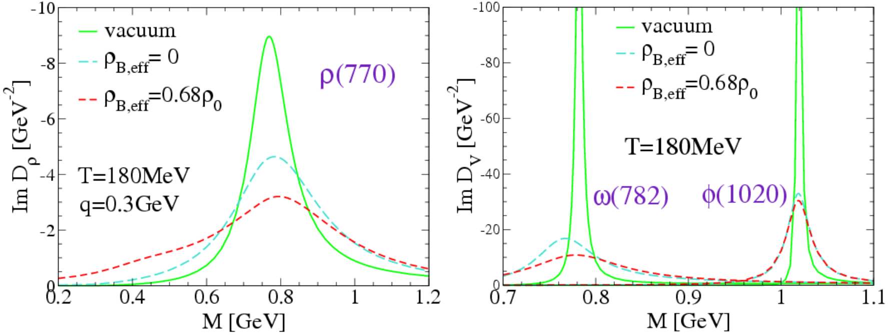
- Baryons important, even at low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

Meson contributions



[GR99]

In-medium spectral functions and baryon effects

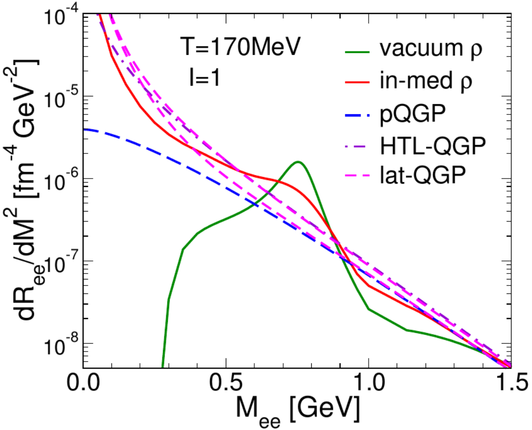


[RW99]

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

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 ⇒ 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)

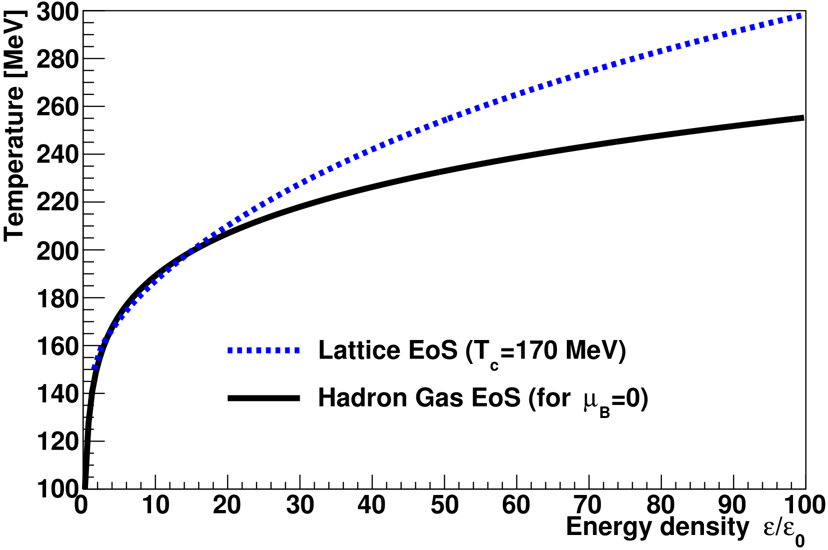
- problem with medium modifications of spectral functions/interactions
- only available in equilibrium many-body QFT models
- use "in-medium cross sections" naively: double counting?!?
- way out: map transport to local-equilibrium fluid
- use ensemble of UrQMD runs with an equation of state
- space-time 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!

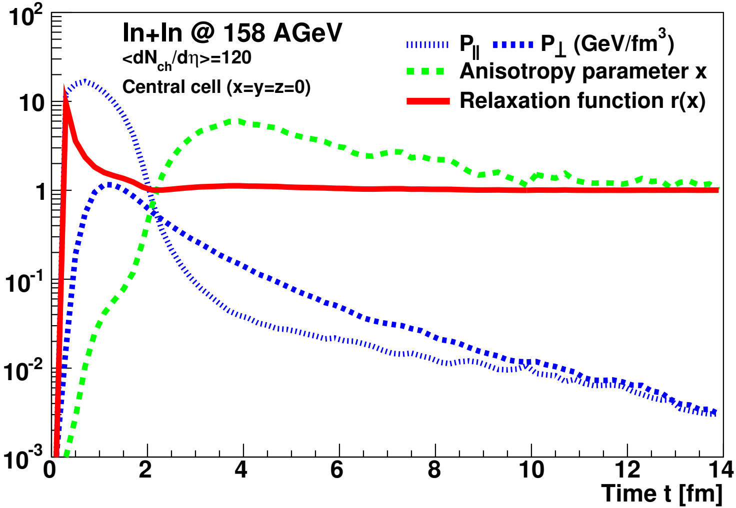
Coarse-grained UrQMD (CGUrQMD)

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



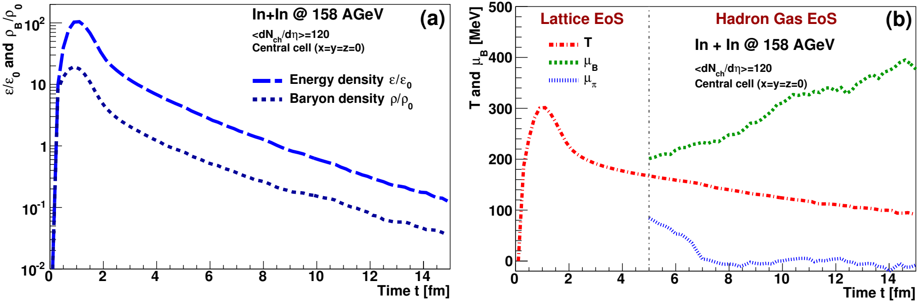
Coarse-grained UrQMD (CGUrQMD)

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



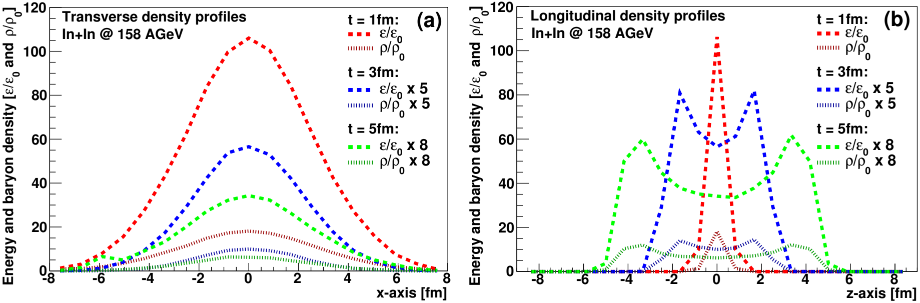
Coarse-grained UrQMD (CGUrQMD)

- energy/baryon density $\Rightarrow T, \mu_B$ (for In+In @ SPS; NA60)
- central “fluid” cell!



