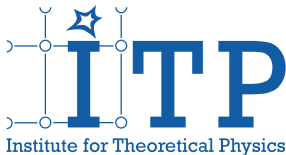


Electromagnetic Probes in a Coarse-Graining Approach

Hendrik van Hees

Goethe University Frankfurt

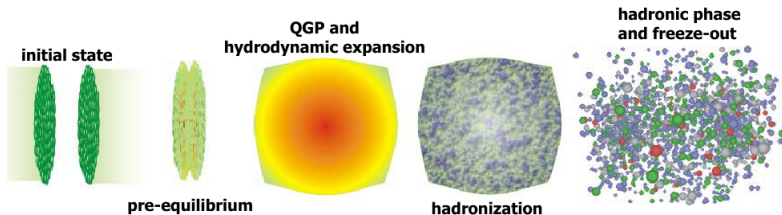
November 26, 2018



- 1 Heavy-ion collisions on one slide
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- 4 Dileptons in heavy-ion collisions
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 - Dielectrons at RHIC
 - Dielectrons at FAIR/RHIC-BES
- 5 Signatures of the QCD-phase structure?
- 6 Conclusions and Outlook

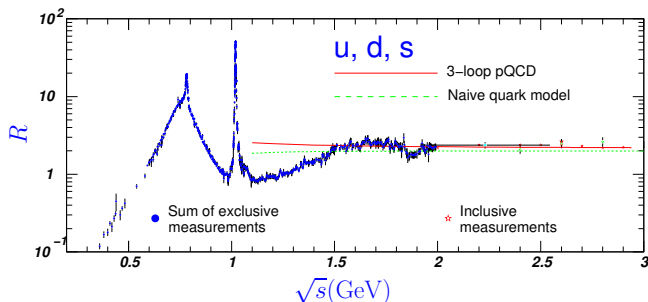
Heavy-Ion collisions in a Nutshell

- theory of strong interactions: Quantum Chromo Dynamics, QCD
- GSISIS: 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: $e^+e^- \rightarrow \text{hadrons}$

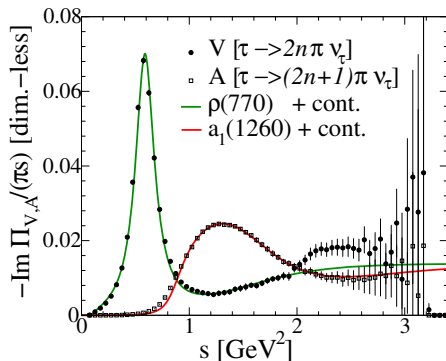
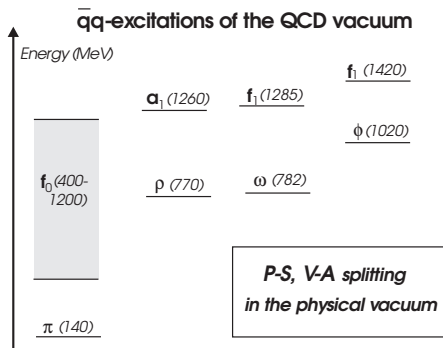


$$R := \frac{\sigma_{e^+e^- \rightarrow \text{hadrons}}}{\sigma_{e^+e^- \rightarrow \mu^+\mu^-}}$$

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

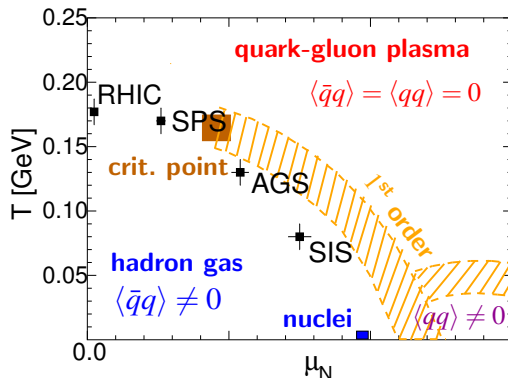
Hadron phenomenology and chiral symmetry

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



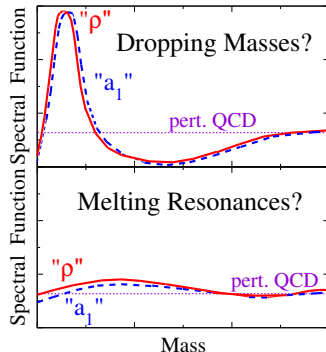
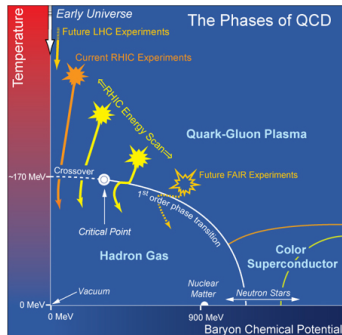
The QCD-phase diagram

- **hot and dense matter**: quarks and gluons close together
- highly energetic collisions $\Rightarrow$ “**deconfinement**”
- quarks and gluons relevant dof $\Rightarrow$ **quark-gluon plasma**
- still strongly interacting $\Rightarrow$ 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**": $m_{\text{had}} \propto \langle \bar{\psi}\psi \rangle$
 - "**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**

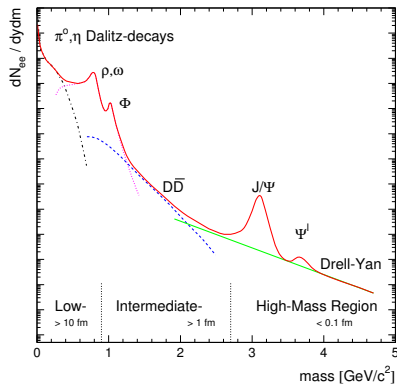
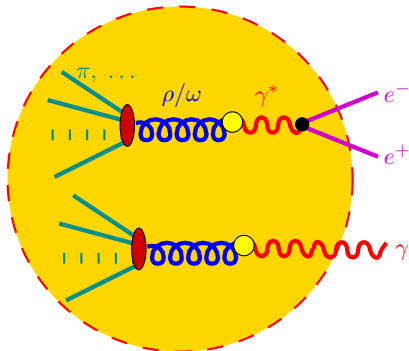


Fig. by A. Drees

Electromagnetic probes from thermal source

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

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

$$\frac{dN_{e^+e^-}}{d^4x d^4q} = -g^{\mu\nu} \frac{\alpha^2}{3q^2\pi^3} \text{Im} \Pi_{\mu\nu}^{(\text{ret})}(q, u) \Big|_{q^2=M_{e^+e^-}^2} f_B(q \cdot u)$$

