

# Dileptons in heavy-ion-collisions

Hendrik van Hees

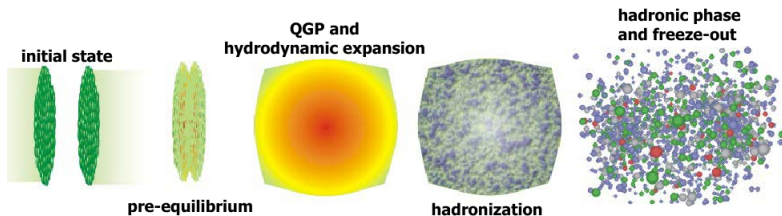
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January 11, 2018

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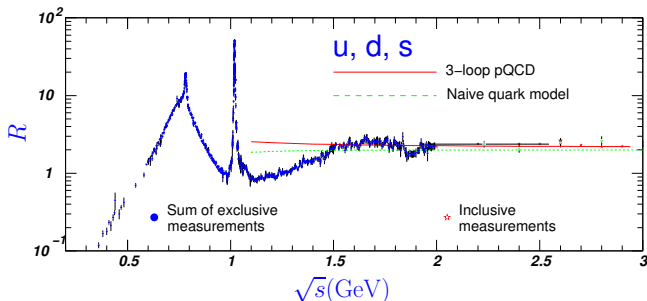
# Heavy-Ion collisions in a Nutshell

- 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  $\mu_B$**



# Electromagnetic probes theory perspective

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

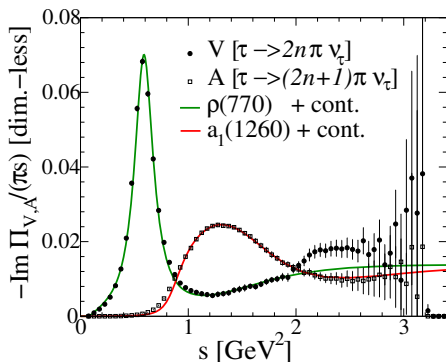
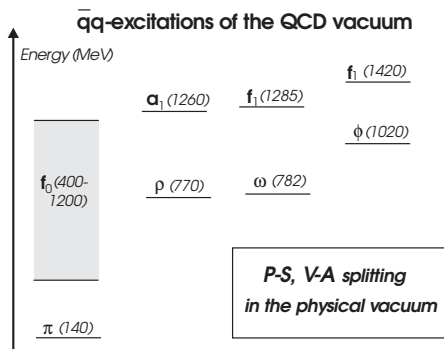


$$R := \frac{\sigma_{e^+e^- \rightarrow \text{hadrons}}}{\sigma_{e^+e^- \rightarrow \mu^+\mu^-}}$$

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

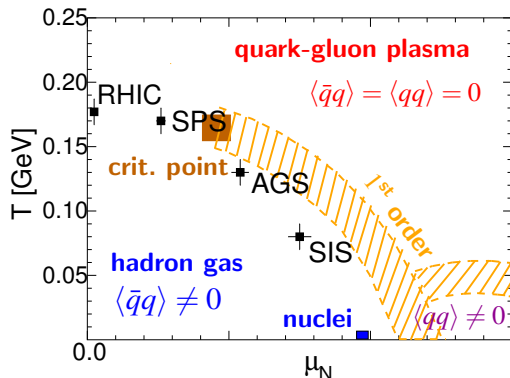
# Hadron phenomenology and chiral symmetry

- 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



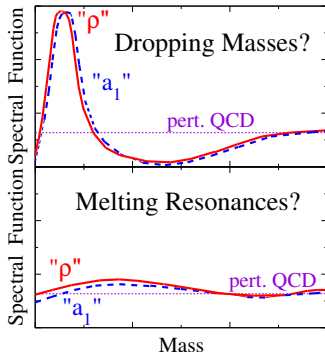
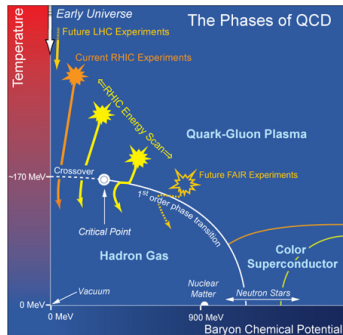
# The QCD-phase diagram

- **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

- $\gamma, l^\pm$ : 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**

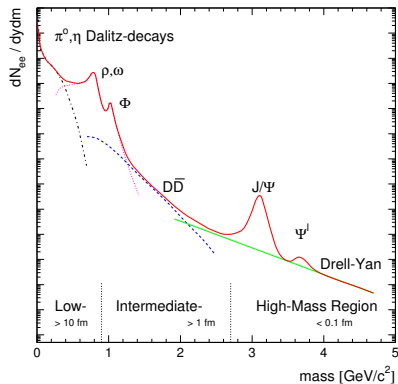
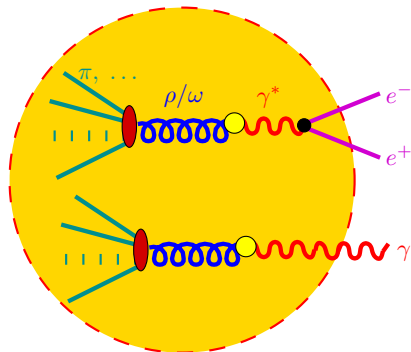


Fig. by A. Drees

# 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  $\alpha$ :  $4\pi\alpha\Pi_{\mu\nu} \simeq \Sigma_{\mu\nu}^{(\gamma)}$
- **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 ( $\rho, \omega, \phi$ )!**

# 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

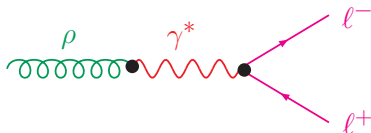
$$\Pi_{\text{em},i}^{\mu\nu} = i \int d^4x \exp(iqx) \Theta(x^0) \langle [j_{\text{em},i}^\mu(x), j_{\text{em},i}^\nu(0)] \rangle$$