Coarse-grained UrQMD (CGUrQMD)

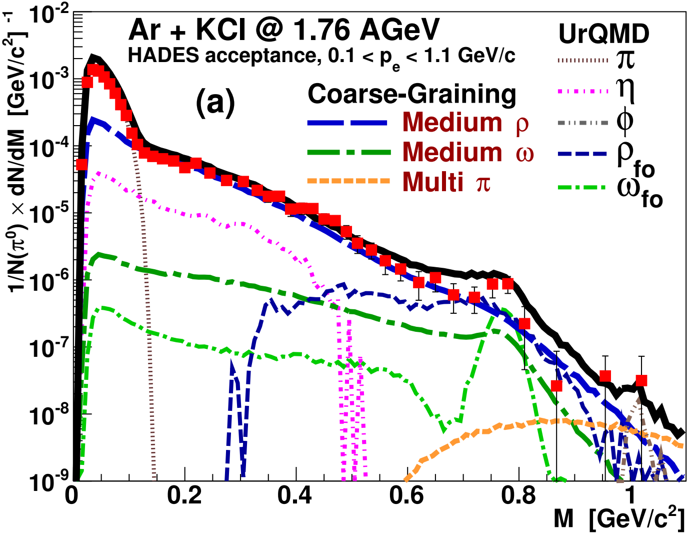
- energy (ϵ) and baryon (ρ) density profiles (for In+In@SPS; NA60)



Dielectrons (SIS/HADES)

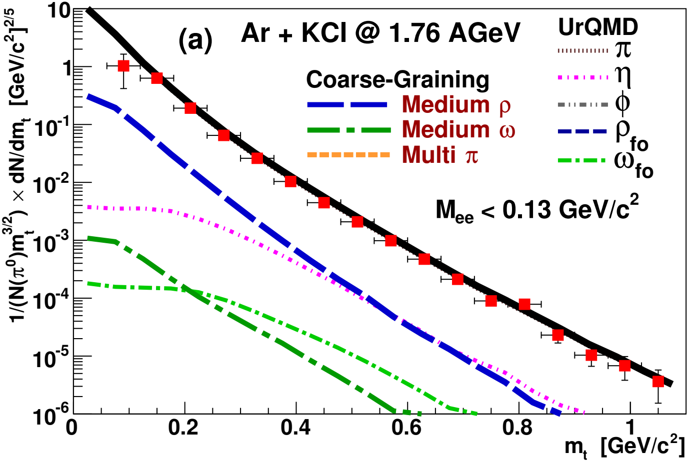
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



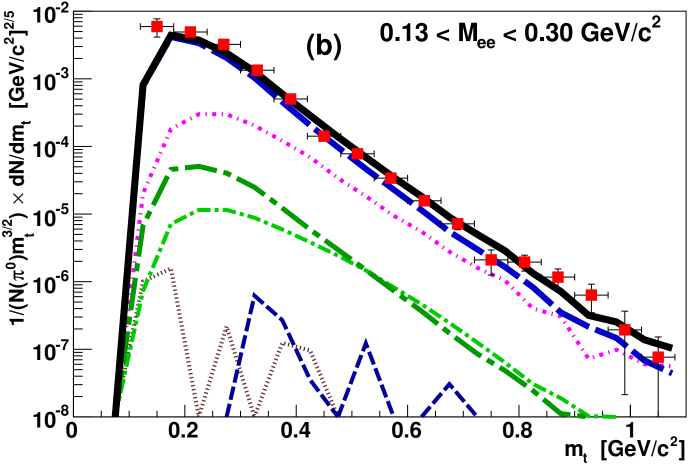
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



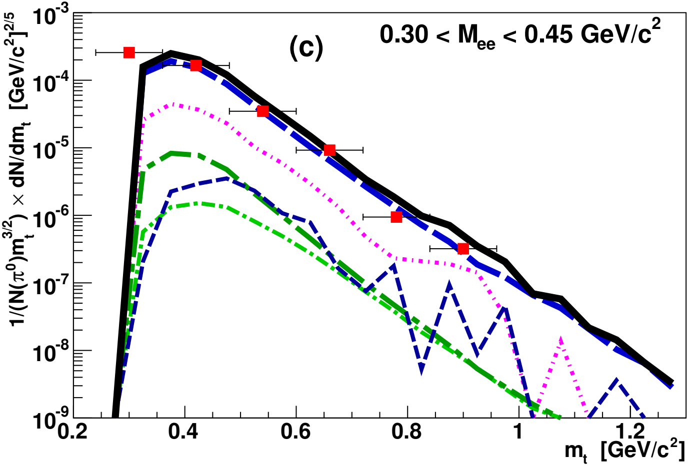
CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

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

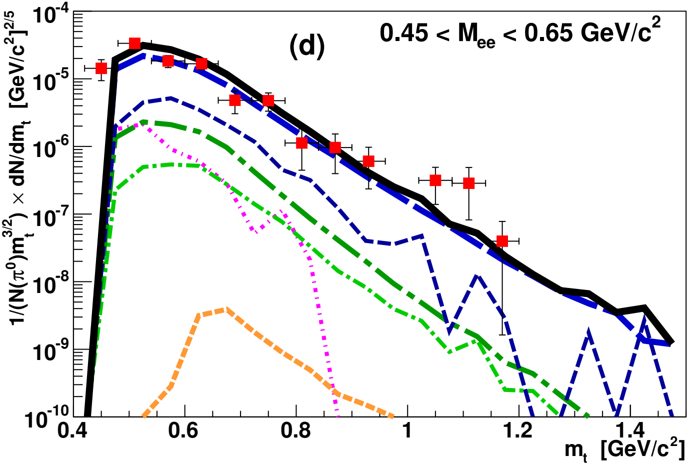


CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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