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

$$\Sigma_{\mu\nu}^\gamma = \text{---} G_\rho \text{---}$$

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

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

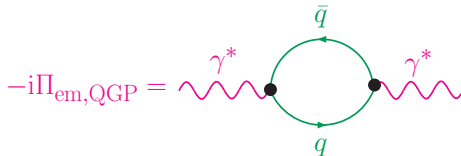
- General: McLerran-Toimela formula

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

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

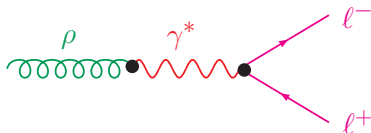
$$\Pi_{\text{em},i}^{\mu\nu} = i \int d^4x \exp(iqx) \Theta(x^0) \langle [j_{\text{em},i}^\mu(x), j_{\text{em},i}^\nu(0)] \rangle$$

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



Radiation from thermal sources: ρ decays

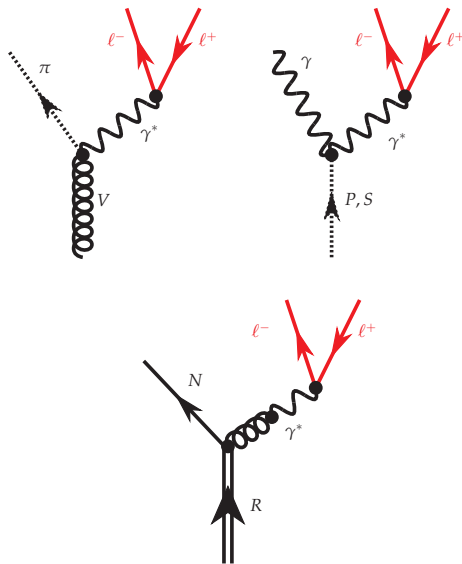
- model assumption: **vector-meson dominance**



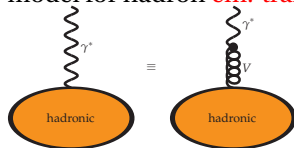
$$\begin{aligned} \frac{dN_{\rho \rightarrow l^+ l^-}^{(\text{MT})}}{d^4x d^4q} &= \frac{M}{q^0} \Gamma_{\rho \rightarrow l^+ l^-}(M) \frac{dN_{\rho}}{d^3\vec{x} d^4q} \\ &= -\frac{\alpha^2}{3\pi^3} \frac{L(M^2)}{M^2} \frac{m_{\rho}^4}{g_{\rho}^2} g_{\mu\nu} \text{Im} D_{\rho}^{\mu\nu}(M, \vec{q}) f_B \left(\frac{q \cdot u - 2\mu_{\pi}(t)}{T(t)} \right) \end{aligned}$$

- 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

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**

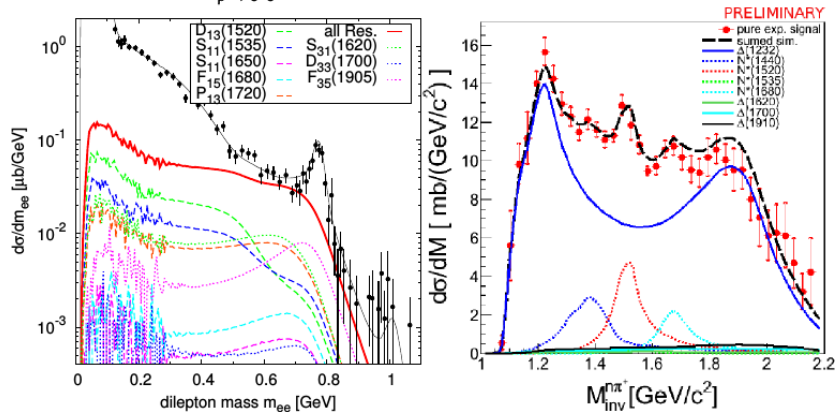


GiBUU: “ ρ meson” in pp

- production through hadron resonances

$$NN \rightarrow NR \rightarrow NN\rho, NN \rightarrow N\Delta \rightarrow NN\pi\rho$$

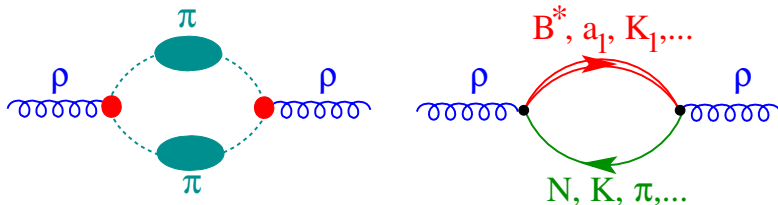
$$\rho \rightarrow e^+e^-$$



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

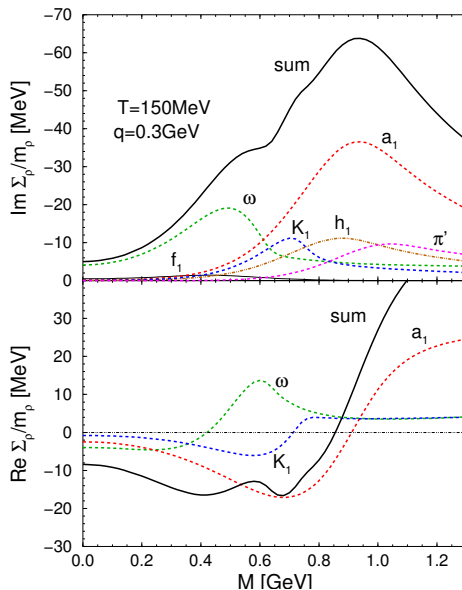
Hadronic many-body theory

- 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, $\pi N \rightarrow \rho N$)
- evaluated at **finite temperature and density**
- self-energies $\Rightarrow$ **mass shift and broadening** in the medium

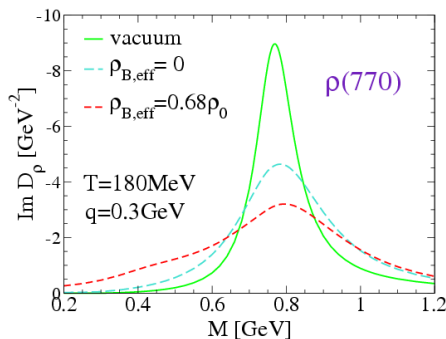


- **Baryons** important, even at low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

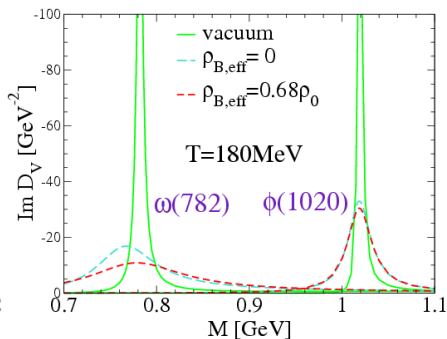
Meson contributions



In-medium spectral functions and baryon effects



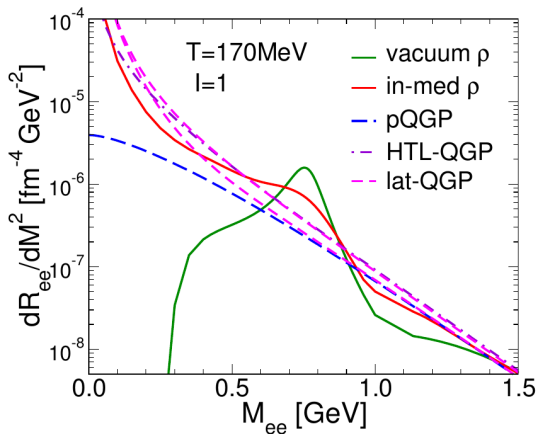
[RW99]



