

Dileptons in heavy-ion-collisions

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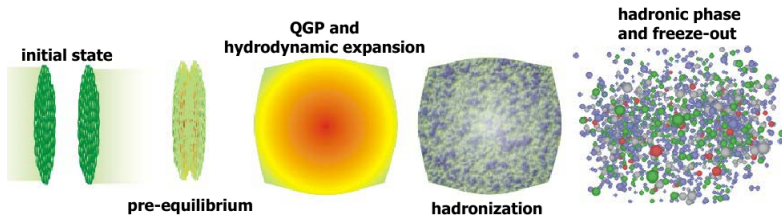
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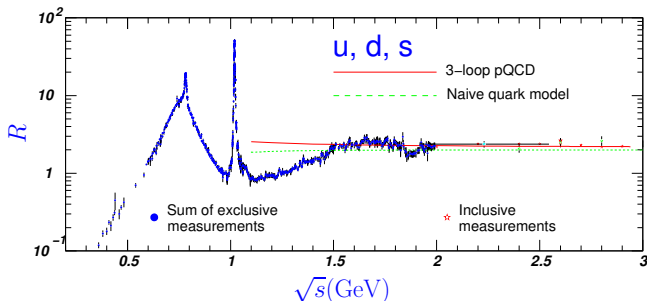
Heavy-Ion collisions in a Nutshell

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



Electromagnetic probes theory perspective

Vacuum Baseline: $e^+e^- \rightarrow \text{hadrons}$

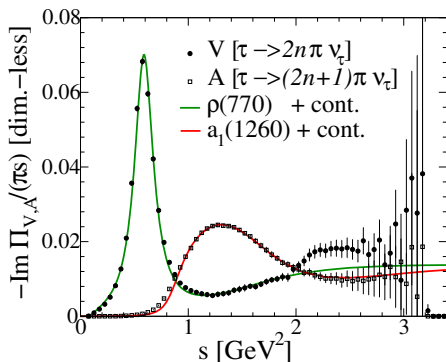
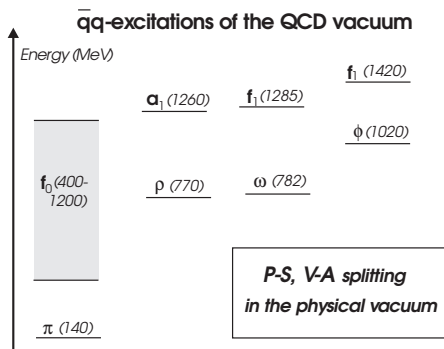


$$R := \frac{\sigma_{e^+e^- \rightarrow \text{hadrons}}}{\sigma_{e^+e^- \rightarrow \mu^+\mu^-}}$$

- 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 $pp \rightarrow \ell^+\ell^-$, $pA \rightarrow \ell^+\ell^-$, $AA \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$)

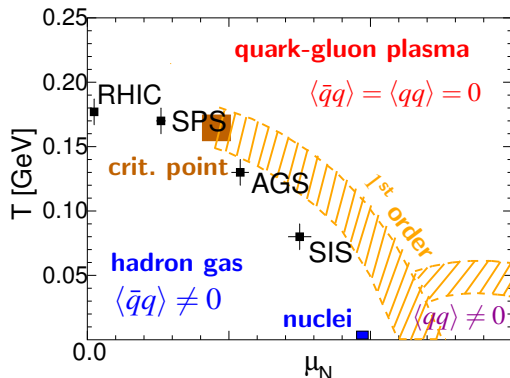
Hadron phenomenology and chiral symmetry

- 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



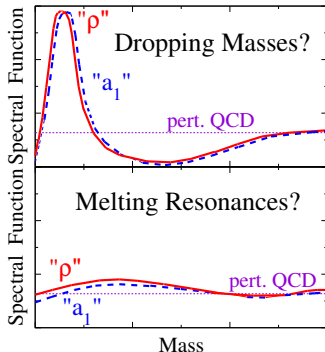
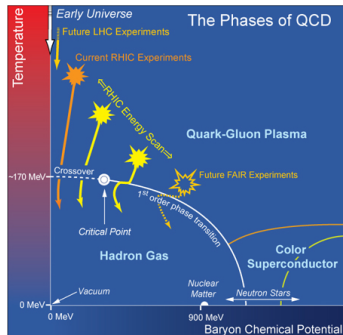
The QCD-phase diagram

- **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: $T_c^Z \simeq T_c^{\text{deconf}}$



- **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

- γ, l^\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**

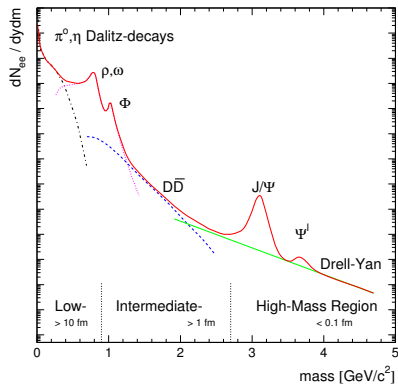
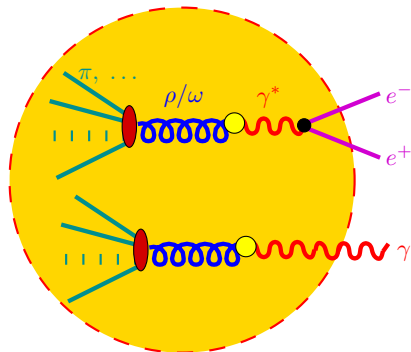


Fig. by A. Drees

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]

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

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

- Lorentz covariant (**dependent on four-velocity of fluid cell, u**)
- $q \cdot u = E_{cm}$: **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**

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

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

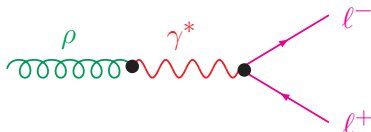
$$\Pi_{\text{em},i}^{\mu\nu} = i \int d^4x \exp(iqx) \Theta(x^0) \langle [j_{\text{em},i}^\mu(x), j_{\text{em},i}^\nu(0)] \rangle$$

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

$$-i\Pi_{\text{em},\text{QGP}} = \text{Diagram}$$

Radiation from thermal sources: ρ decays

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

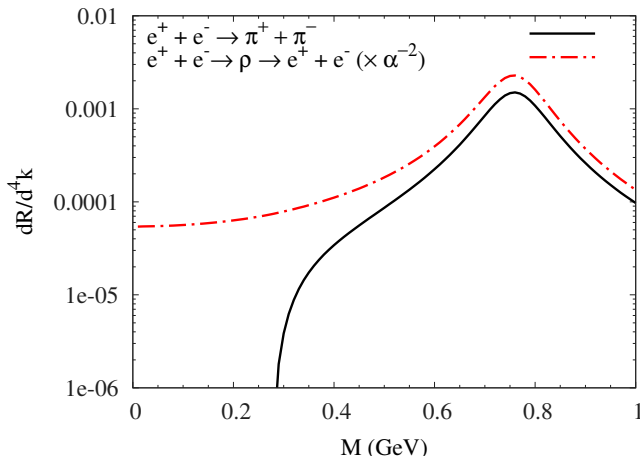


$$\begin{aligned}\frac{dN_{\rho \rightarrow l+l-}^{(\text{MT})}}{d^4x d^4q} &= \frac{M}{q^0} \Gamma_{\rho \rightarrow l+l-}(M) \frac{dN_{\rho}}{d^3\vec{x} d^4q} \\ &= -\frac{\alpha^2}{3\pi^3} \frac{L(M^2)}{M^2} \frac{m_{\rho}^4}{g_{\rho}^2} g_{\mu\nu} \text{Im} D_{\rho}^{\mu\nu}(M, \vec{q}) f_B \left(\frac{q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