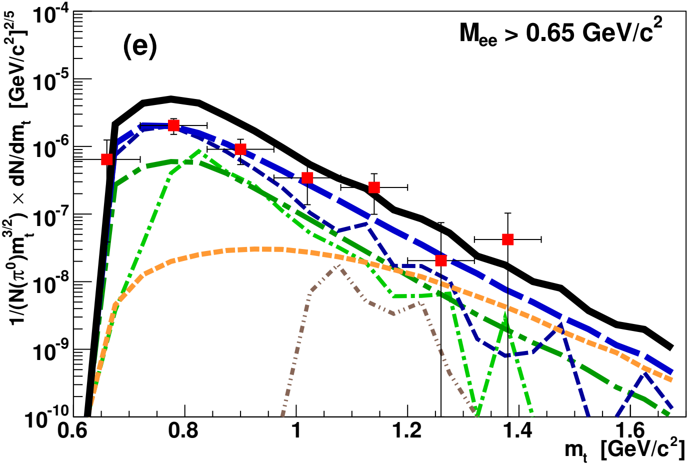


- dielectron spectra from $\mathrm{Ar}+\mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow \mathrm{e}^+\mathrm{e}^-$ (SIS/HADES)
- m_t spectra
- $0.45\,\mathrm{GeV} M_{\mathrm{ee}} < 0.65\,\mathrm{GeV}$



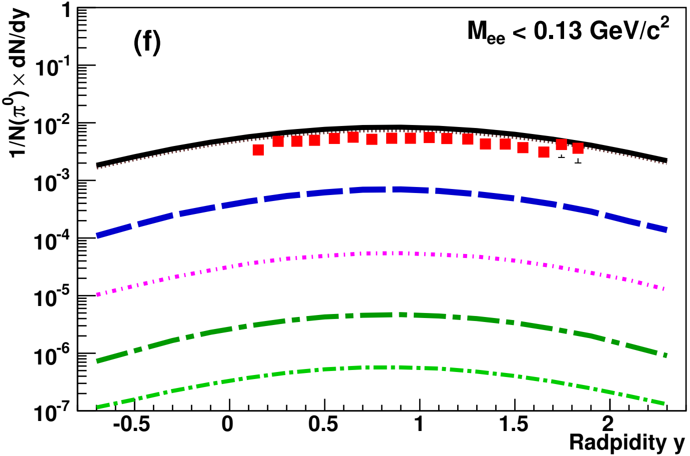
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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

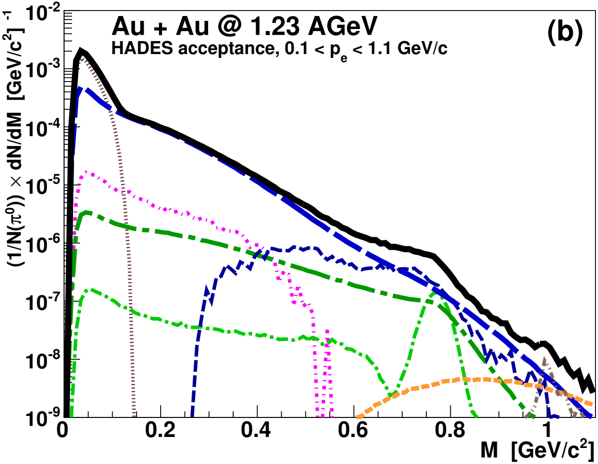


CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



CGUrQMD: Au+Au (1.23 AGeV) (SIS/HADES)

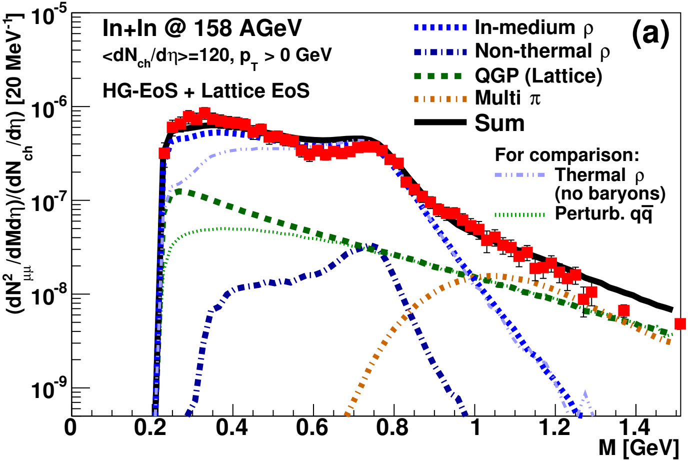


- caveat: pp/np acceptance filter with single-e cut, $p_t < 100$ MeV
- correct filter urgently needed!
- excellent agreement with preliminary HADES data

Dimuons (SPS/NA60)

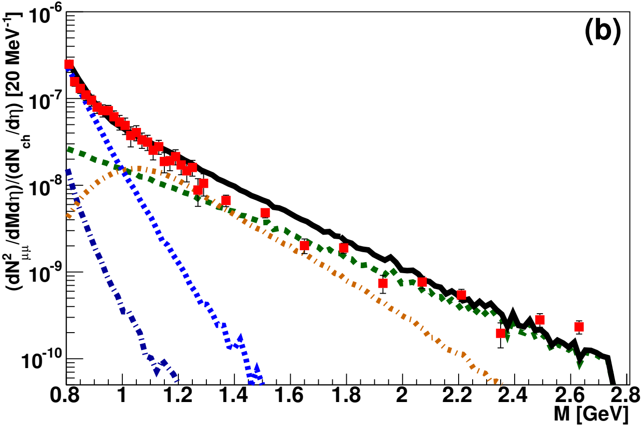
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