- 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: $\rho$ decays

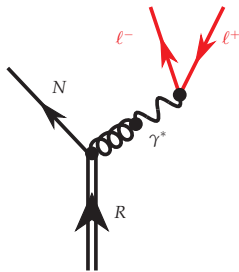
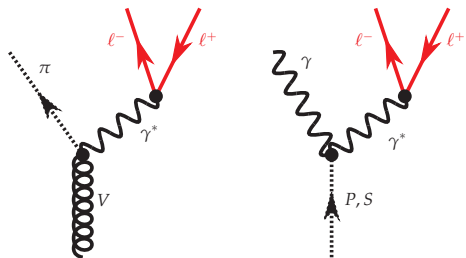
- model assumption: **vector-meson dominance**



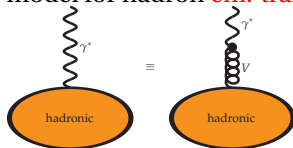
$$\begin{aligned}\frac{dN_{\rho \rightarrow l+l-}^{(\text{MT})}}{d^4x d^4q} &= \frac{M}{q^0} \Gamma_{\rho \rightarrow l+l-}(M) \frac{dN_{\rho}}{d^3\vec{x} d^4q} \\ &= -\frac{\alpha^2}{3\pi^3} \frac{L(M^2)}{M^2} \frac{m_{\rho}^4}{g_{\rho}^2} g_{\mu\nu} \text{Im} D_{\rho}^{\mu\nu}(M, \vec{q}) f_B \left(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

- 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  $\rho$  propagator at given  $T(t)$ ,  $\mu_{\text{meson/baryon}}(t)$
- analogous for  $\omega$  and  $\phi$

# Transition form factors: “ $\rho$ 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
- $V: \omega \rightarrow \pi + \gamma^* \rightarrow \pi + l^+ + l^-$
- $P, S: \pi, \eta \rightarrow \gamma + \gamma^* \rightarrow \gamma + l^+ + l^-$
- $R$ : Baryon resonances  
 $\Delta, N^* \rightarrow N + V \rightarrow N + \gamma^* \rightarrow N + l^+ + l^-$
- vector-meson dominance
- model for hadron em. trans. FF

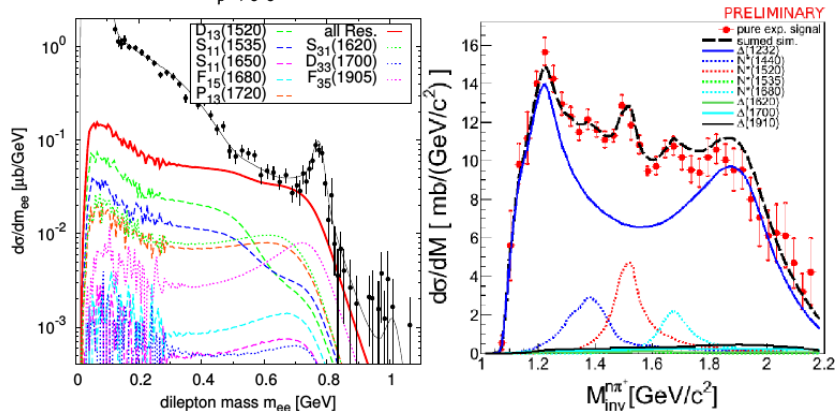


# GiBUU: “ $\rho$ meson” in $pp$

- production through hadron resonances

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

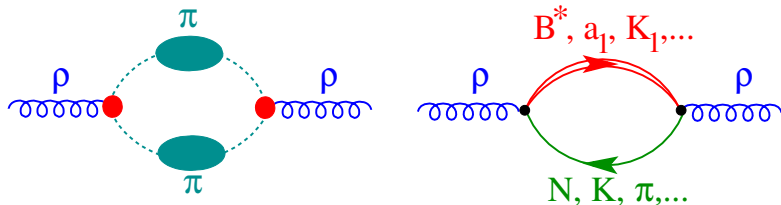
$$\rho \rightarrow e^+e^-$$



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

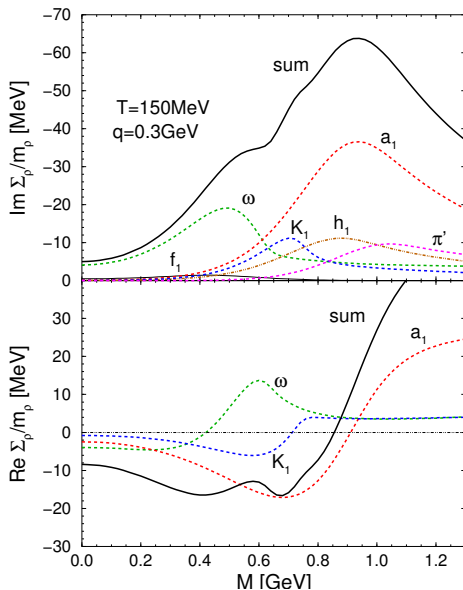
# Hadronic many-body theory

- 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



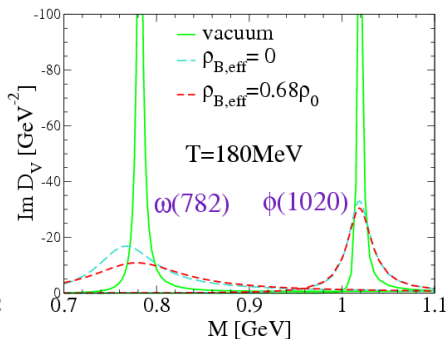
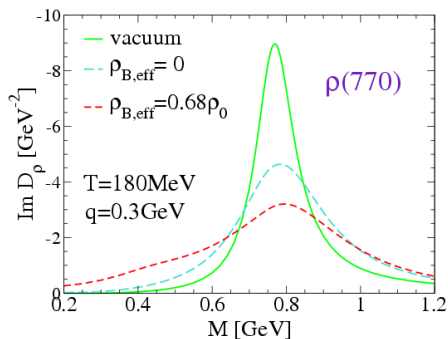
- **Baryons** important, even at low **net** baryon density  $n_B - n_{\bar{B}}$
- reason:  $n_B + n_{\bar{B}}$  relevant (CP inv. of strong interactions)