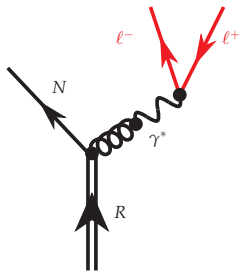
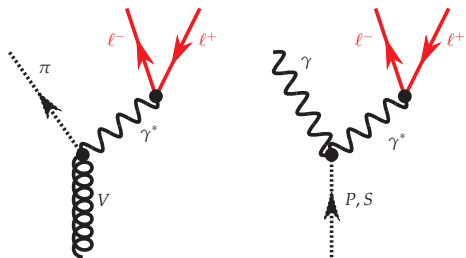
- special case of McLerran-Toimela (MT) formula
- $M^2 = q^2$: invariant mass, M , of dilepton pair
- $L(M^2) = (1 + 2m_l^2/M^2) \sqrt{1 - 4m_l^2/M^2}$: dilepton phase-space factor
- $D_{\rho}^{\mu\nu}(M, \vec{q})$: (four-transverse part of) in-medium ρ propagator at given $T(t)$, $\mu_{\text{meson/baryon}}(t)$
- analogous for ω and ϕ

“ ρ ” shape: dependence on processes looked at

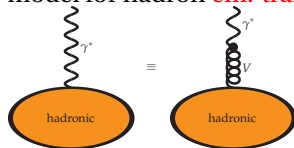
- look at “transition rates” $\sum_i' \sum_f |\mathcal{M}_{fi}|^2$ (averaged over i /summed over f)
- for $e^+ + e^- \rightarrow \pi^+ + \pi^-$ (“PDG definition”)
- for $e^+ + e^- \rightarrow \rho \rightarrow e^+ + e^-$ (s channel)
(annihilation part to Bhabba scattering via the ρ scaled by $\alpha^{-2} \simeq 137^2$)
- plot vs. $M = \sqrt{s}$



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 : $\omega \rightarrow \pi + \gamma^* \rightarrow \pi + e^+ + e^-$
- P, S : $\pi, \eta \rightarrow \gamma + \gamma^* \rightarrow \gamma + e^+ + e^-$
- R : Baryon resonances
 - $\Delta, N^* \rightarrow N + V \rightarrow N + \gamma^* \rightarrow N + e^+ + e^-$
- vector-meson dominance
- model for hadron em. trans. FF

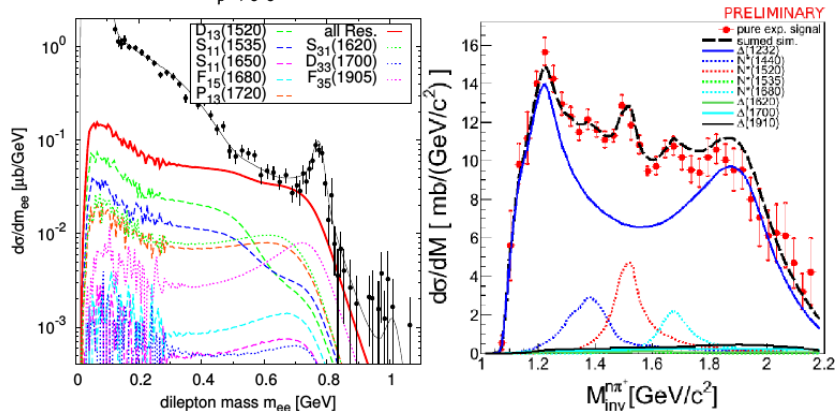


GiBUU: “ ρ meson” in pp

- production through hadron resonances

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

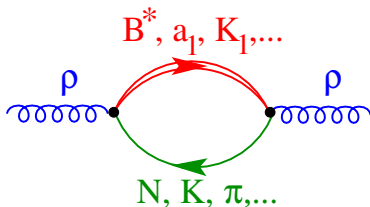
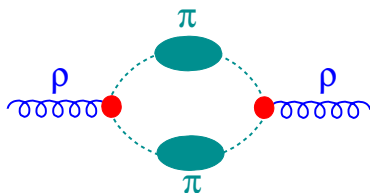
$$\rho \rightarrow e^+e^-$$



- 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

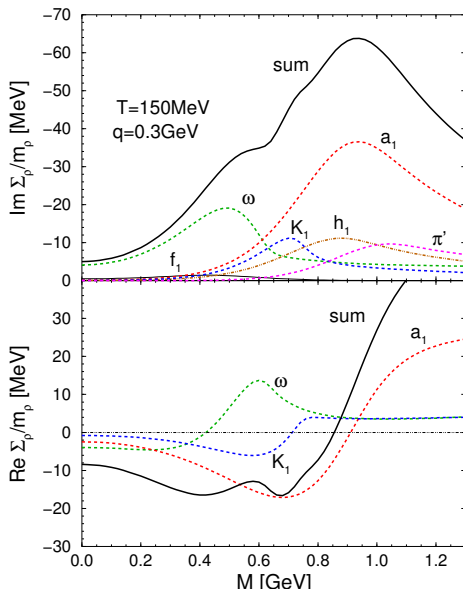
Hadronic many-body theory

- 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

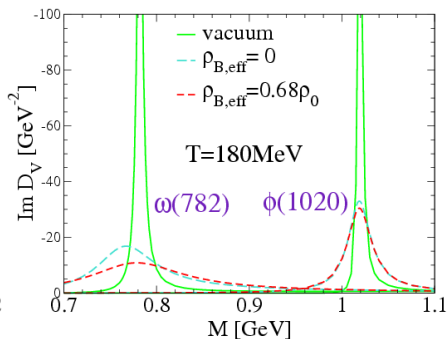
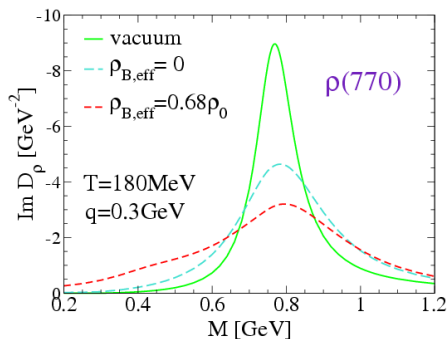


- **Baryons** important, even at low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

Meson contributions



In-medium spectral functions and baryon effects



[RW99]

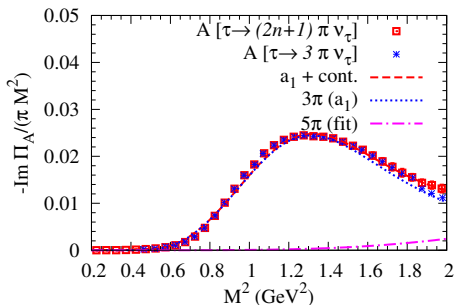
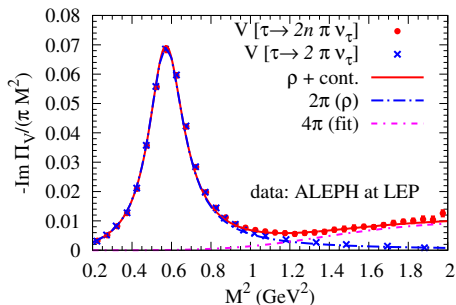
- **baryon effects** important
 - large contribution to broadening of the peak
 - responsible for most of the strength at small M

Radiation from thermal sources: multi- π processes

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

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

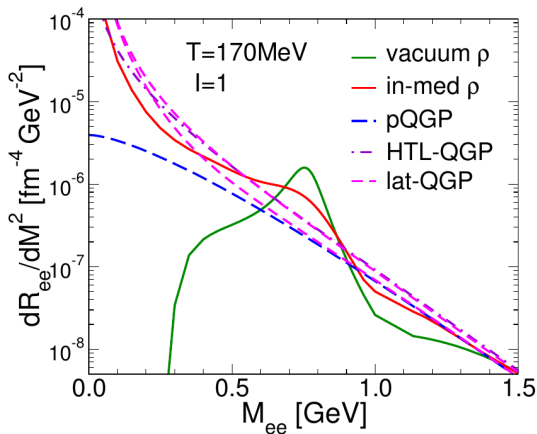
- avoid double counting: leave out two-pion piece and $a_1 \rightarrow \rho + \pi$ (already contained in ρ spectral function)



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

Dilepton rates: Hadron gas \leftrightarrow QGP

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



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, μ_B, μ_π, \dots
 - \Rightarrow use equilibrium rates locally

Coarse-grained UrQMD (CGUrQMD)