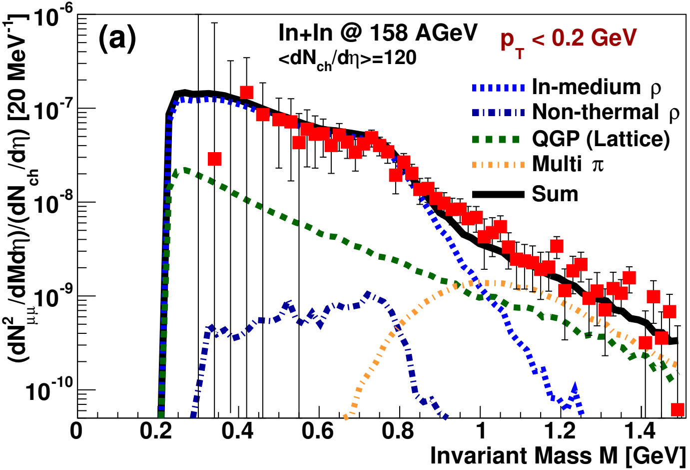
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\text{In}+\text{In}(158\,A\text{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120$)
- higher IMR: provides averaged true temperature
  $\langle T \rangle_{1.5\,\text{GeV} \lesssim M \lesssim 2.4\,\text{GeV}} = 205\text{-}230\,\text{MeV}$
- clearly above $T_c \simeq 150\text{-}160\,\text{MeV}$
  (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) [EHWB15]
- min-bias data ($\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120$)
- $p_T < 0.2\,\text{GeV}$



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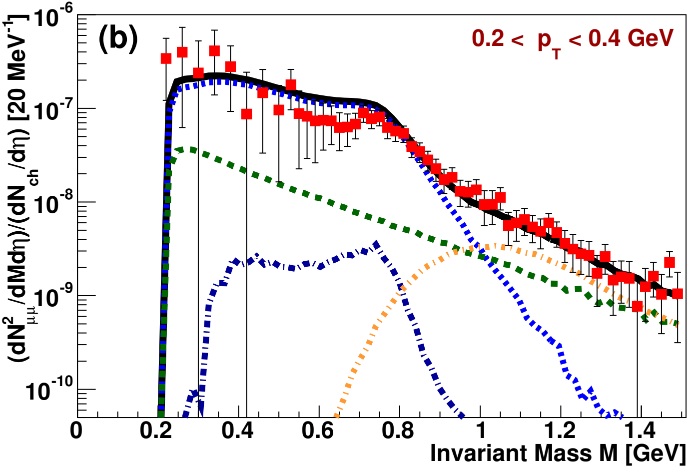
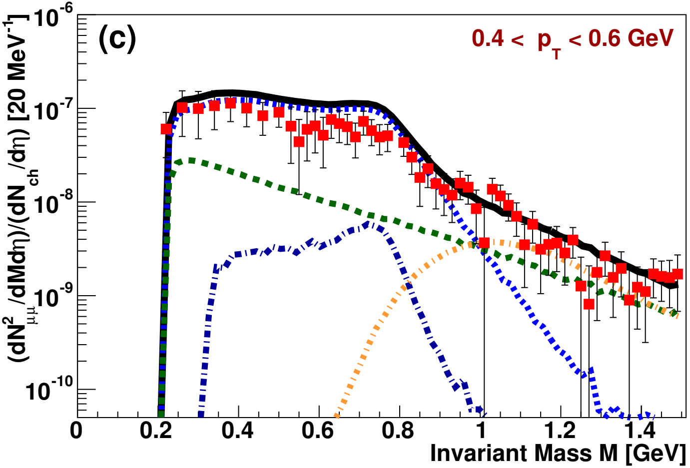
- min-bias data ($\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120$)
- $0.2\text{ GeV} < p_T < 0.4\text{ GeV}$



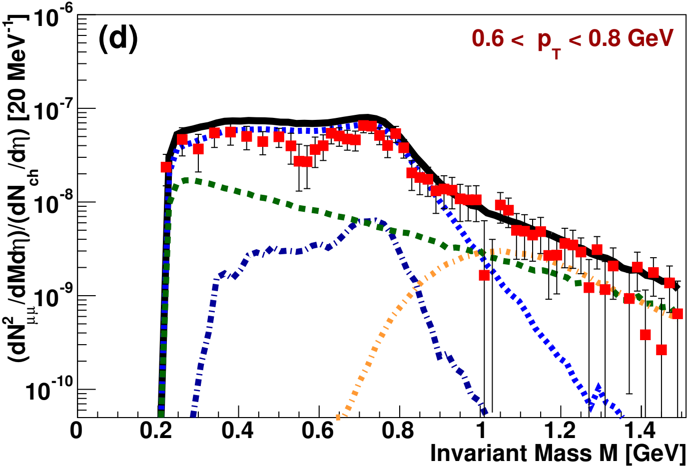
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



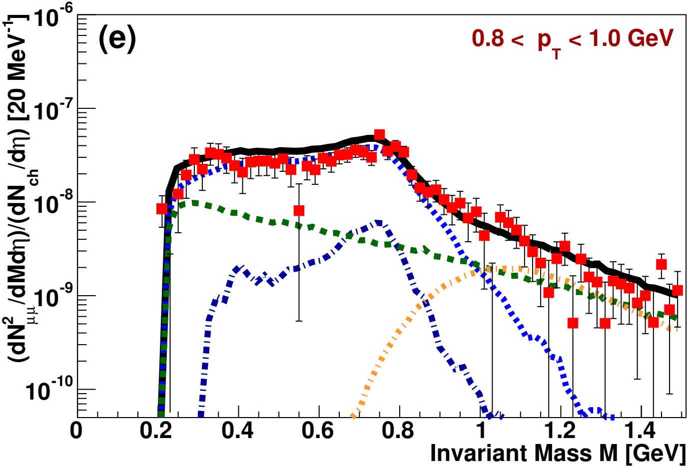
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



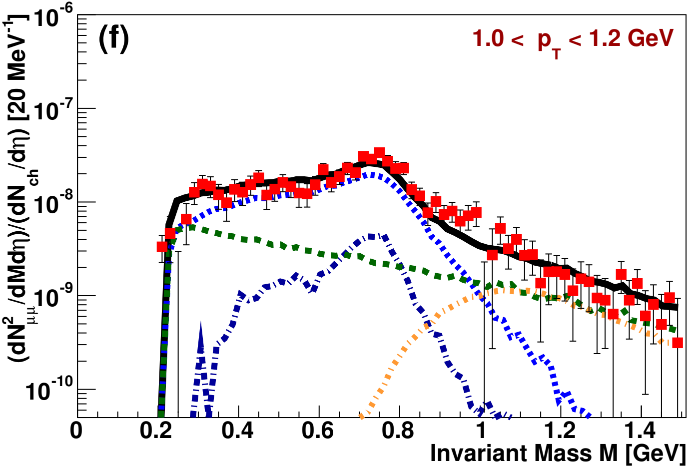
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