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

Dilepton rates: Hadron gas $\leftrightarrow$ 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 $T, \mu_B, \mu_\pi, \dots$
 - $\Rightarrow$ use equilibrium rates locally

Coarse-grained UrQMD (CGUrQMD)

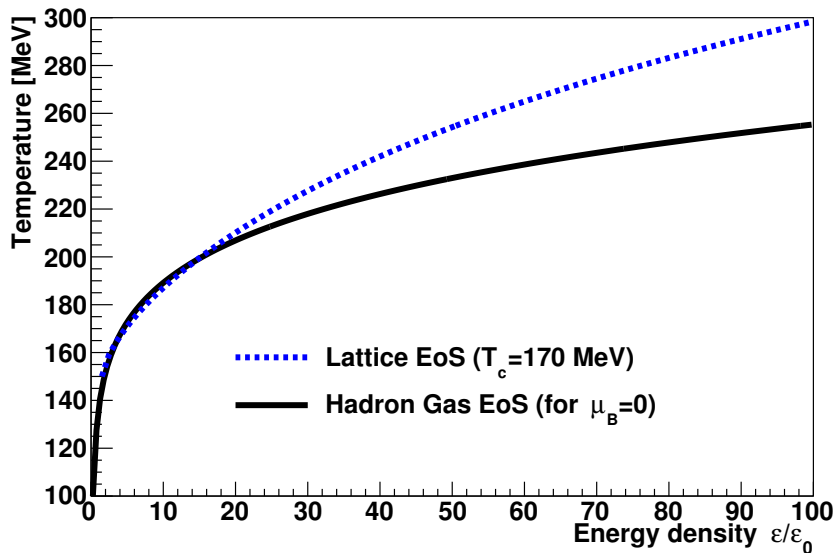
- problem with **medium modifications** of spectral functions/interactions
- only available in equilibrium many-body QFT models
- use “in-medium cross sections” naively: **double counting?!?**
- way out: map transport to **local-equilibrium fluid**
- use **ensemble of UrQMD** runs with an **equation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

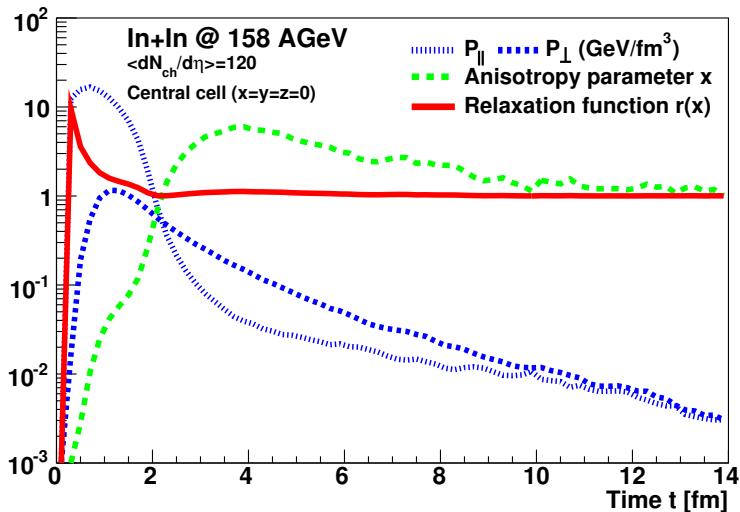
Coarse-grained UrQMD (CGUrQMD)

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



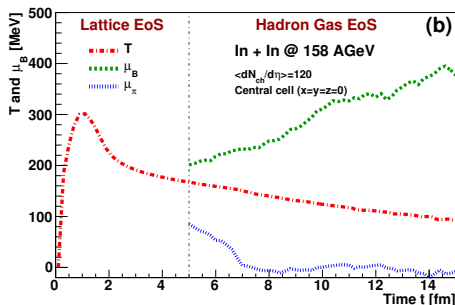
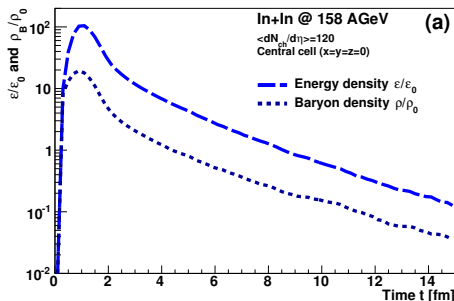
Coarse-grained UrQMD (CGUrQMD)

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



Coarse-grained UrQMD (CGUrQMD)

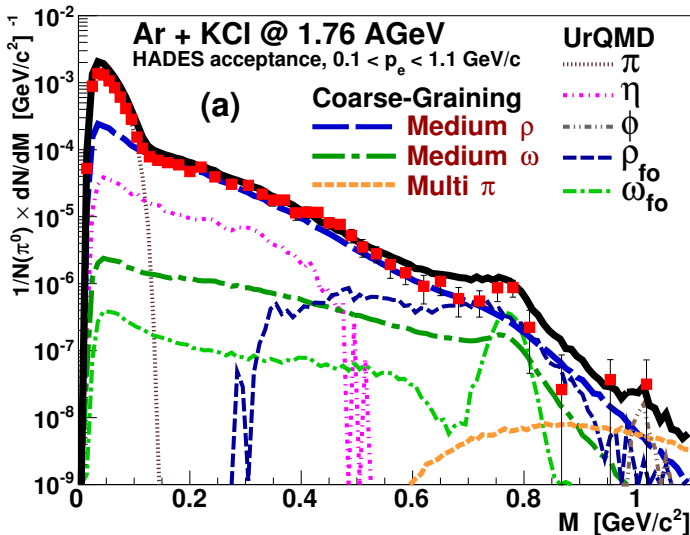
- energy/baryon density $\Rightarrow T, \mu_B$ (for In+In @ SPS; NA60)
- central “fluid” cell!