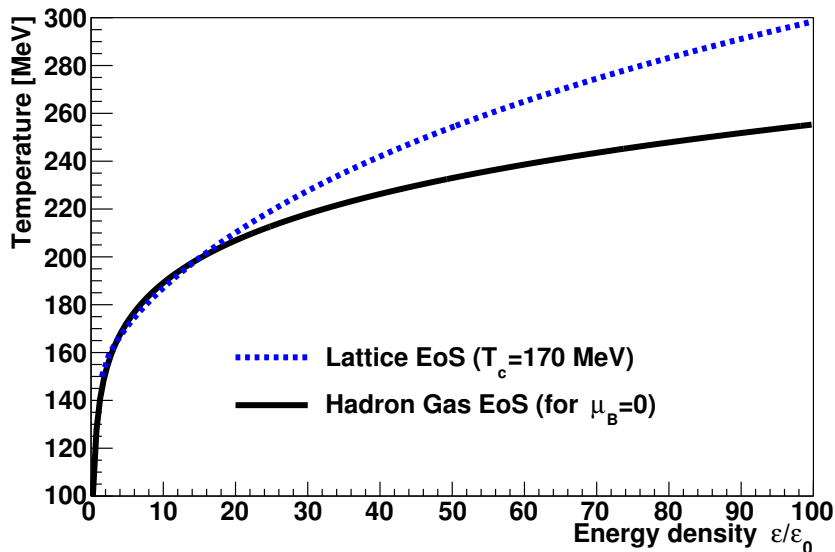
- problem with **medium modifications** of spectral functions/interactions
- only available in equilibrium many-body QFT models
- use “in-medium cross sections” naively: **double counting?!?**
- way out: map transport to **local-equilibrium fluid**
- use **ensemble of UrQMD** runs with an **equation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

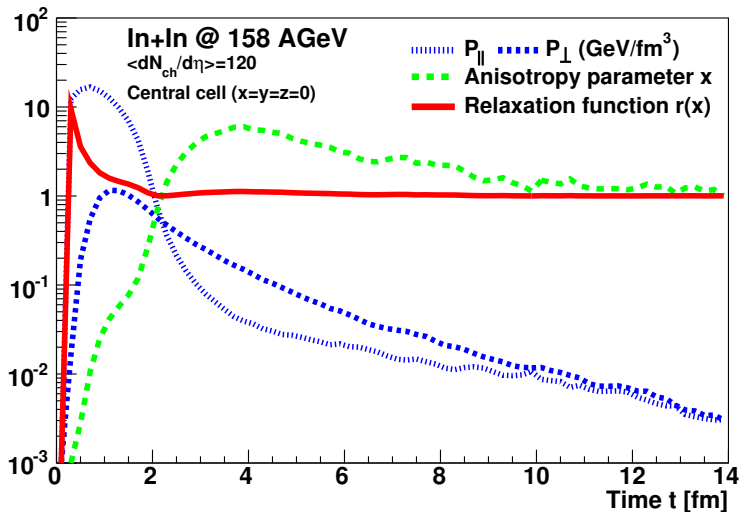
Coarse-grained UrQMD (CGUrQMD)

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



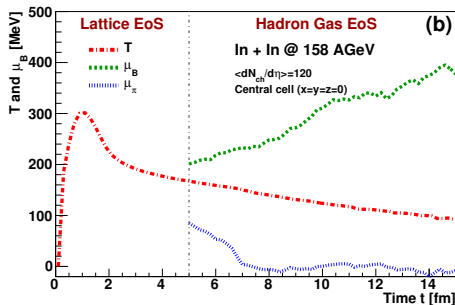
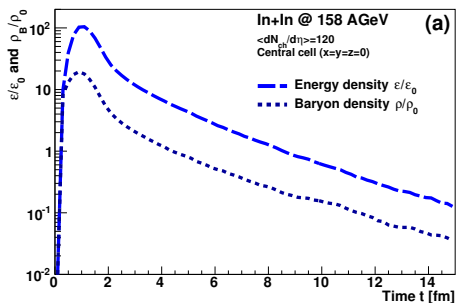
Coarse-grained UrQMD (CGUrQMD)

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



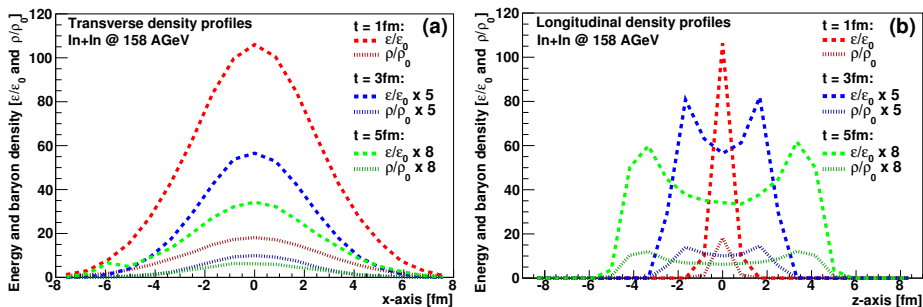
Coarse-grained UrQMD (CGUrQMD)

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



Coarse-grained UrQMD (CGUrQMD)

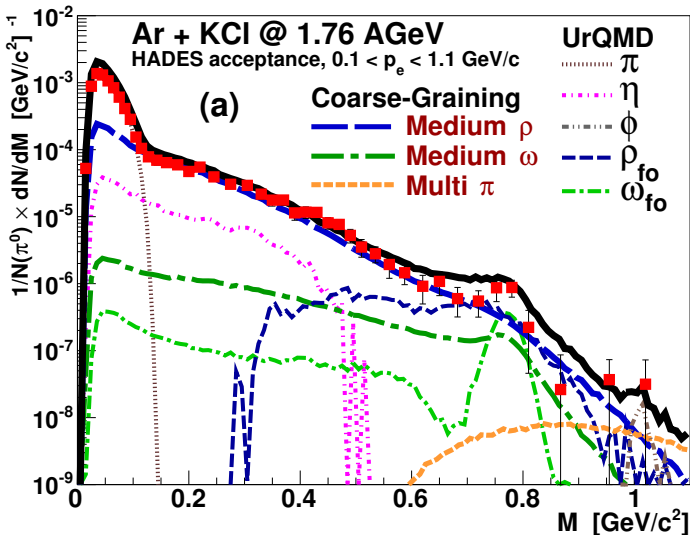
- energy (ϵ) and baryon (ρ) density profiles (for In+In@SPS; NA60)



Dielectrons (SIS/HADES)

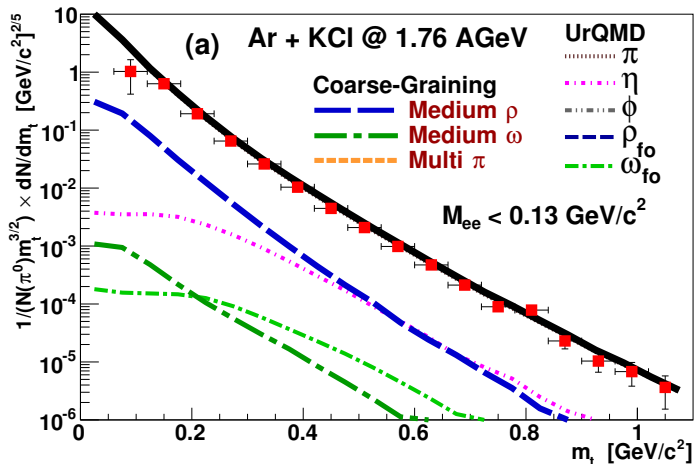
CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

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



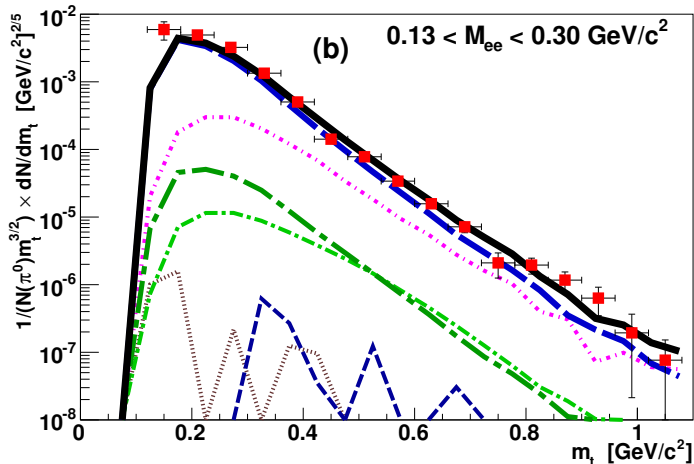
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- dielectron spectra from Ar + KCl(1.76 AGeV) $\rightarrow e^+e^-$ (SIS/HADES)
- m_t spectra
- $M_{ee} < 0.13$ GeV