# Meson contributions





# In-medium spectral functions and baryon effects

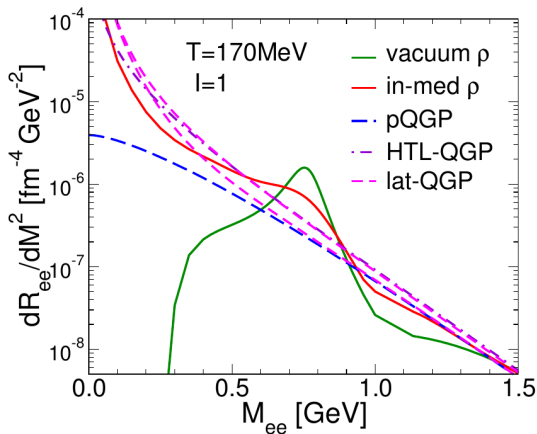


[RW99]

- **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  $\gamma$  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  $T, \mu_B, \mu_\pi, \dots$
  - $\Rightarrow$  use equilibrium rates locally

# Coarse-grained UrQMD (CGUrQMD)

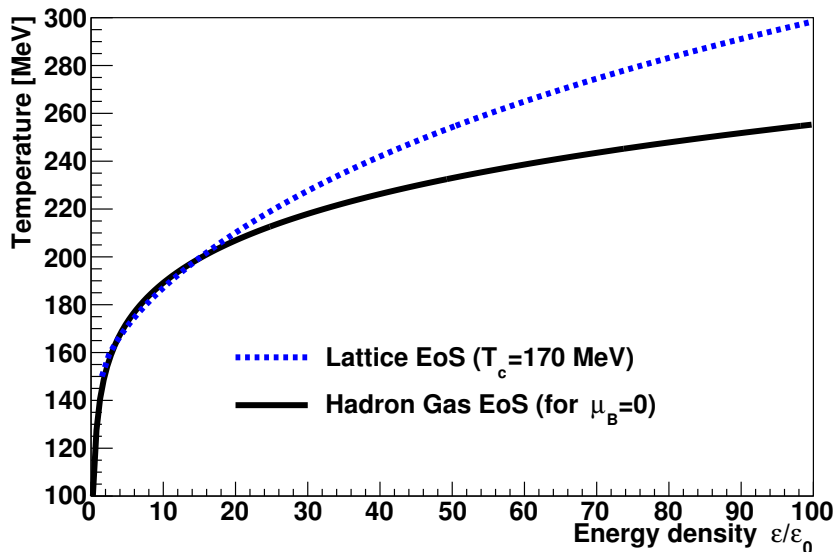
- problem with **medium modifications** of spectral functions/interactions
- only available in equilibrium many-body QFT models
- use “in-medium cross sections” naively: **double counting?!?**
- way out: map transport to **local-equilibrium fluid**
- use **ensemble of UrQMD** runs with an **equation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

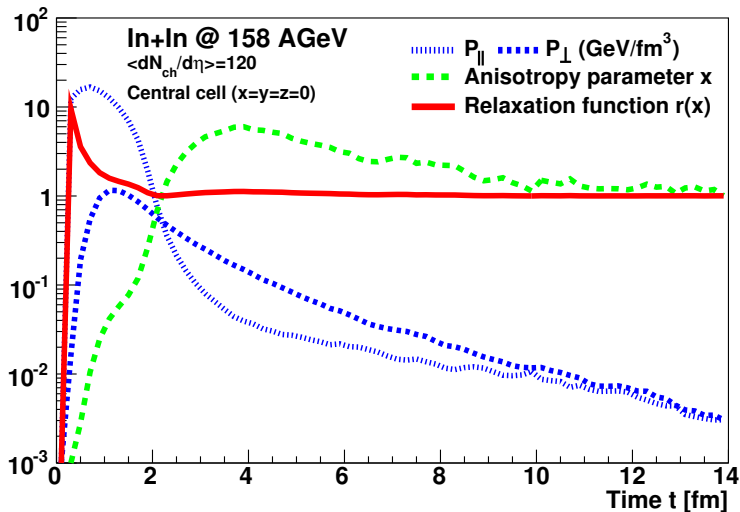
# Coarse-grained UrQMD (CGUrQMD)

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



# Coarse-grained UrQMD (CGUrQMD)

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

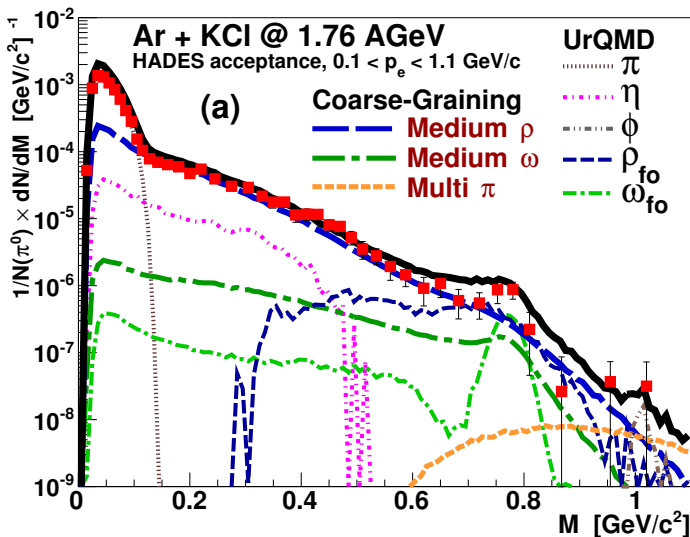


# Dielectrons (SIS/HADES)



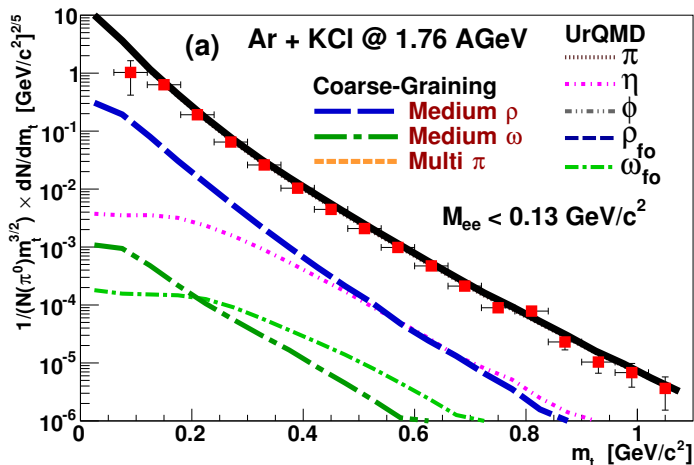
# CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