Dielectrons (SIS/HADES)

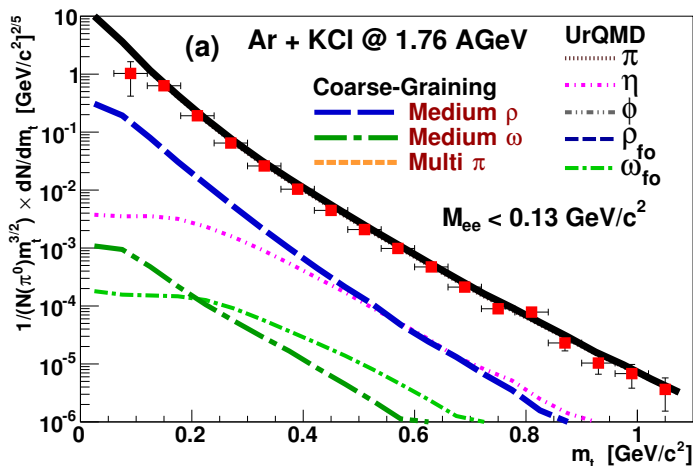
CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

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



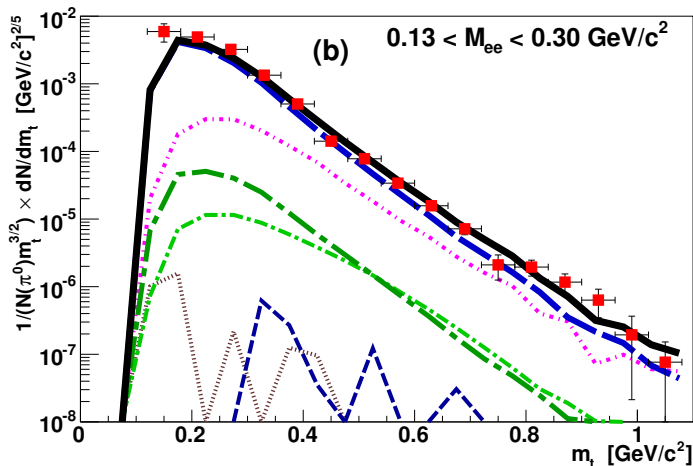
CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

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



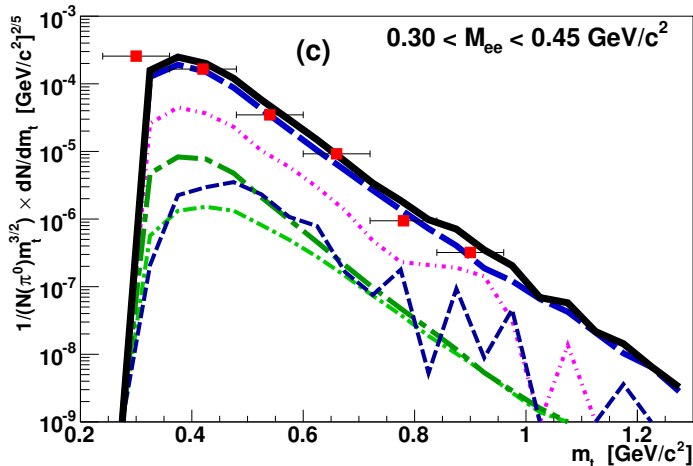
CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

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



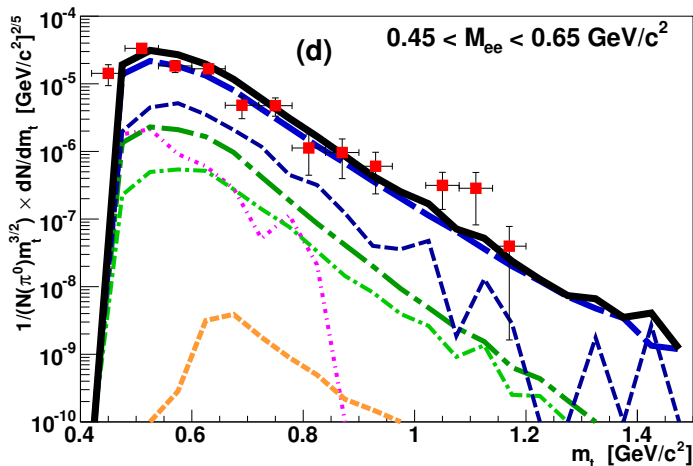
CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

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



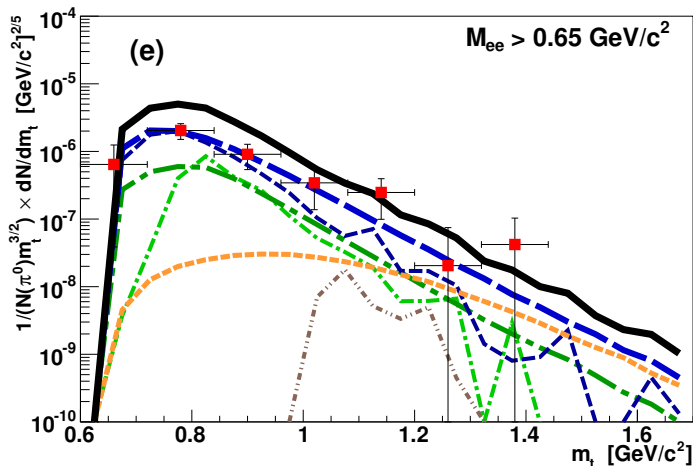
CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

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



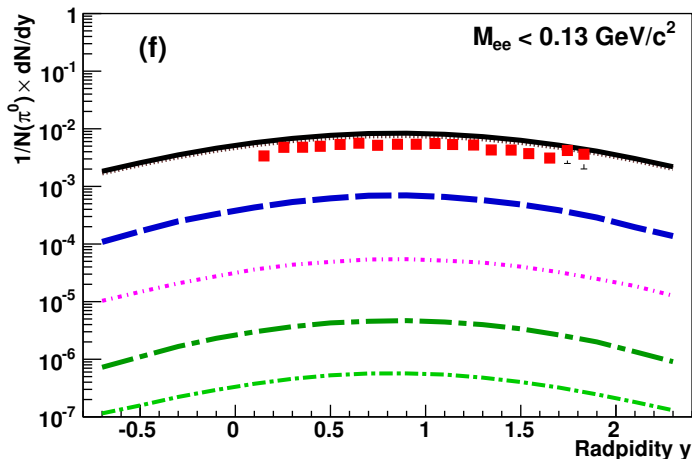
CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