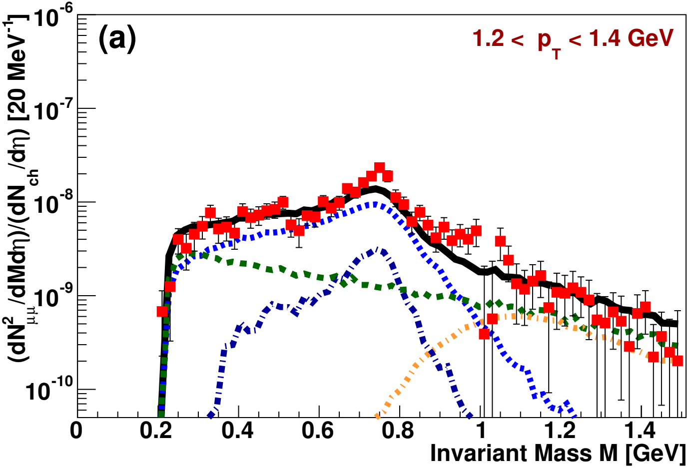
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



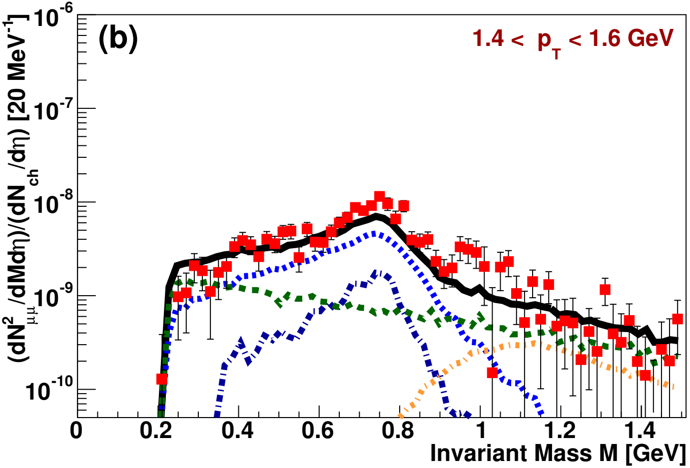
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



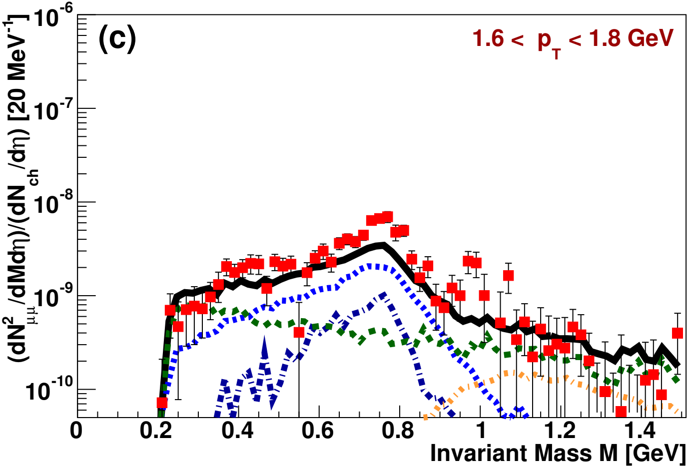
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



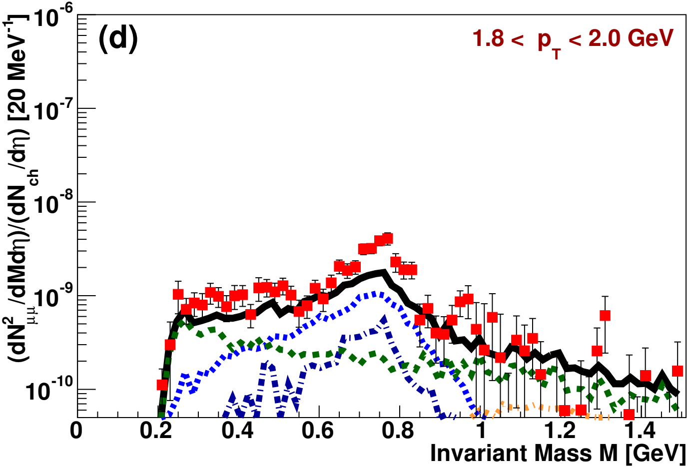
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



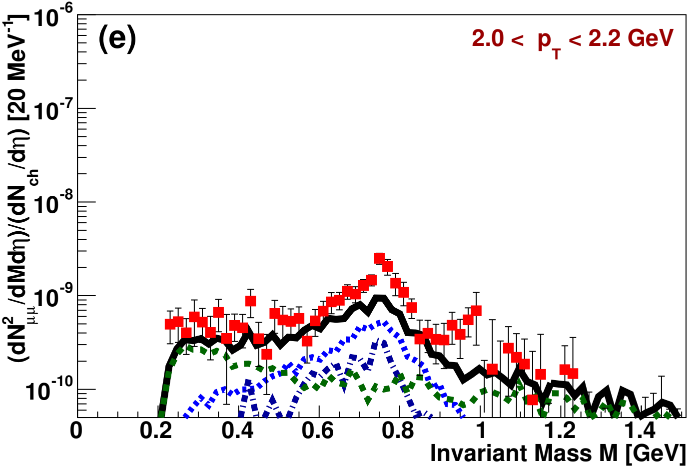
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



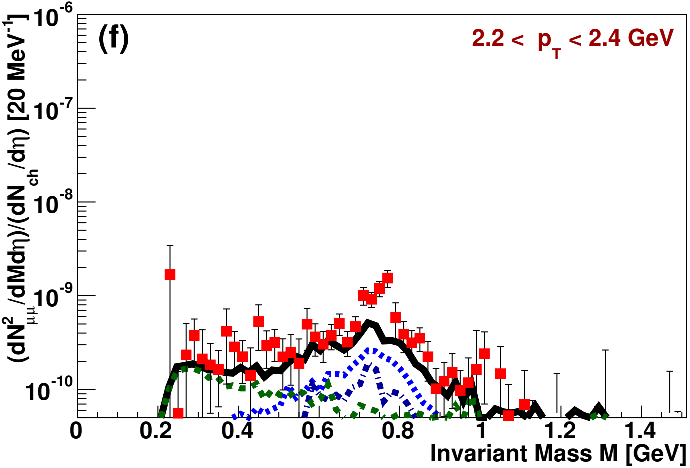
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