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



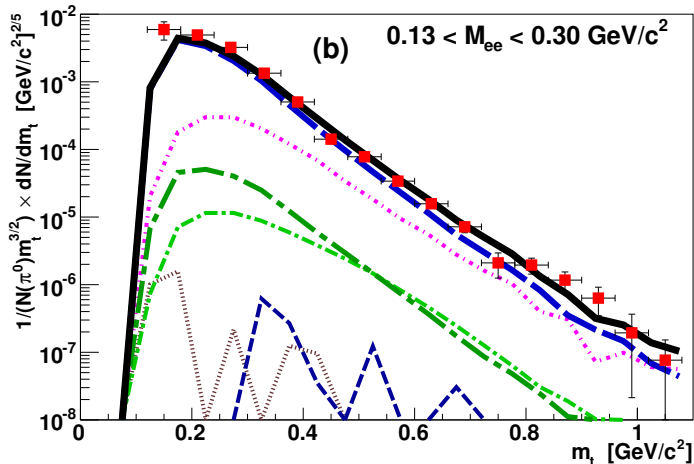
# CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

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



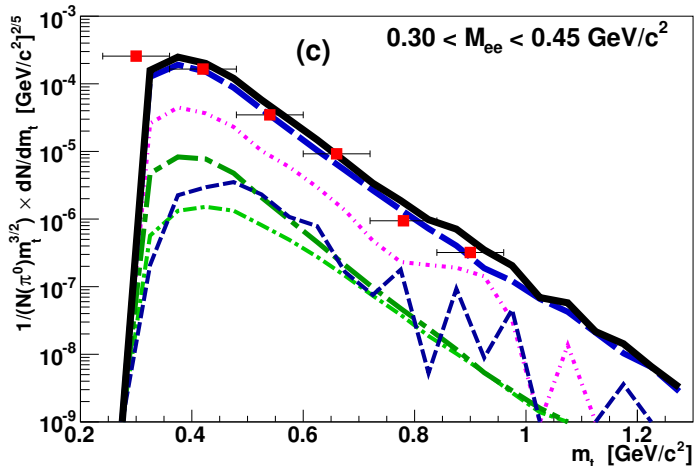
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- dielectron spectra from Ar + KCl(1.76 AGeV)  $\rightarrow e^+e^-$  (SIS/HADES)
- $m_t$  spectra
- $0.13 \text{ GeV} < M_{ee} < 0.30 \text{ GeV}$



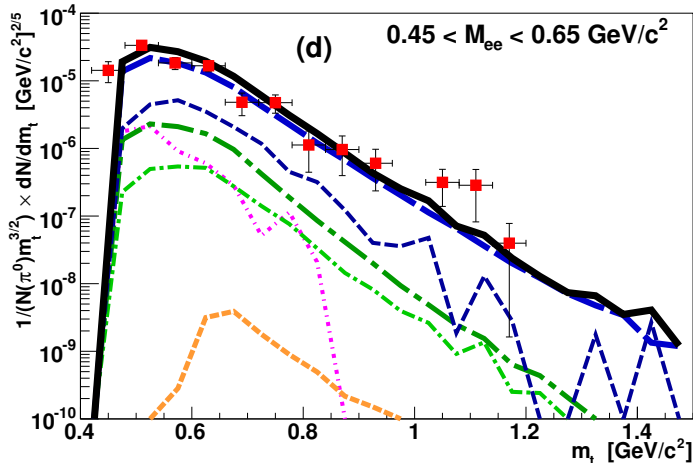
# CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

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



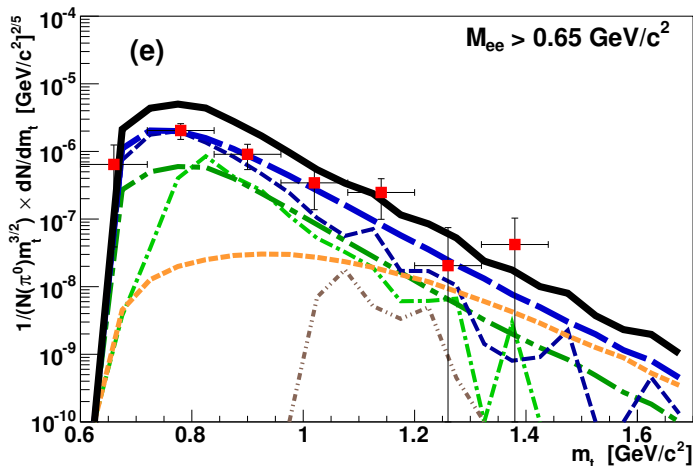
# CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

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



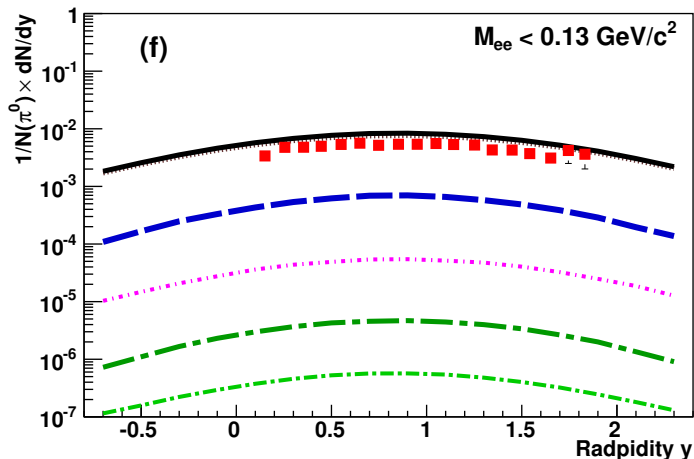
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- $m_t$  spectra
- $M_{ee} > 0.65$  GeV