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

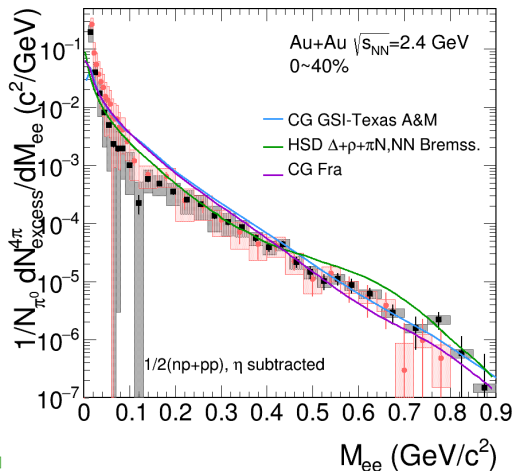


CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

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



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



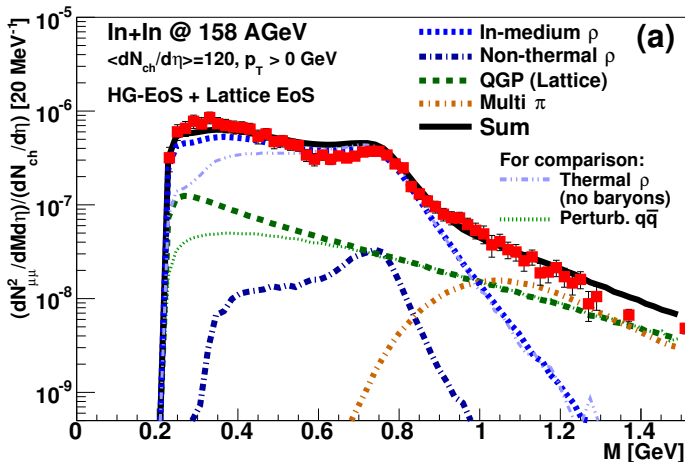
[T. Galtyuk, Quark Matter 2017 talk]

- 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)

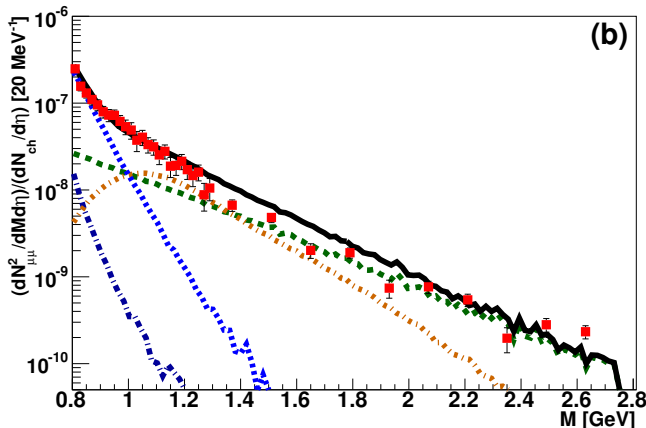
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)



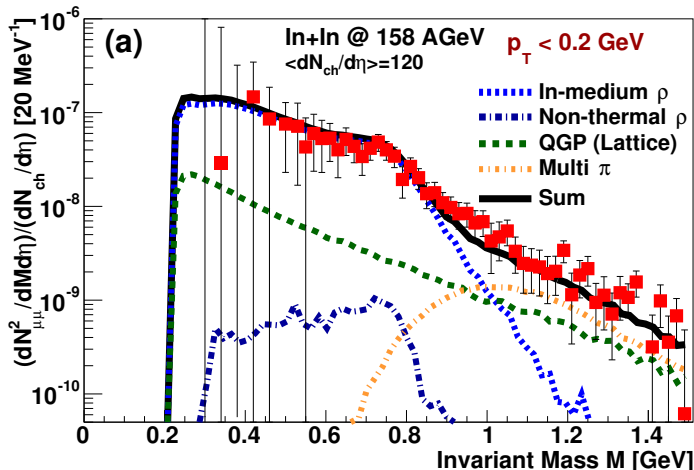
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- 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!)



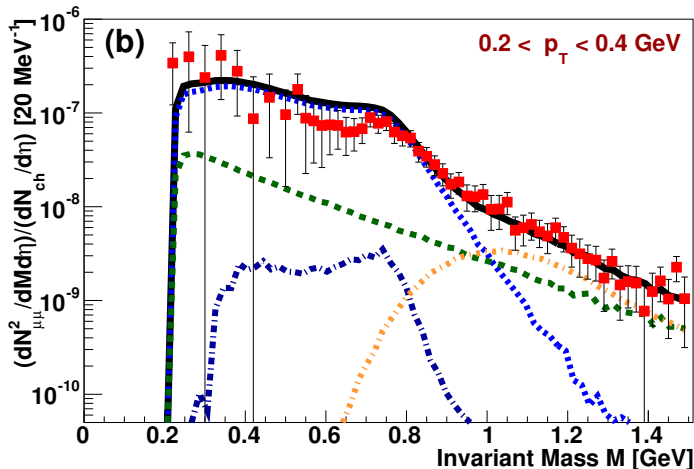
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $p_T < 0.2$ GeV



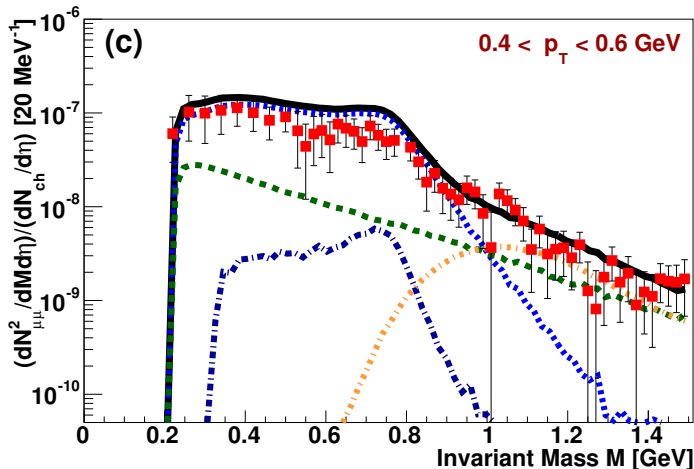
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $0.2 \text{ GeV} < p_T < 0.4 \text{ GeV}$



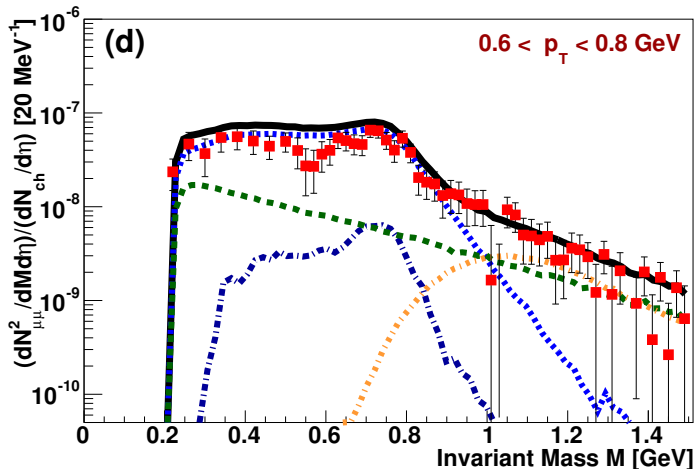
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $0.4 \text{ GeV} < p_T < 0.6 \text{ GeV}$