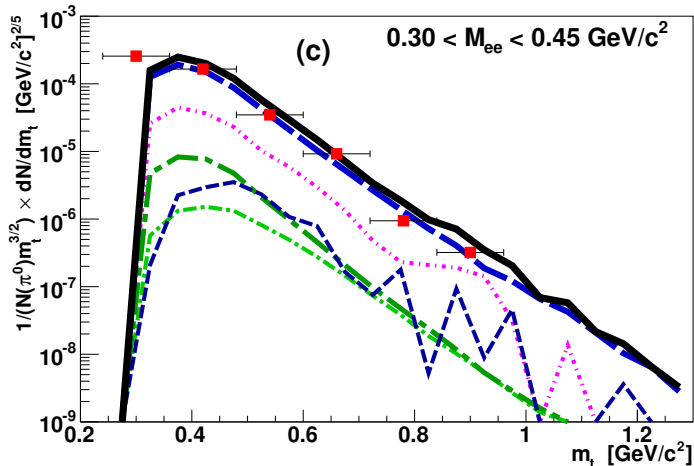
CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

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



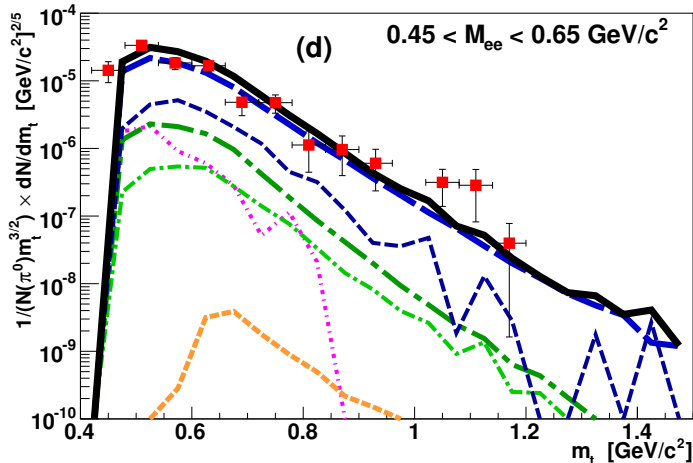
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- m_t spectra
- $0.3 \text{ GeV} M_{ee} < 0.45 \text{ GeV}$



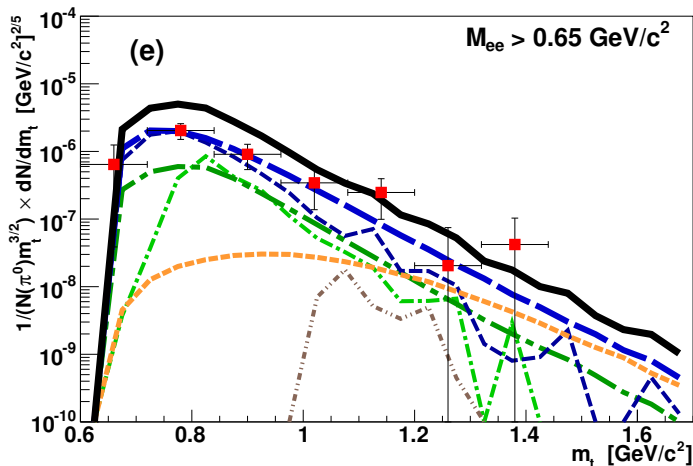
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- dielectron spectra from Ar + KCl(1.76 AGeV) $\rightarrow e^+e^-$ (SIS/HADES)
- m_t spectra
- $0.45 \text{ GeV} < M_{ee} < 0.65 \text{ GeV}$



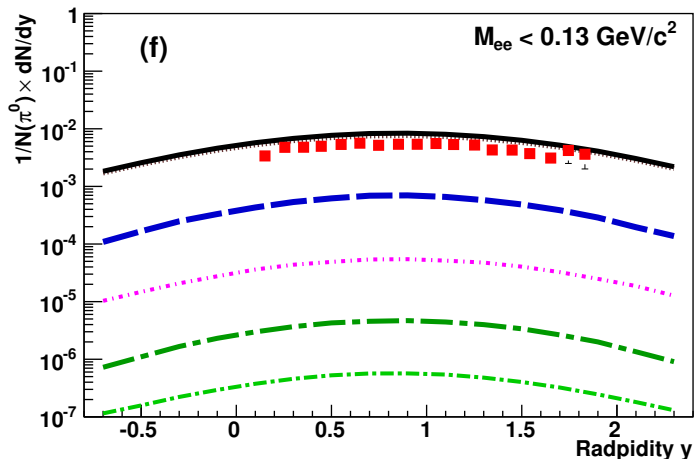
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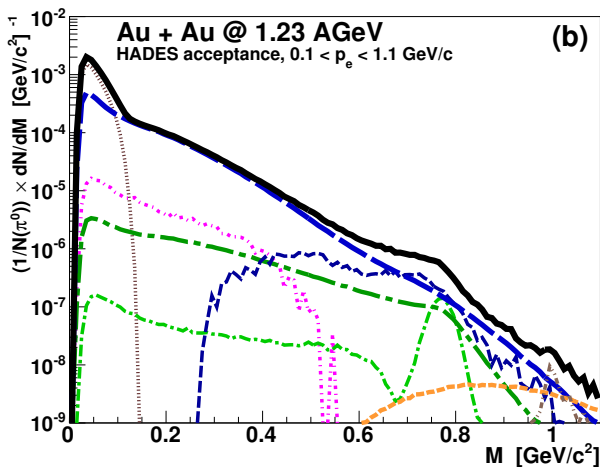
- dielectron spectra from Ar + KCl(1.76 AGeV) $\rightarrow e^+e^-$ (SIS/HADES)
- m_t spectra
- $M_{ee} > 0.65$ GeV



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

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



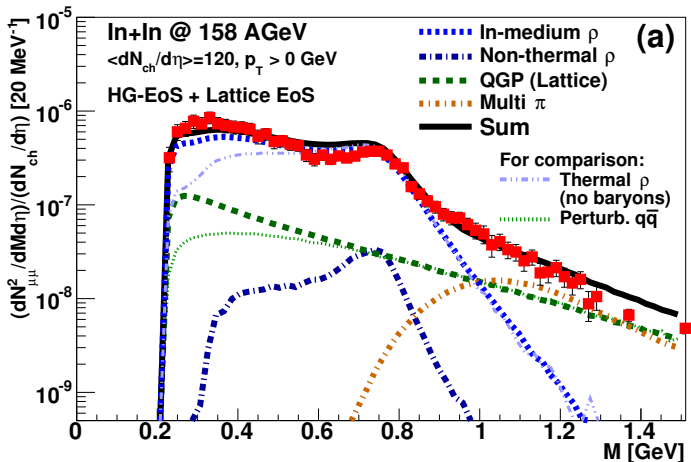


- caveat: pp/np acceptance filter with single-e cut, $p_t < 100$ MeV
- correct filter urgently needed!
- excellent agreement with preliminary HADES data

Dimuons (SPS/NA60)

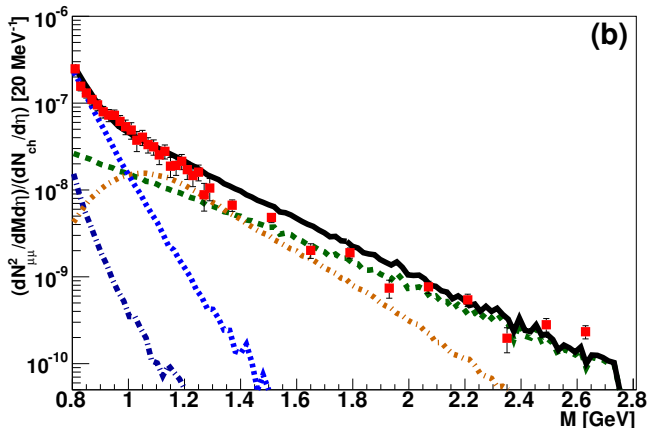
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