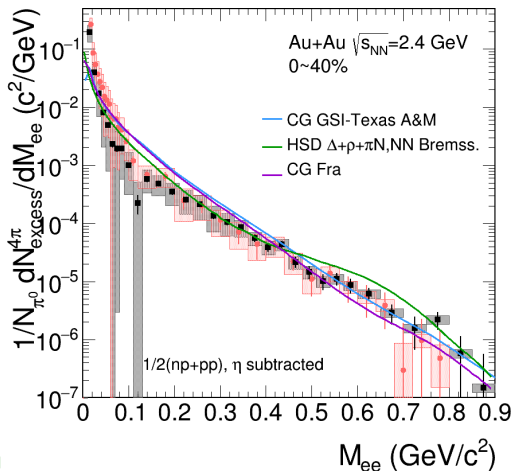


# CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

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



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



[T. Galtyuk, Quark Matter 2017 talk]

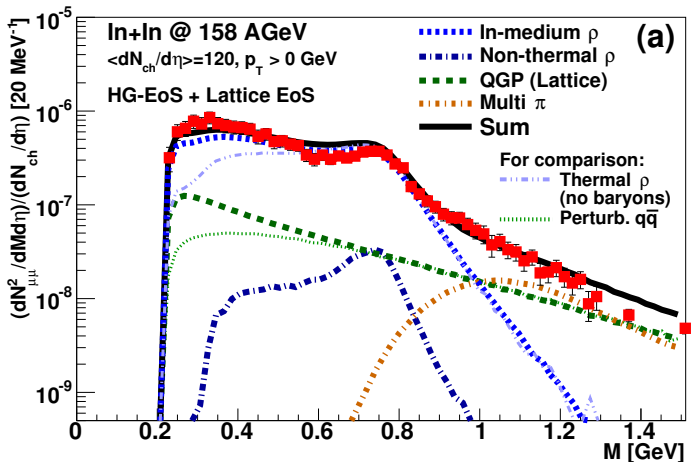
- good agreement between models and data
- consistency between two independent coarse-grained-UrQMD simulations
- based on same Rapp-Wambach in-medium rates



# Dimuons (SPS/NA60)

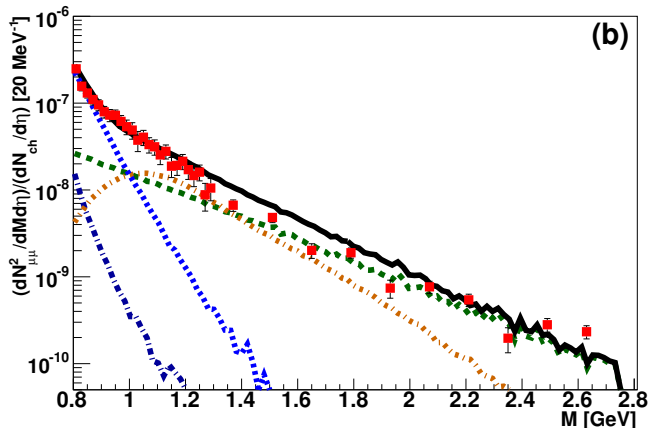
# CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



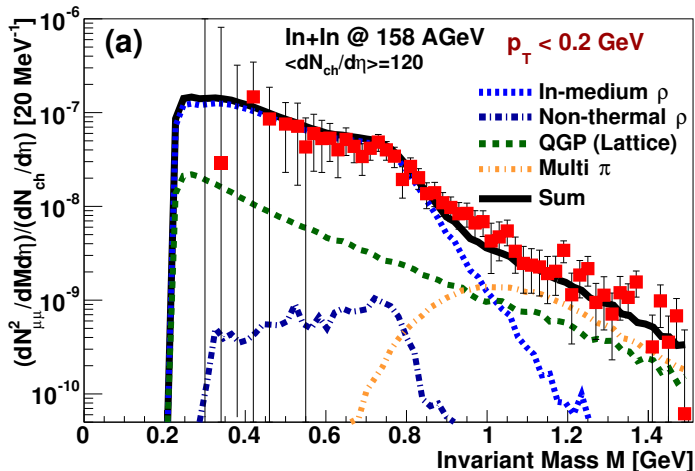
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- dimuon spectra from In + In(158 AGeV)  $\rightarrow \mu^+ \mu^-$  (NA60) [EHWB15]
- min-bias data ( $dN_{\text{ch}}/dy = 120$ )
- higher IMR: provides **averaged true temperature**  
 $\langle T \rangle_{1.5 \text{ GeV} \lesssim M \lesssim 2.4 \text{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



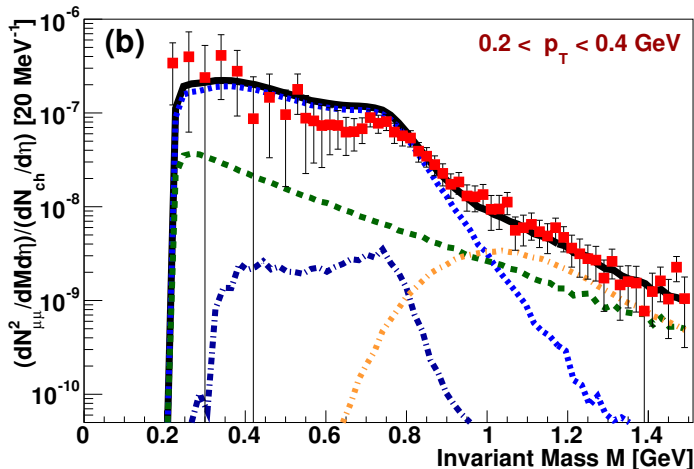
# CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- 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



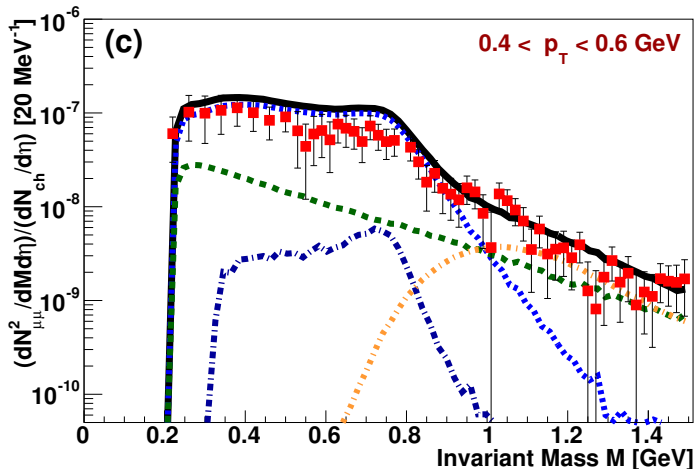
# CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