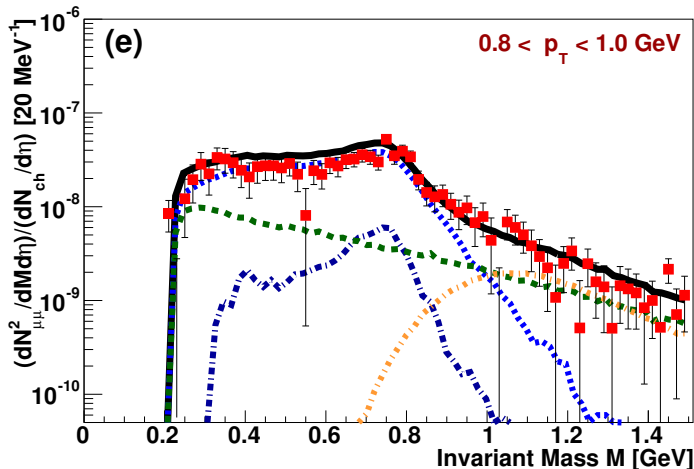
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $0.6 \text{ GeV} < p_T < 0.8 \text{ GeV}$



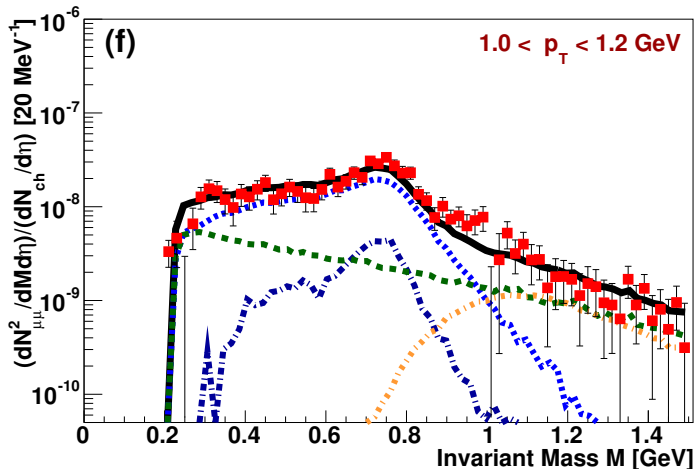
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $0.8 \text{ GeV} < p_T < 1.0 \text{ GeV}$



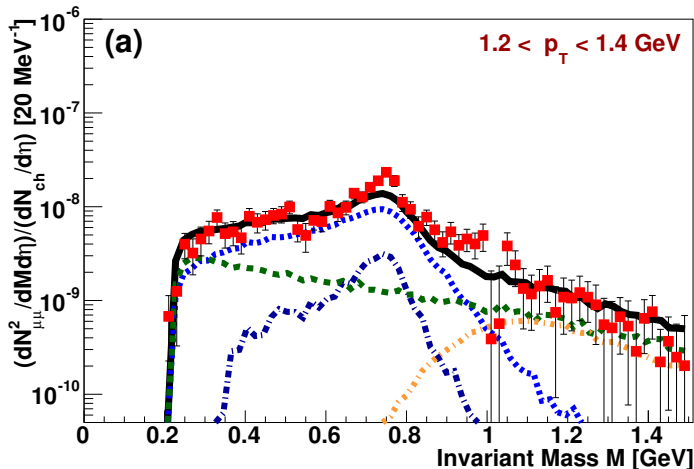
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $1.0 \text{ GeV} < p_T < 1.2 \text{ GeV}$



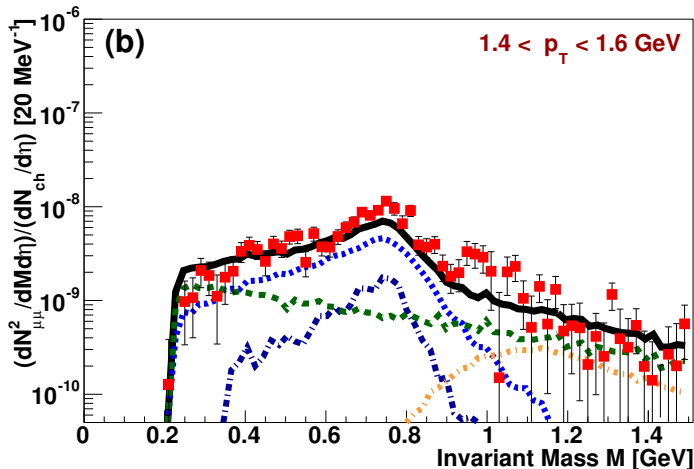
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $1.2 \text{ GeV} < p_T < 1.4 \text{ GeV}$



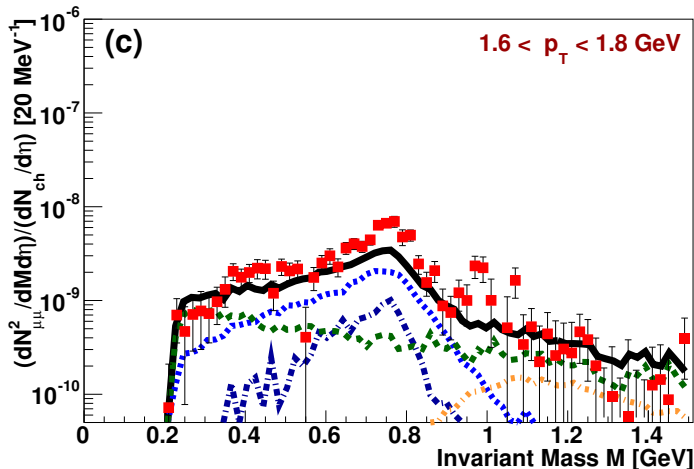
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $1.4 \text{ GeV} < p_T < 1.6 \text{ GeV}$



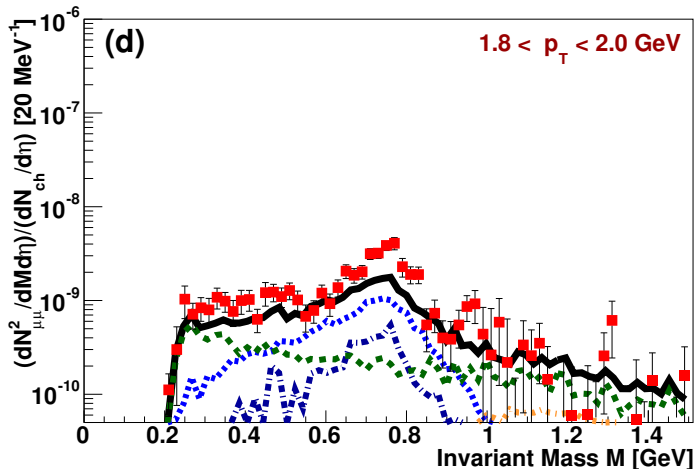
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $1.6 \text{ GeV} < p_T < 1.8 \text{ GeV}$