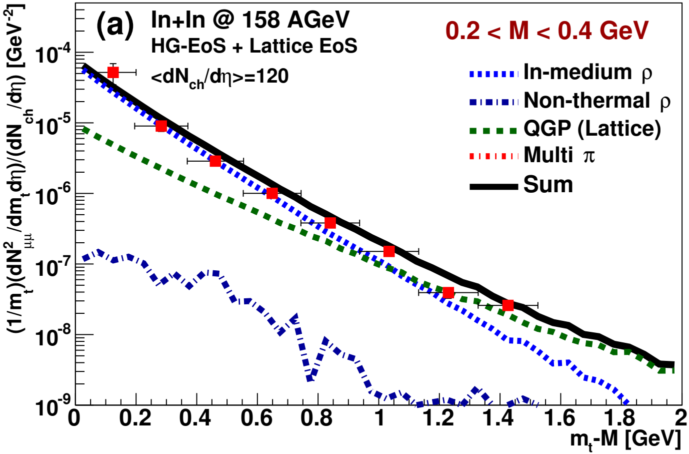
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



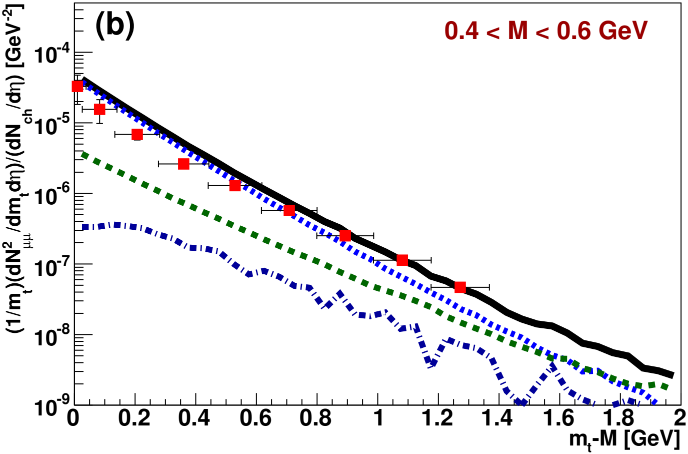
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



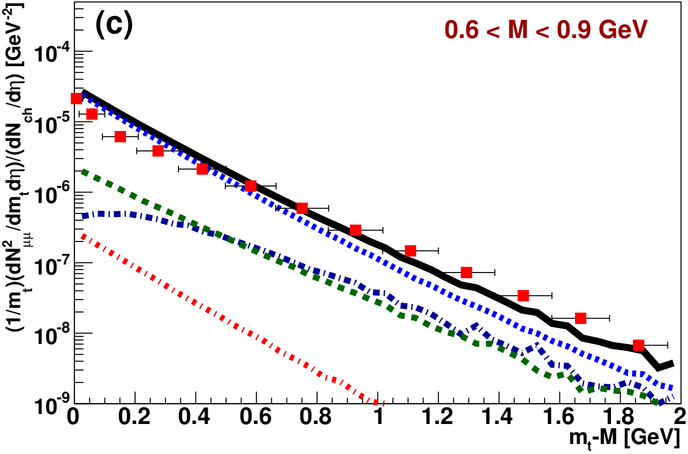
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



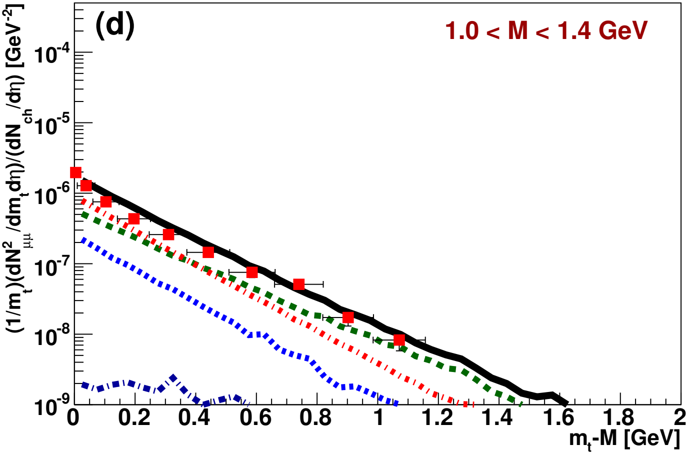
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



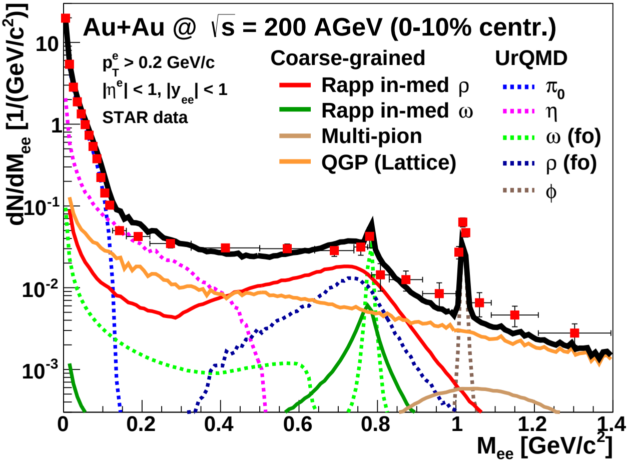
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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