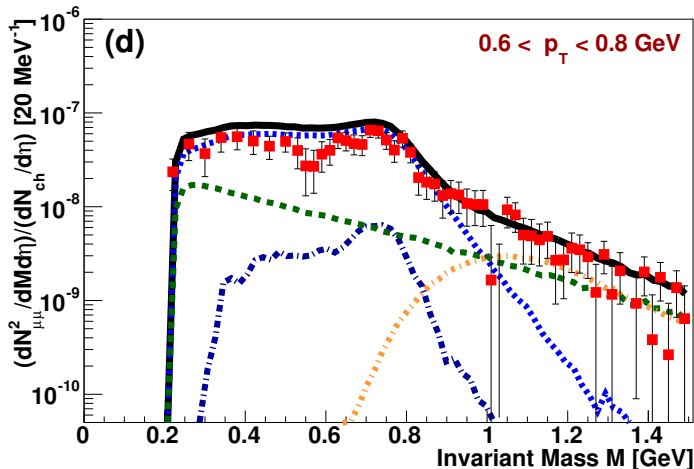
# CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



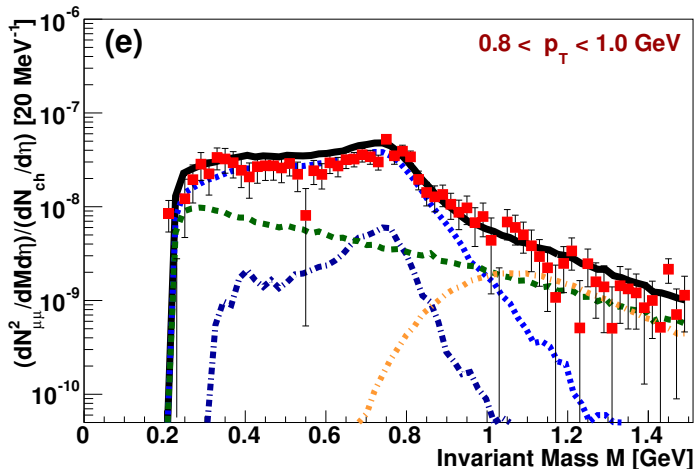
# CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



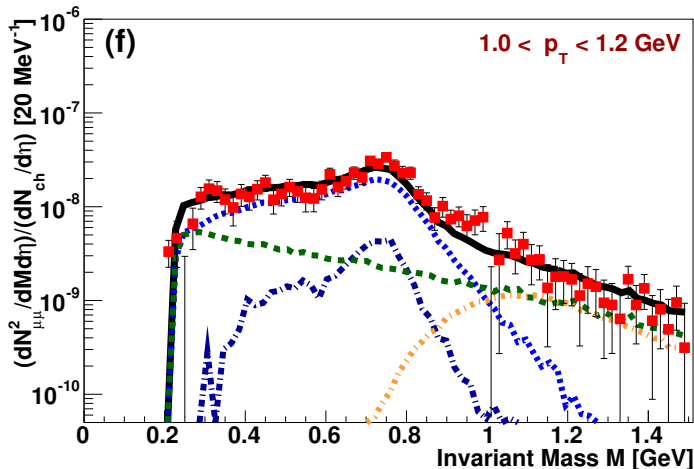
# CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



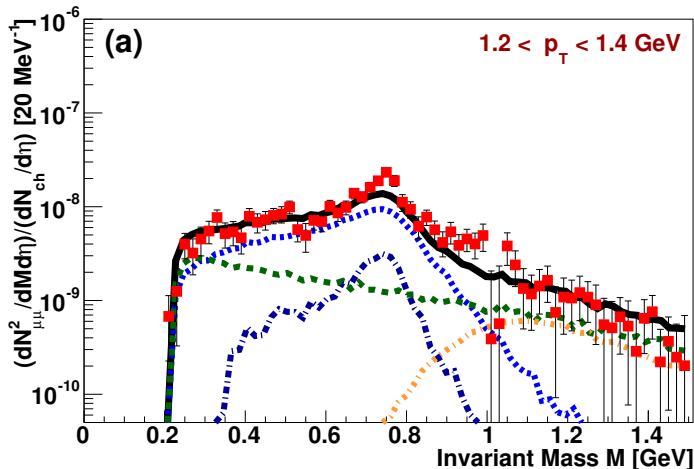


- dimuon spectra from In + In(158 AGeV)  $\rightarrow \mu^+ \mu^-$  (NA60) [EHWB15]
- min-bias data ( $dN_{\text{ch}}/dy = 120$ )
- $1.0 \text{ GeV} < p_T < 1.2 \text{ GeV}$



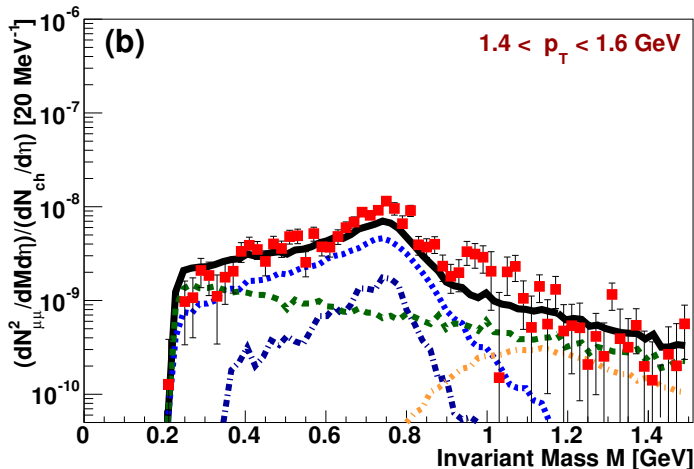
# CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