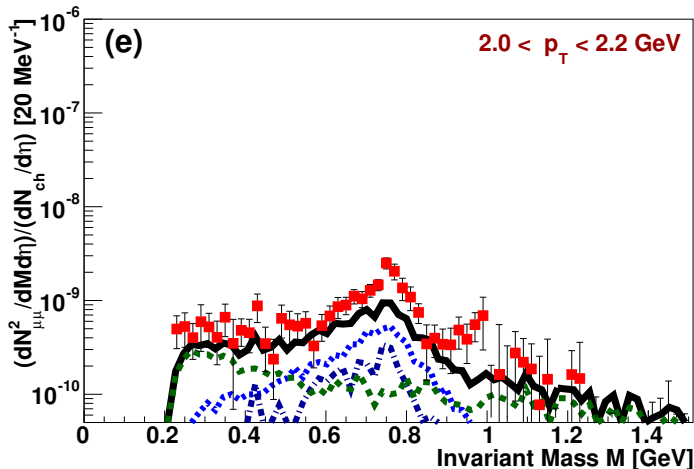
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $1.8 \text{ GeV} < p_T < 2.0 \text{ GeV}$



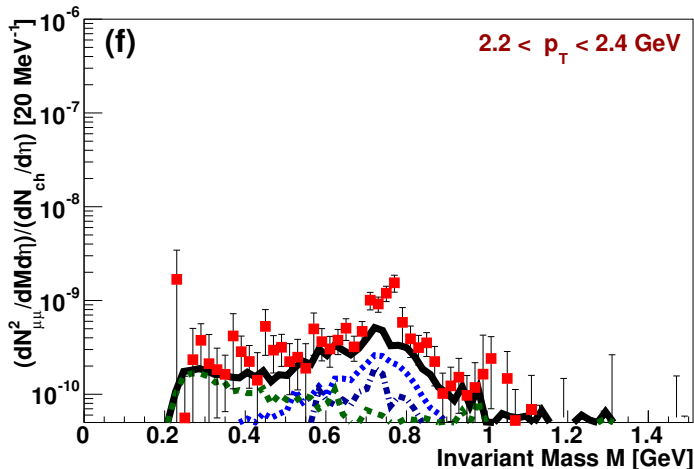
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $2.0 \text{ GeV} < p_T < 2.2 \text{ GeV}$



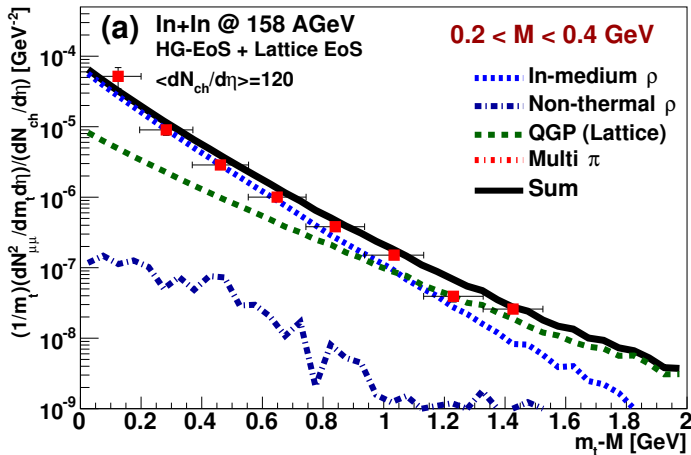
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $2.2 \text{ GeV} < p_T < 2.4 \text{ GeV}$



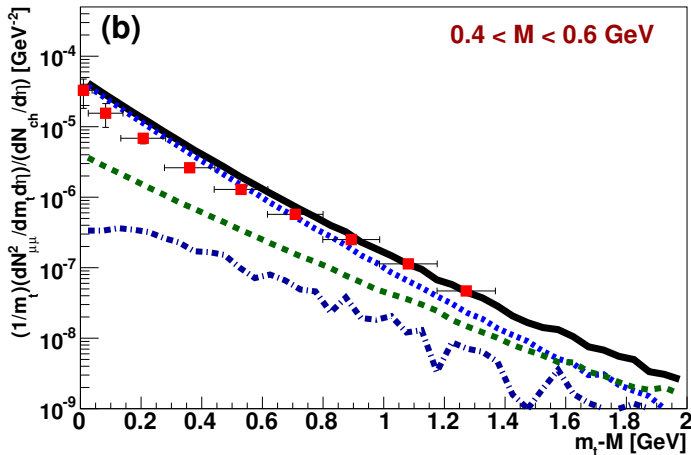
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)

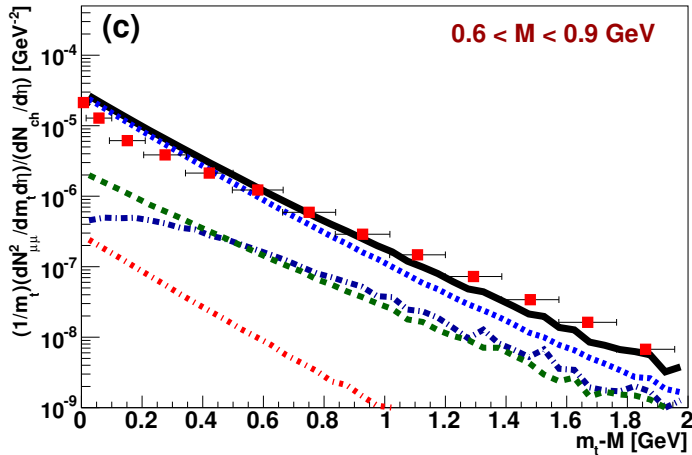


CGUrQMD: In+In (158 AGeV) (SPS/NA60)

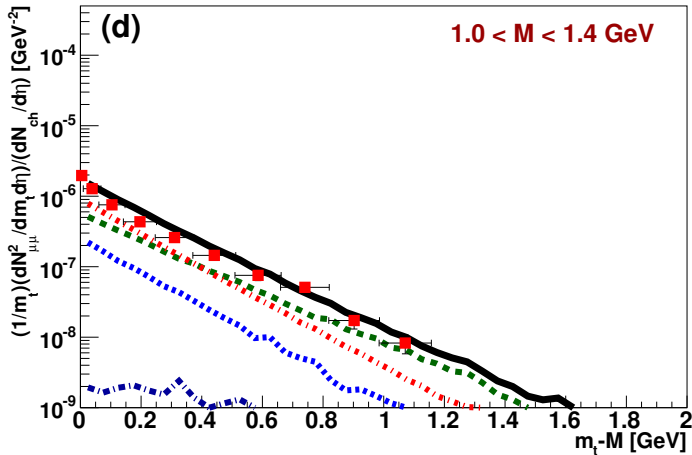
- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)



- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)