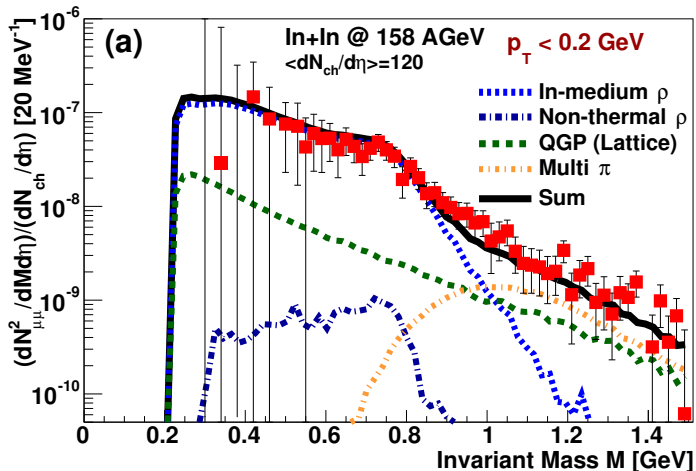
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- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- higher IMR: provides **averaged true temperature**
 $\langle T \rangle_{1.5 \text{ GeV} \lesssim M \lesssim 2.4 \text{ GeV}}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



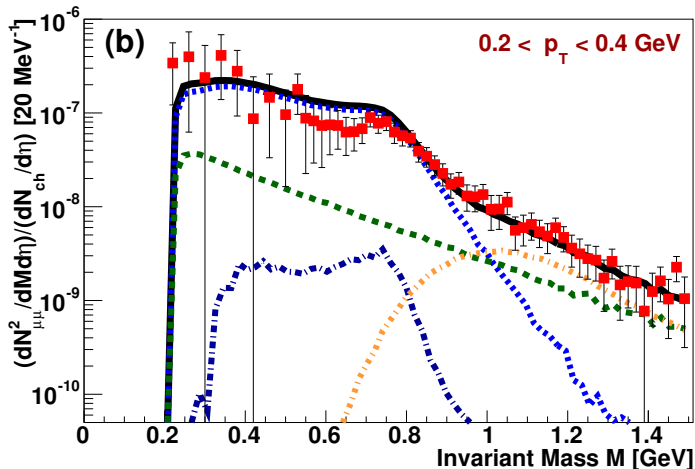
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- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $p_T < 0.2$ GeV



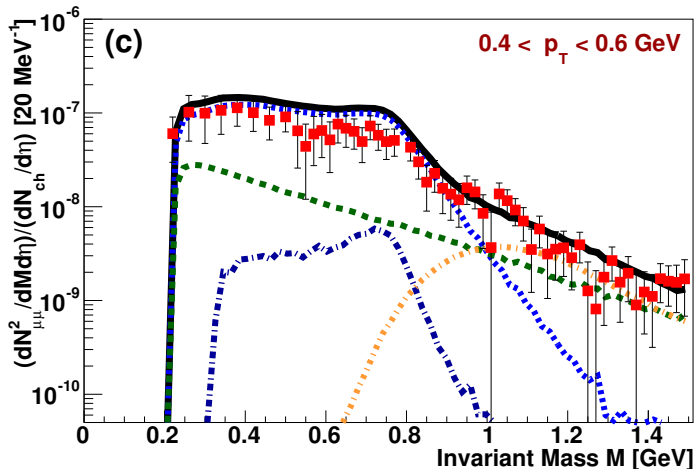
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- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $0.2 \text{ GeV} < p_T < 0.4 \text{ GeV}$



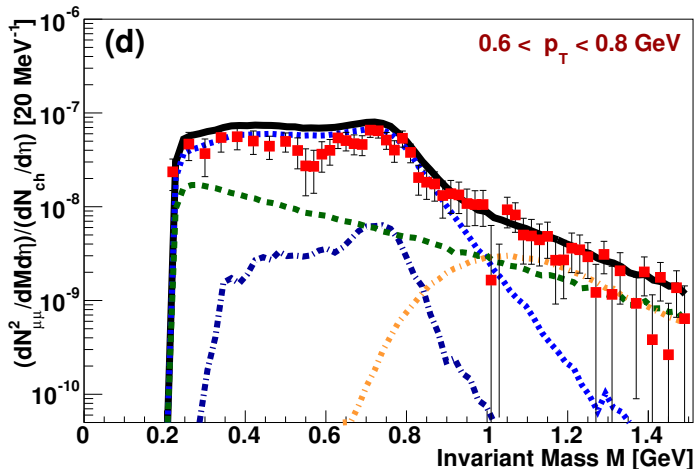
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



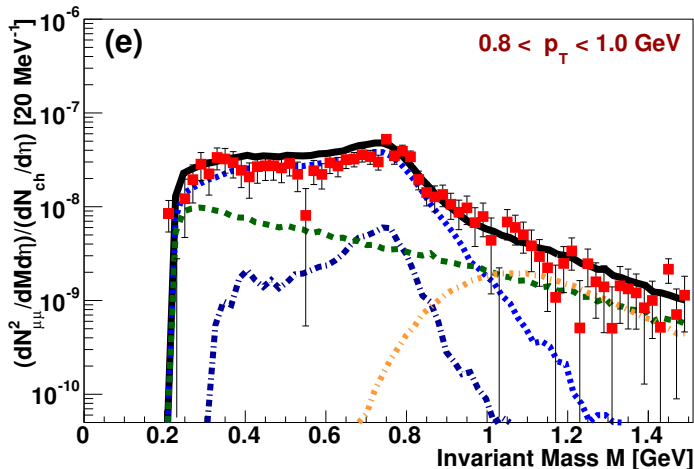
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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

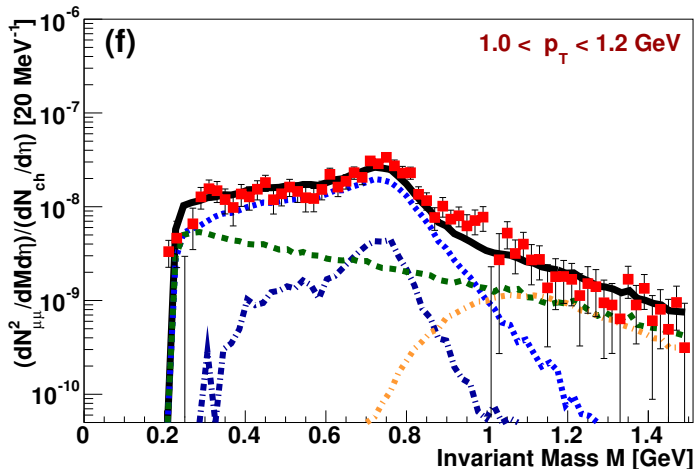


CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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

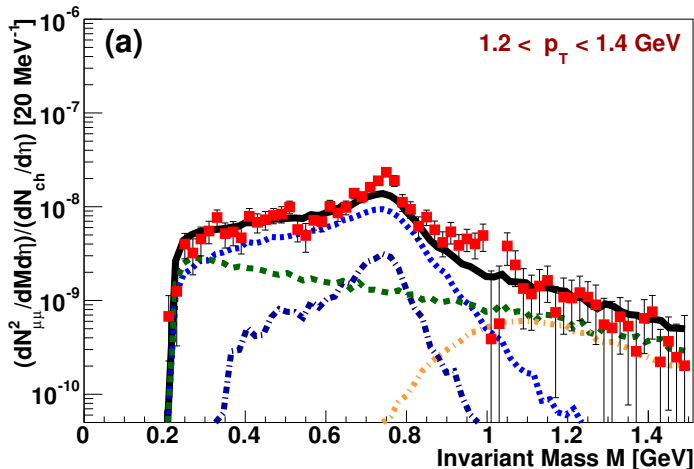


- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $1.0 \text{ GeV} < p_T < 1.2 \text{ GeV}$