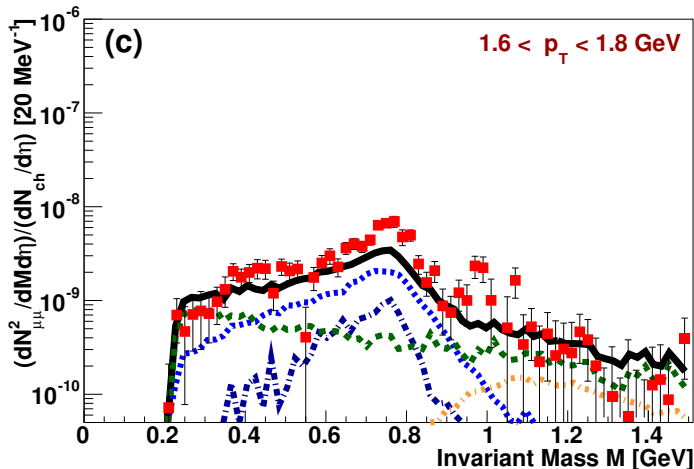
# CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



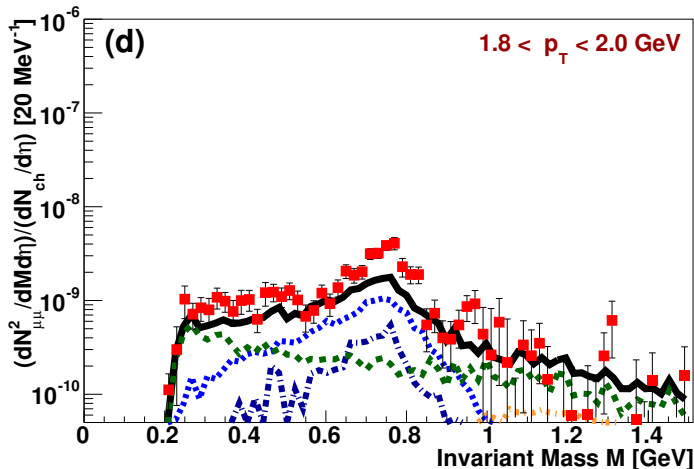
# CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



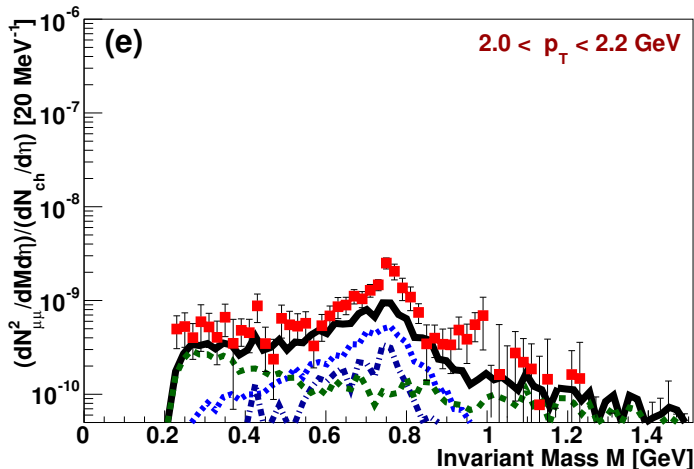
# CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



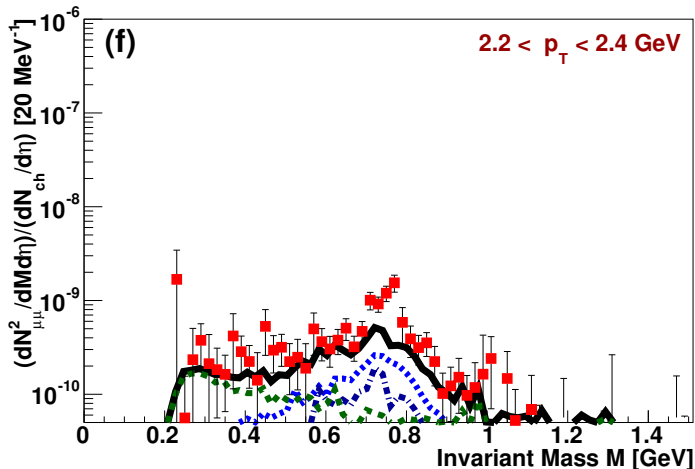
# CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



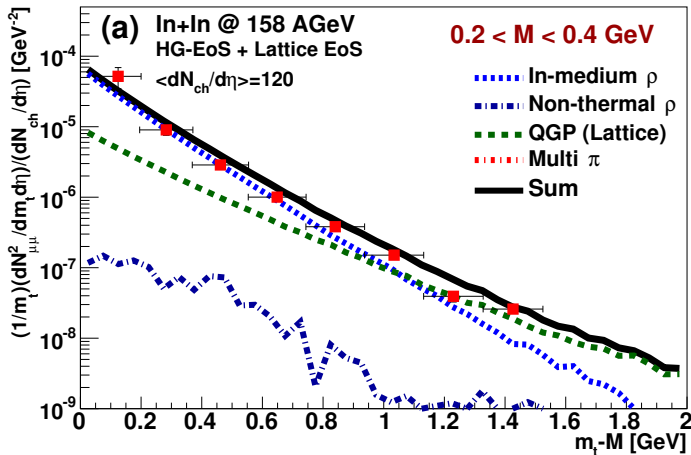
# CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



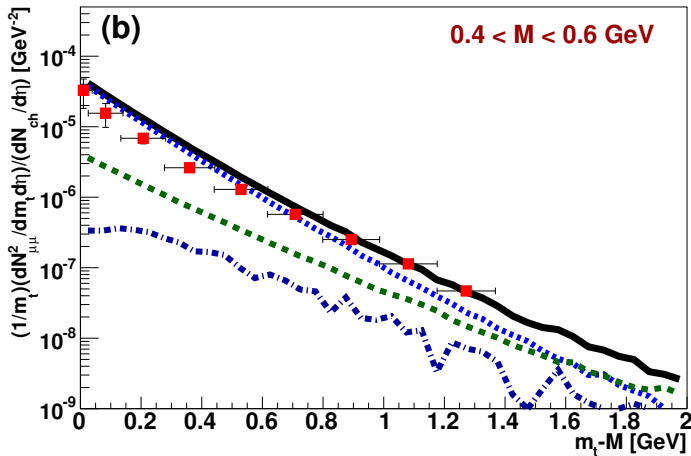
# CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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