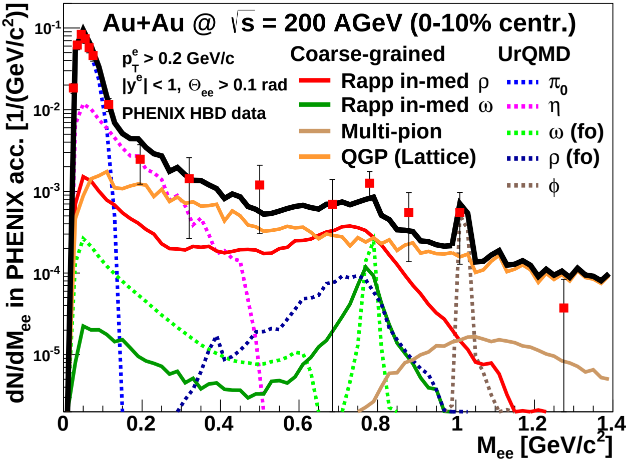


Dielectrons at RHIC

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

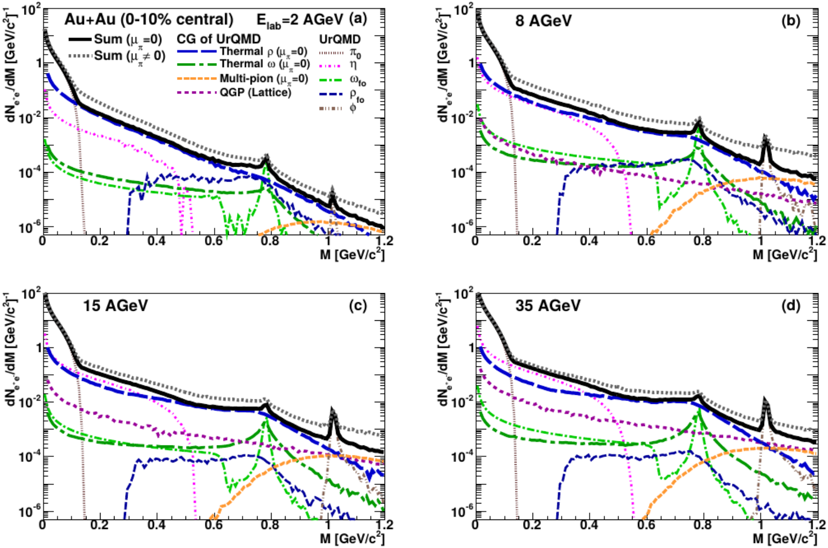


CGUrQMD: Au+Au ($\sqrt{s_{NN}} = 200\,\mathrm{GeV}$) (RHIC/PHENIX)



Dielectrons at RHIC-BES/FAIR/NICA

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



NB: also photon spectra [EHB16]

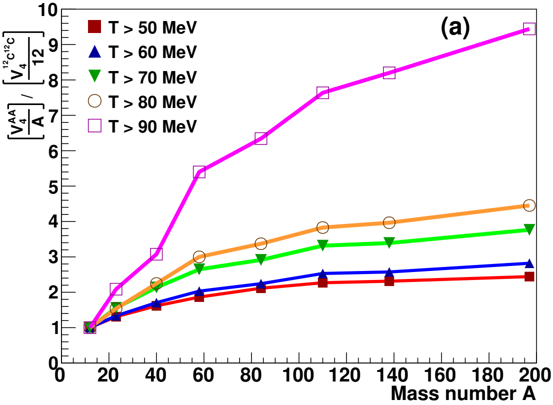
Signatures of the QCD-phase structure?

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 [EHB16, RH16]
  similar study in [GHR+16]
- caveat: phase transition not really implemented!!!

Four Volume

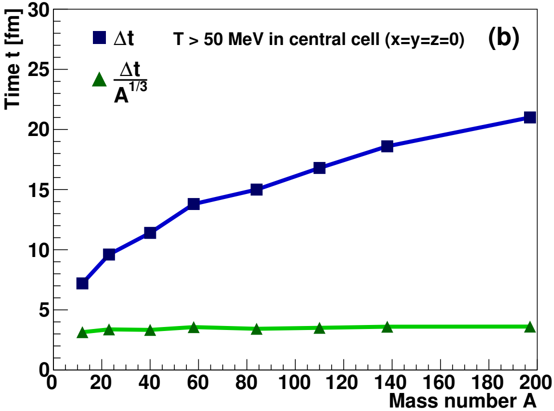
- central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76\,A\text{GeV}$
- $\frac{V_{AA}^{(4)}/A}{V_{CC}^{(4)}/12}$ of cells larger than various T



- how to explain “scaling behavior”?

Lifetime of the central cell

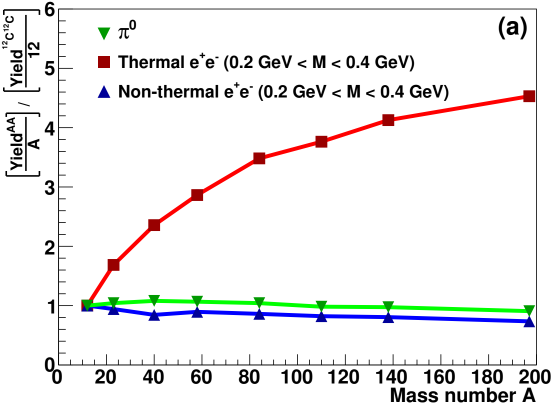
- central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76\,A\text{GeV}$



- $\Delta t \propto A^{1/3}$
- $A \propto V^{(3)}$ 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

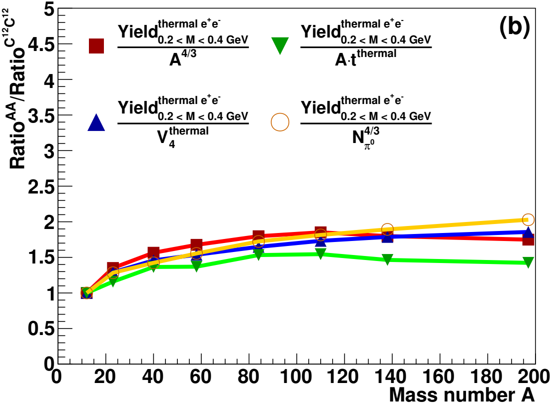
- central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76\,A\text{GeV}$
- $\dfrac{\text{yield}_{AA}/A}{\text{yield}_{CC}/12}$



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

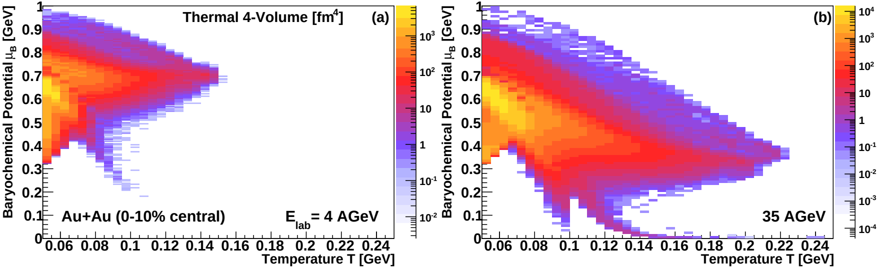
Scaling behavior of thermal-dilepton yield