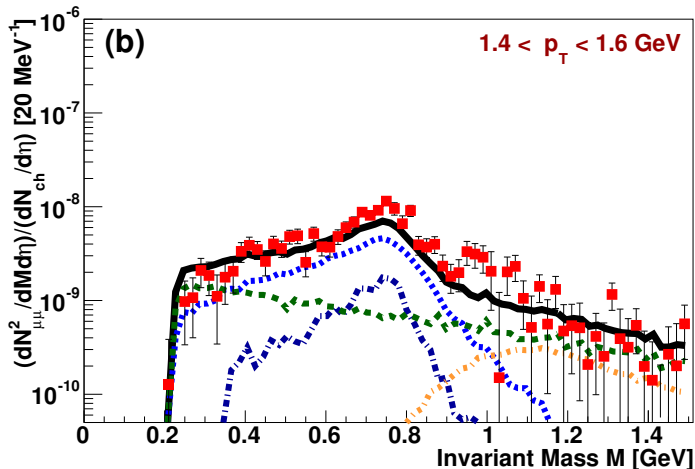
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



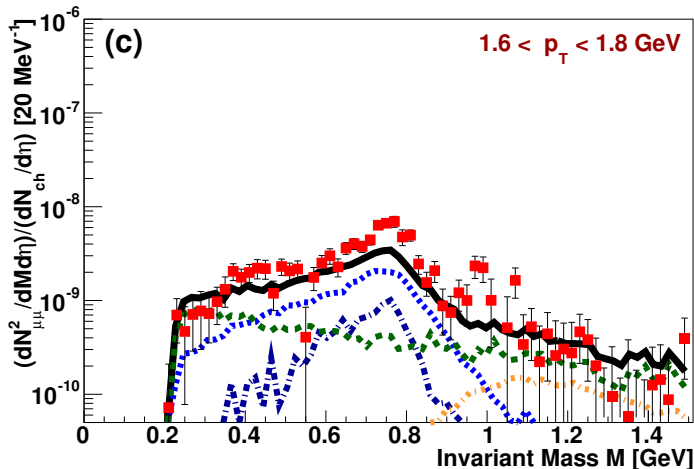
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



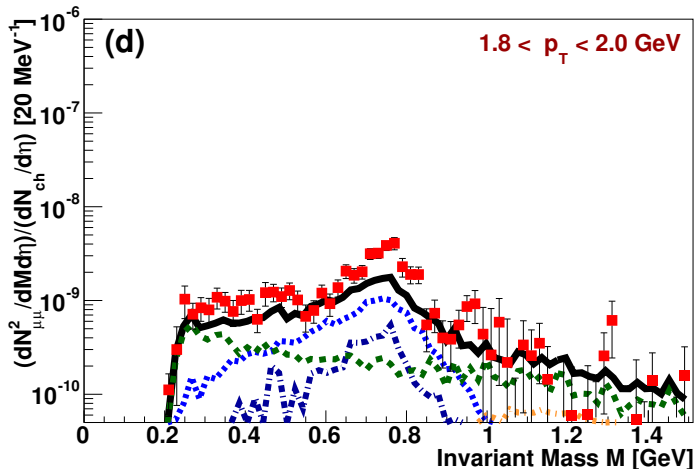
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



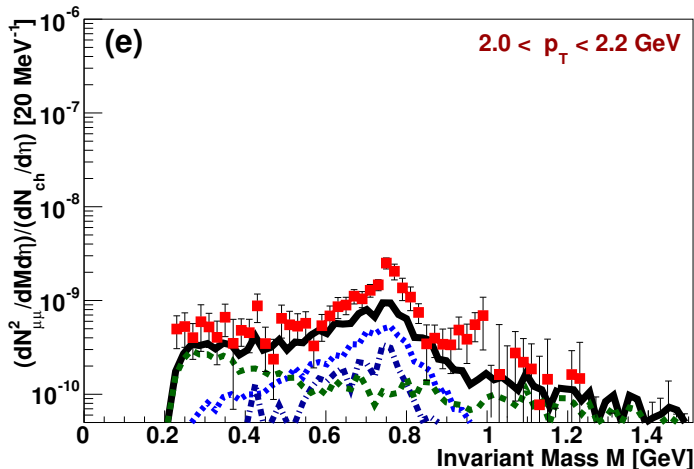
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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

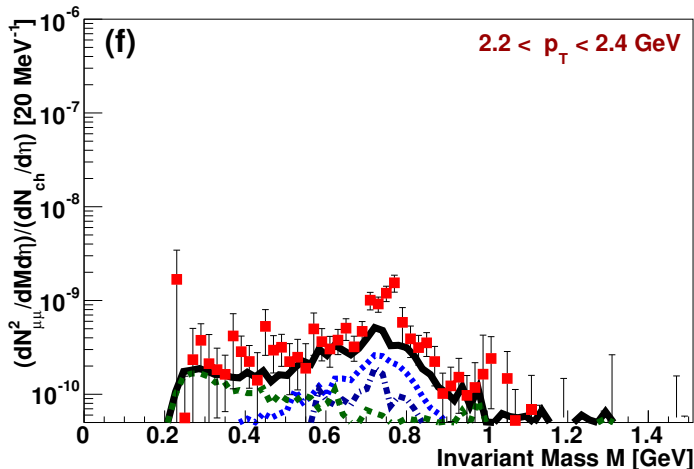


CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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

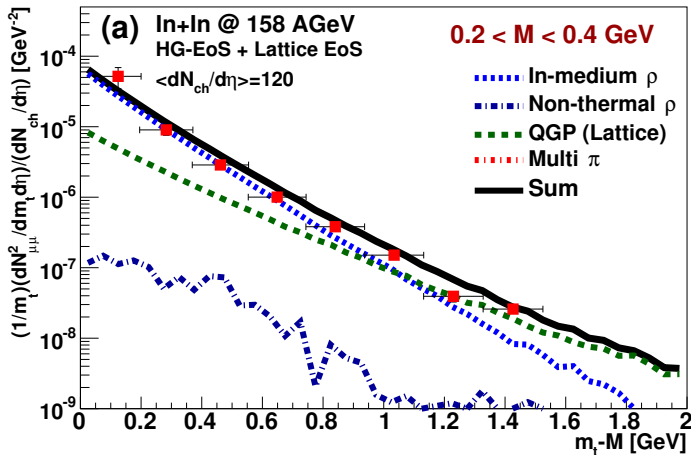


- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $2.2 \text{ GeV} < p_T < 2.4 \text{ GeV}$

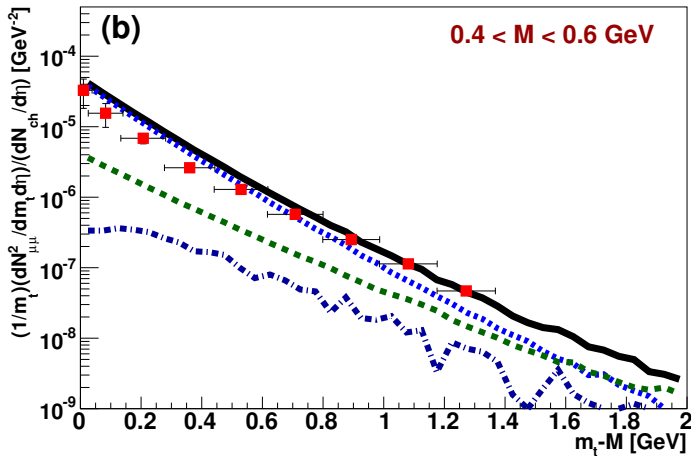


CGUrQMD: In+In (158 AGeV) (SPS/NA60)

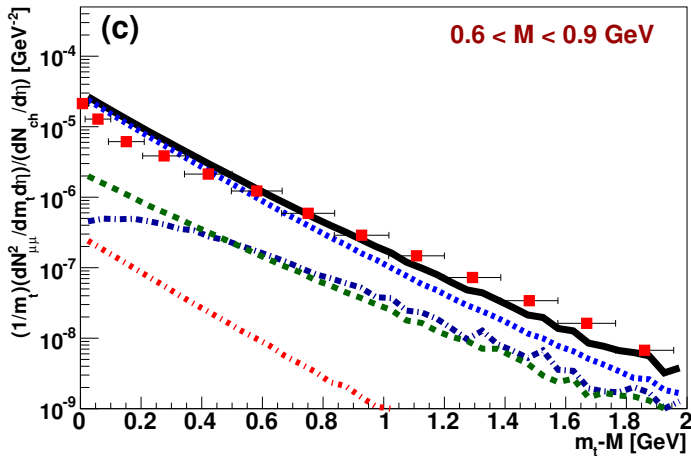
- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)