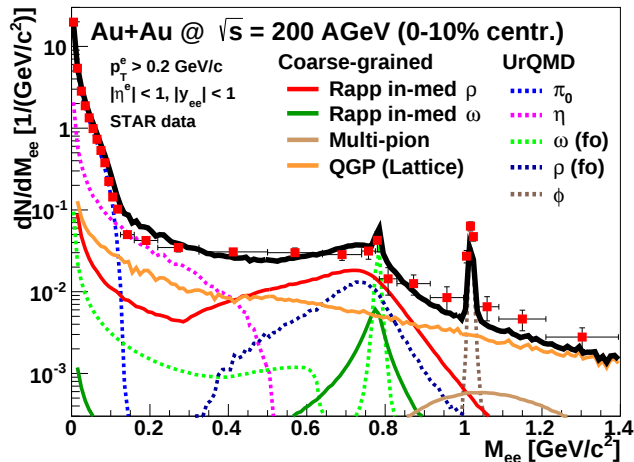


- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)

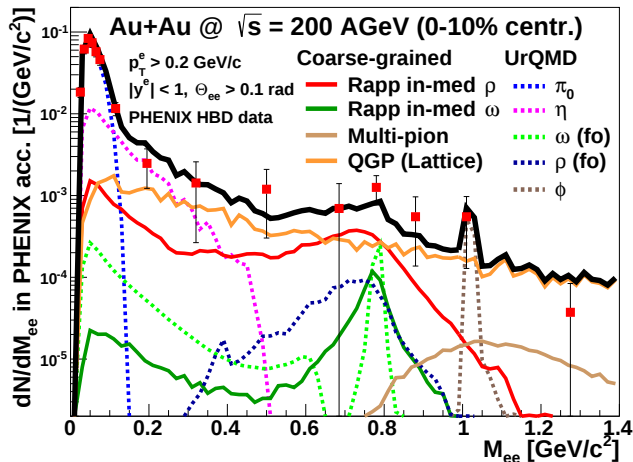


Dielectrons at RHIC

CGUrQMD: Au+Au ($\sqrt{s}_{NN} = 200$ GeV) (RHIC/STAR)

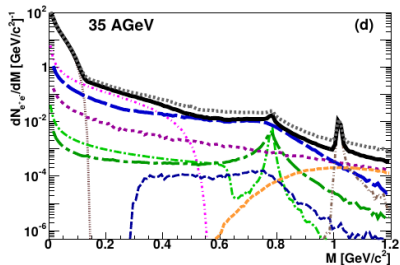
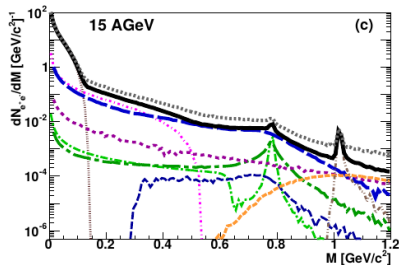
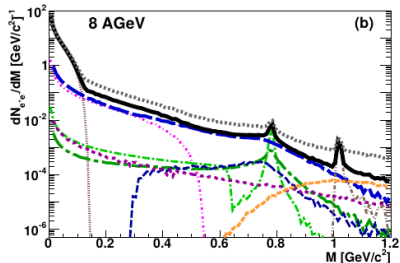
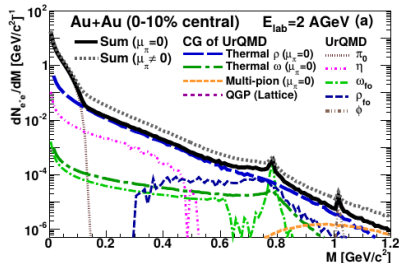


CGUrQMD: Au+Au ($\sqrt{s}_{NN} = 200$ GeV) (RHIC/PHENIX)



Dielectrons at RHIC-BES/FAIR/NICA

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



NB: also photon spectra [EHB16b]

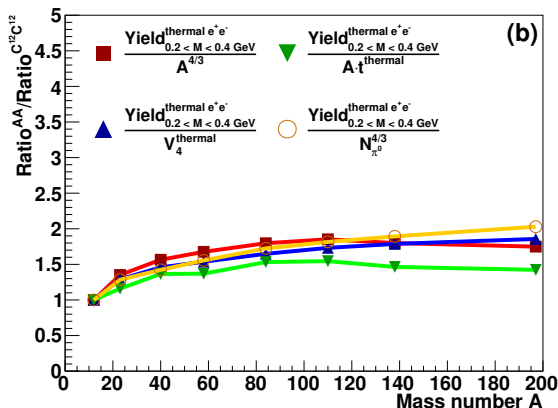
Signatures of the QCD-phase structure?

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

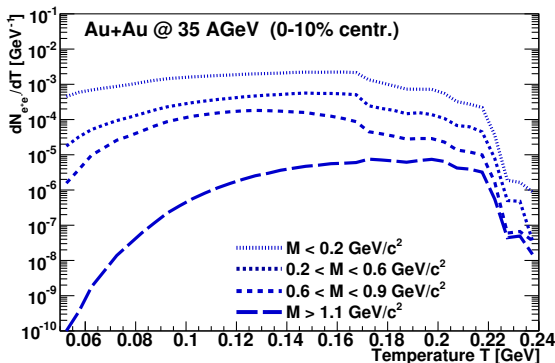
- central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76 \text{ AGeV}$



- 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

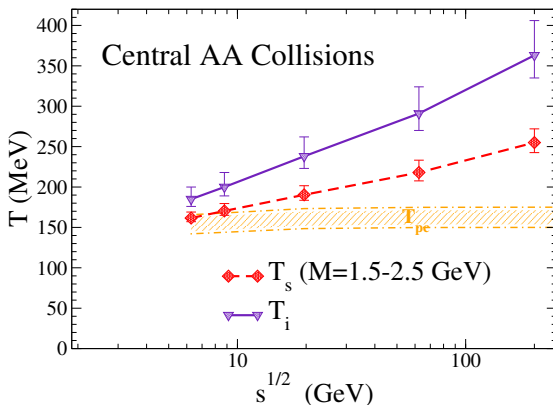
Mass-temperature relation in dilepton emission

- 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 $D\bar{D}$ 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)



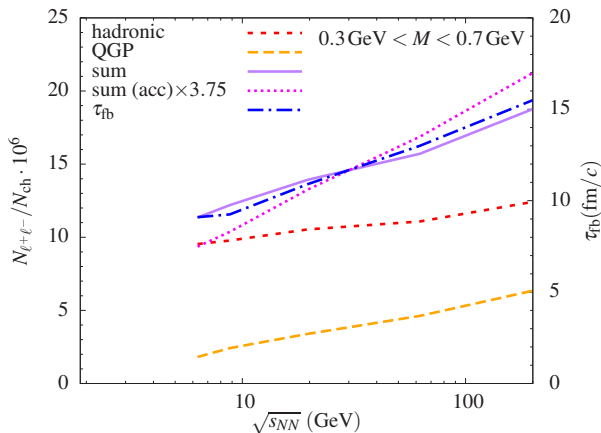
Dilepton systematics in the beam-energy scan

- thermal-fireball model [RH16, EHB16a]
- invariant-mass slope in IMR $\Rightarrow$ 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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