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



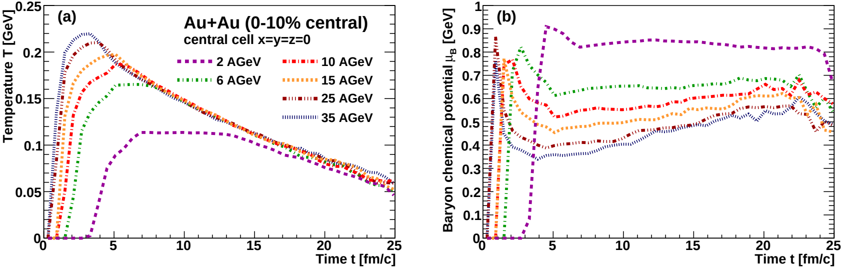
- thermal-dilepton yield roughly $\propto V_{\text{therm}}^{(4)} \propto A^{4/3} \propto A t_{\text{therm}} \propto N_{\pi^0}^{4/3}$
- at low(est) beam energies:
  lifetime of "medium" $\hat{=}$ time nuclei pass through each other

- thermal four-volume (fm^4) [EHB16]



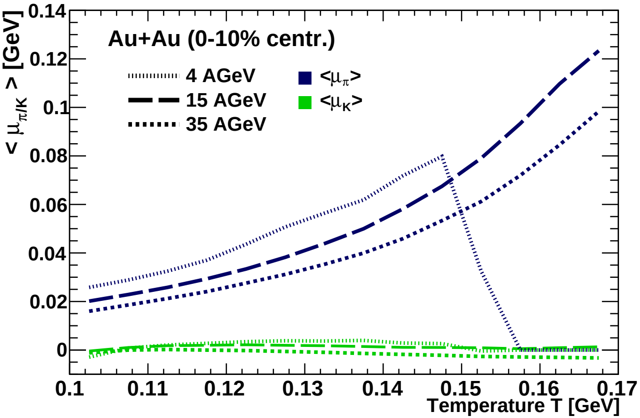
Dilepton systematics in the beam-energy scan

- T and μ_B vs. t [EHB16]



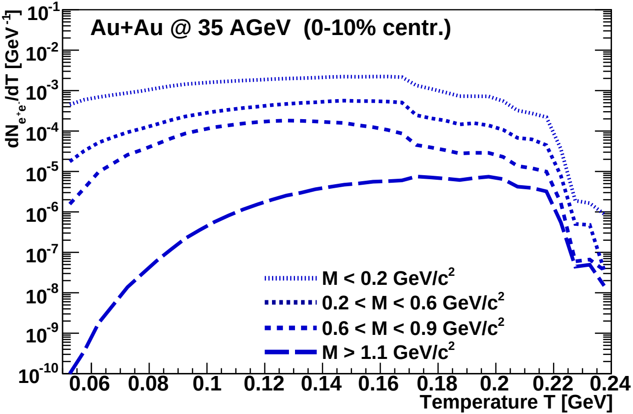
Dilepton systematics in the beam-energy scan

- $\mu_{\pi/K}$-temperature relation [EHB16]



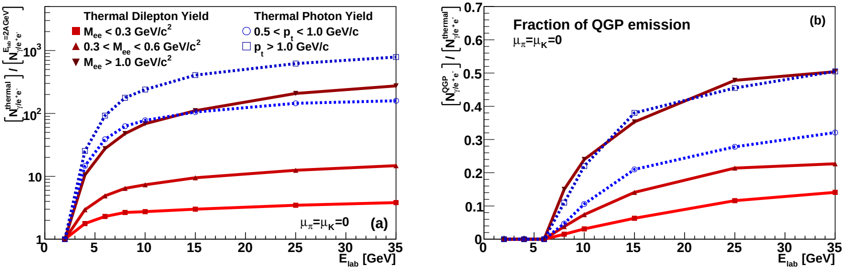
Dilepton systematics in the beam-energy scan

- mass-temperature relation in dilepton emission [EHB16]



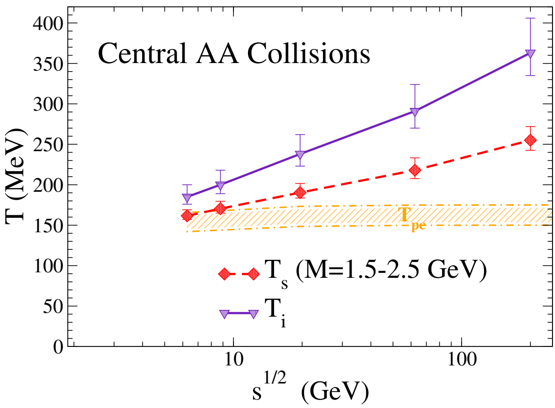
Dilepton systematics in the beam-energy scan

- excitation function e^+e^-/γ yield and QGP fraction [EHB16]



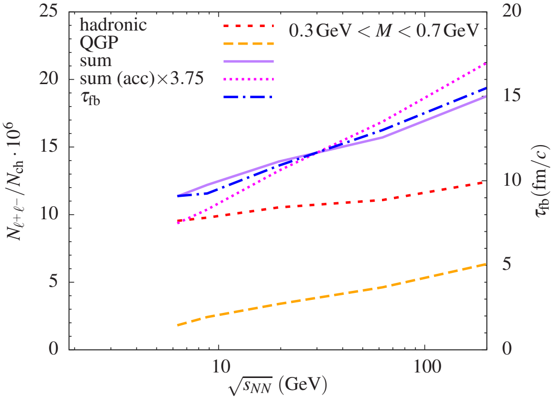
Dilepton systematics in the beam-energy scan

- thermal-fireball model [RH16]
- 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 future FAIR and NICA accelerators
- dilepton yield as fireball-lifetime clock



Opportunity for LHCb in fixed target experiments

- Pb (2.76 TeV) on fixed gas target (Ar)
- $\sqrt{s_{NN}} \simeq 72\,\text{GeV}$: additional point in "excitation functions"
- $\mathrm{d}N_{\text{ch}}/\mathrm{d}y \simeq 400$ (as Pb-Pb in SPS!)
- high precision using $\mu^+\mu^-$ (similar to NA60)
- down to low q_{t}?!? (medium effects largest)
- good control over correlated $\mathrm{D}\overline{\mathrm{D}}$ background $\Rightarrow$ precision measurement of a true T in $M_\phi < M_{\mu^+\mu^-} \lesssim 2.5\,\text{GeV}$
- biased to earlier (hot) parts of fireball evolution!

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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