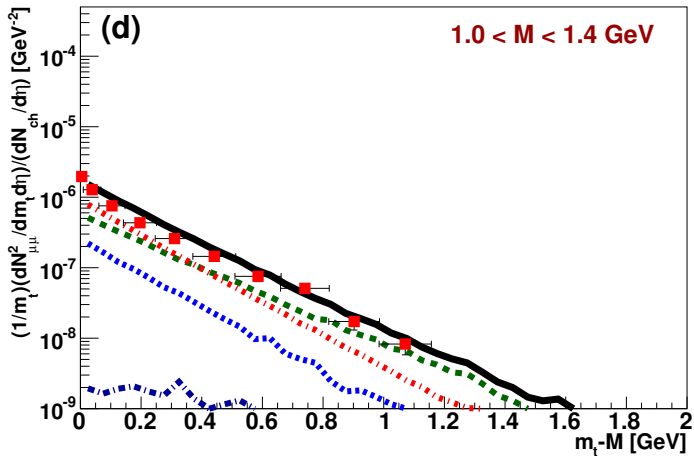
- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)



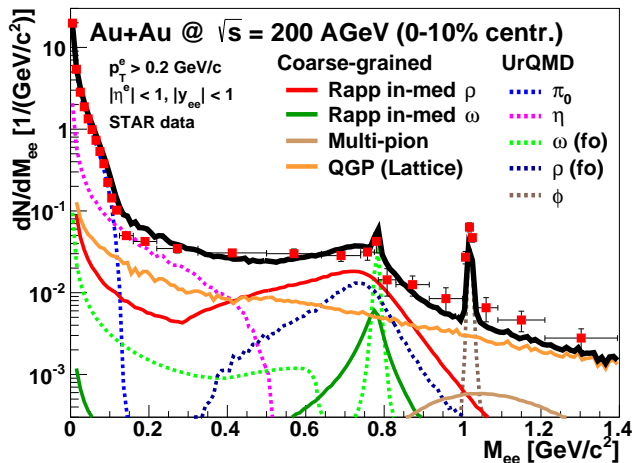
- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)

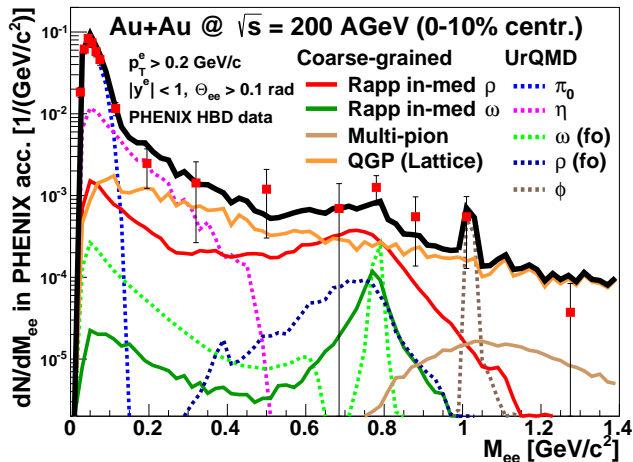


- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [EHWB15]
- min-bias data ($dN_{\text{ch}}/dy = 120$)



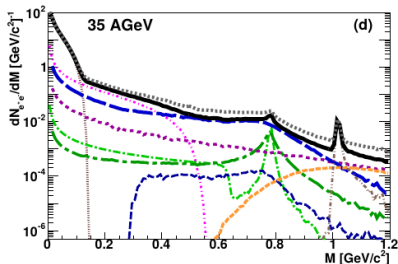
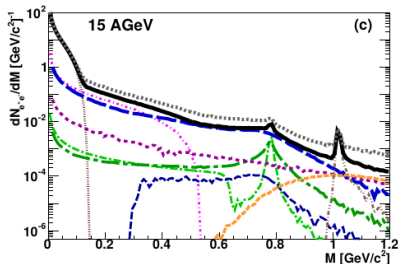
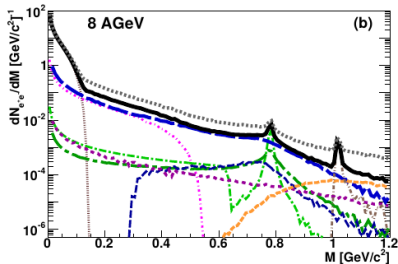
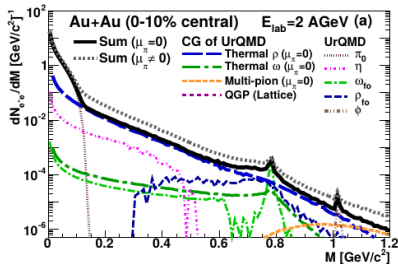
Dielectrons at RHIC





Dielectrons at RHIC-BES/FAIR/NICA

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



NB: also photon spectra [EHB16b]

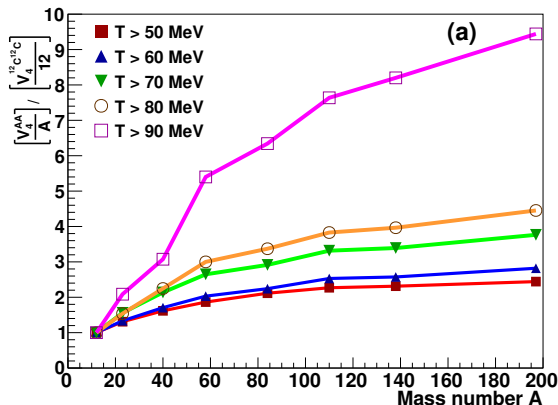
Signatures of the QCD-phase structure?

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!!!

Four Volume

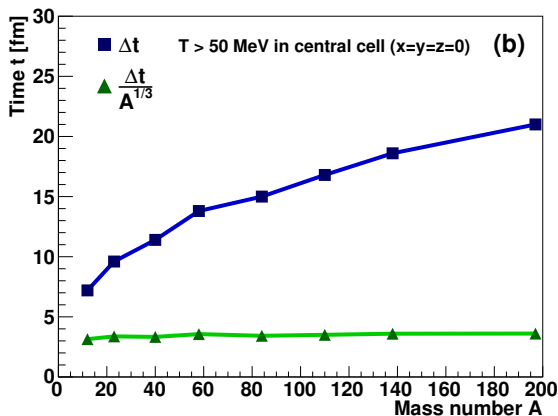
- central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76 \text{ AGeV}$
- $\frac{V_{AA}^{(4)}/A}{V_{CC}^{(4)}/12}$ of cells larger than various T



- how to explain “scaling behavior”?

Lifetime of the central cell

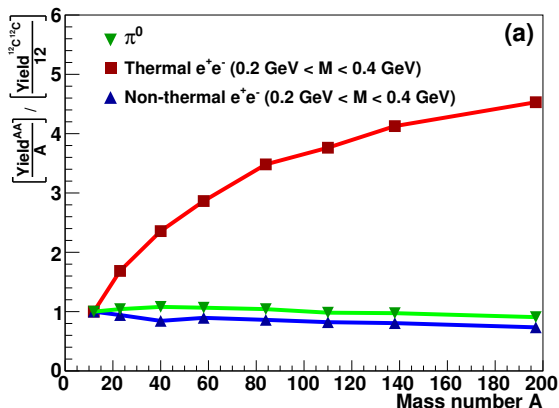
- central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76 \text{ AGeV}$



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

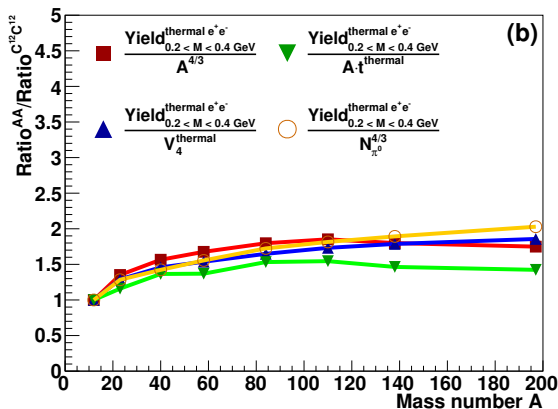
- central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76 \text{ AGeV}$
- $\frac{\text{yield}_{AA}/A}{\text{yield}_{CC}/12}$



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

Scaling behavior of thermal-dilepton yield

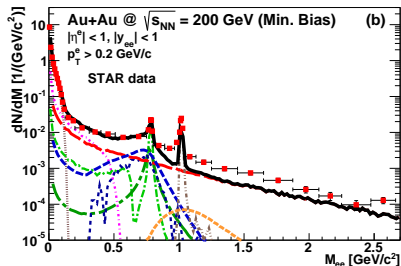
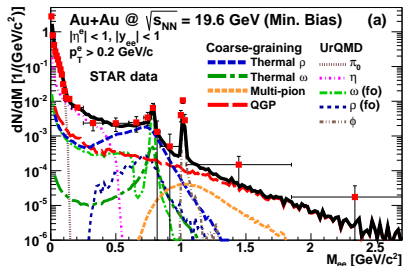
- central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76 \text{ AGeV}$



- 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

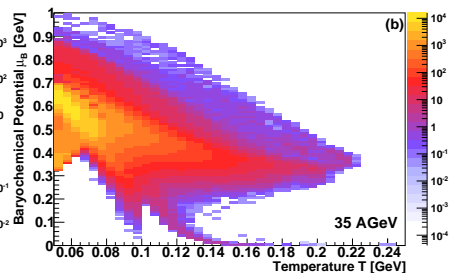
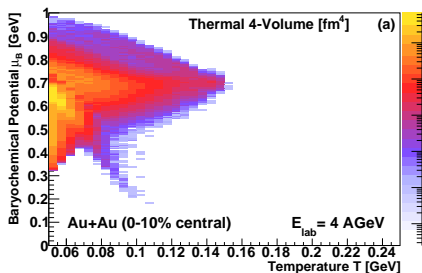
Dilepton systematics in the beam-energy scan

- T and μ_B vs. t [EHB16b, EHB16a]



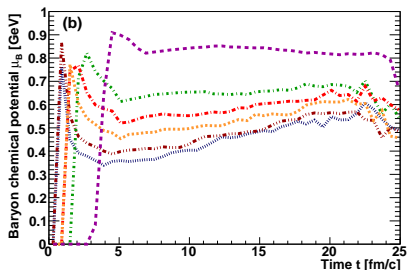
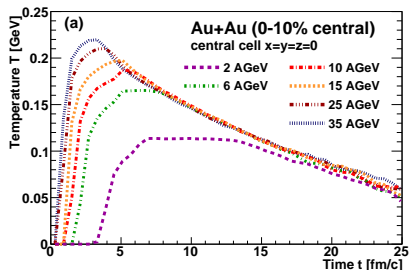
Dilepton systematics in the beam-energy scan

- thermal four-volume (fm^4) [EHB16b, EHB16a]



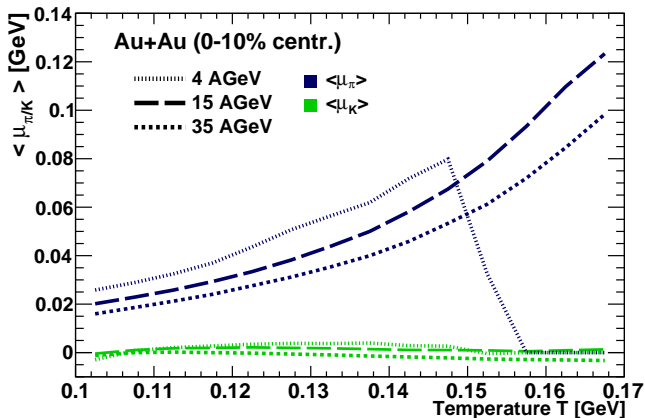
Dilepton systematics in the beam-energy scan

- T and μ_B vs. t [EHB16b, EHB16a]



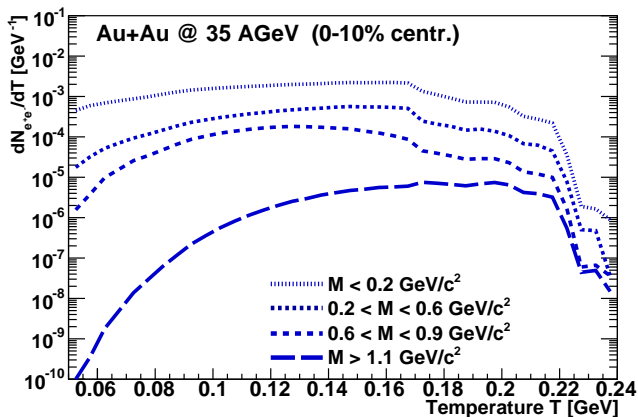
Dilepton systematics in the beam-energy scan

- $\mu_{\pi/K}$ -temperature relation [EHB16b, EHB16a]



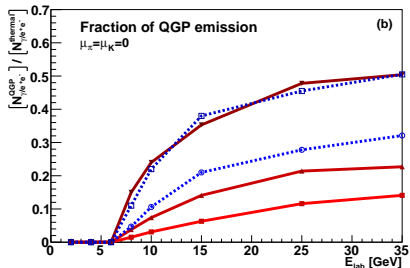
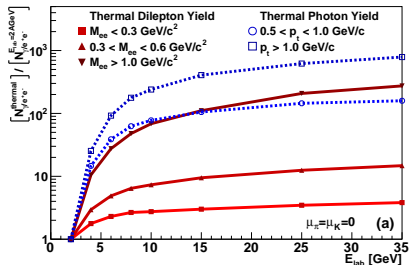
Dilepton systematics in the beam-energy scan

- mass-temperature relation in dilepton emission [EHB16b, EHB16a]



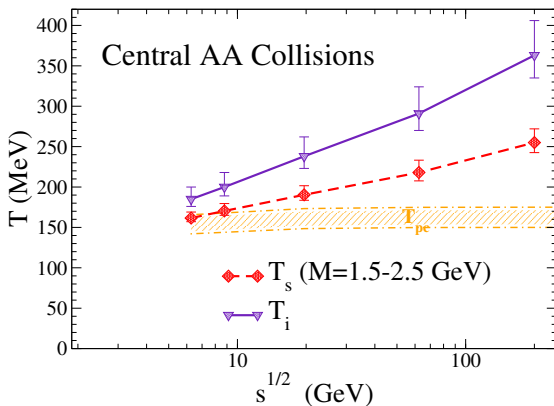
Dilepton systematics in the beam-energy scan

- excitation function e^+e^-/γ yield and QGP fraction [EHB16b, EHB16a]



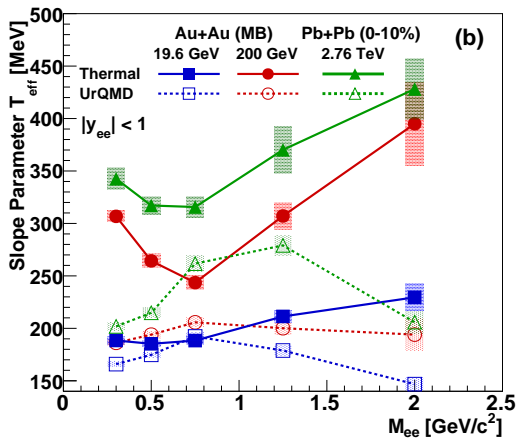
Dilepton systematics in the beam-energy scan

- 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



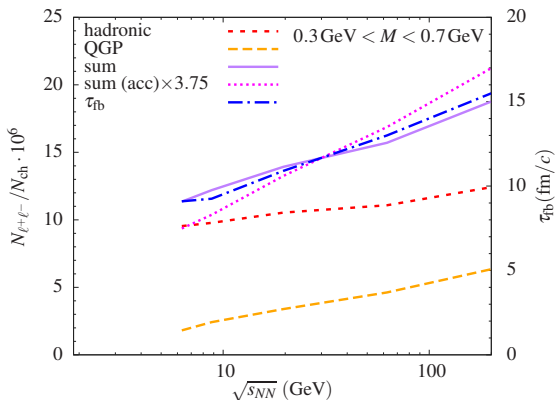
Dilepton systematics in the beam-energy scan

- excitation function e^+e^-/γ yield and QGP fraction [EHB16b, EHB16a]



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**



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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