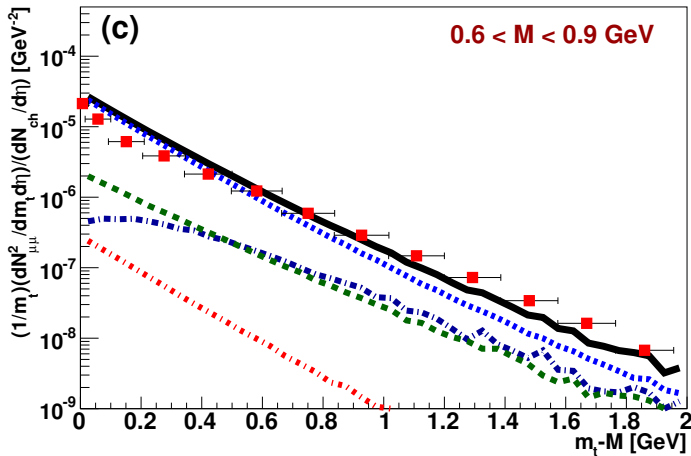




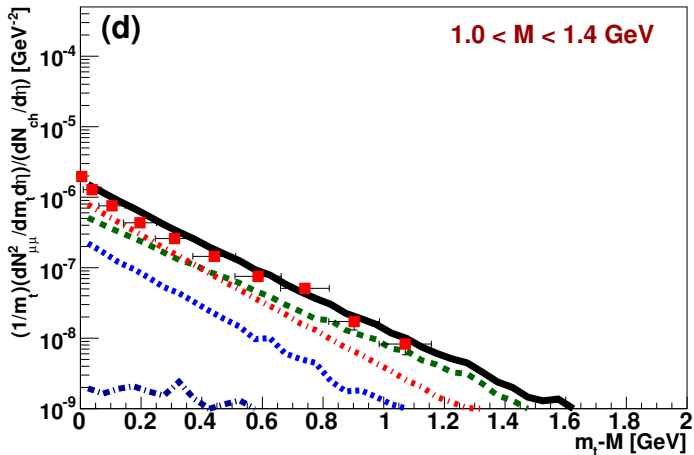
- dimuon spectra from In + In(158 AGeV)  $\rightarrow \mu^+ \mu^-$  (NA60) [EHWB15]
- min-bias data ( $dN_{\text{ch}}/dy = 120$ )



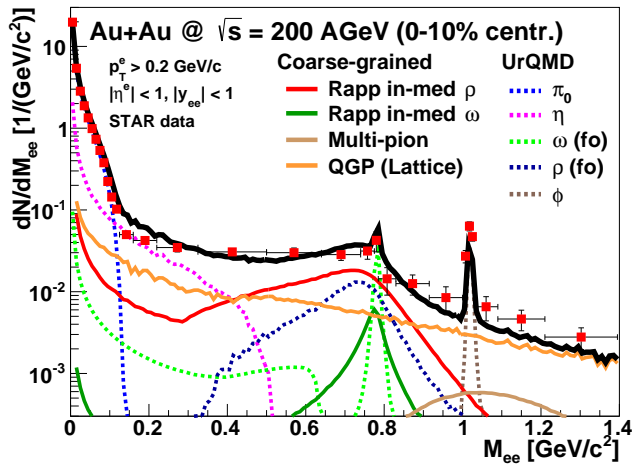
- dimuon spectra from In + In(158 AGeV)  $\rightarrow \mu^+ \mu^-$  (NA60) [EHWB15]
- min-bias data ( $dN_{\text{ch}}/dy = 120$ )

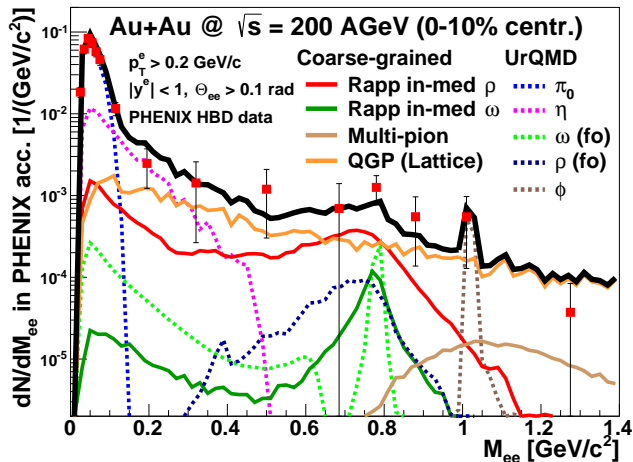


- dimuon spectra from In + In(158 AGeV)  $\rightarrow \mu^+ \mu^-$  (NA60) [EHWB15]
- min-bias data ( $dN_{\text{ch}}/dy = 120$ )



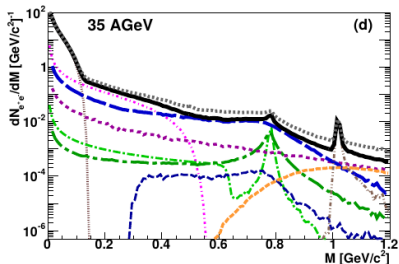
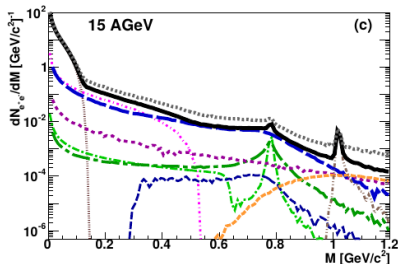
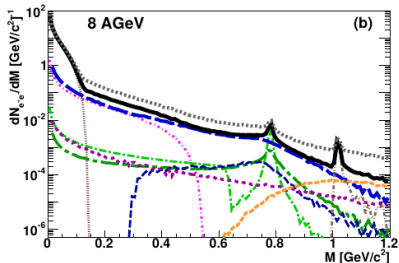
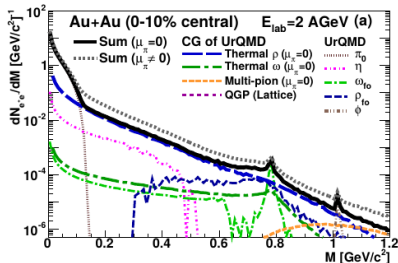
# Dielectrons at RHIC





# Dielectrons at RHIC-BES/FAIR/NICA

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



NB: also photon spectra [\[EHB16b\]](#)



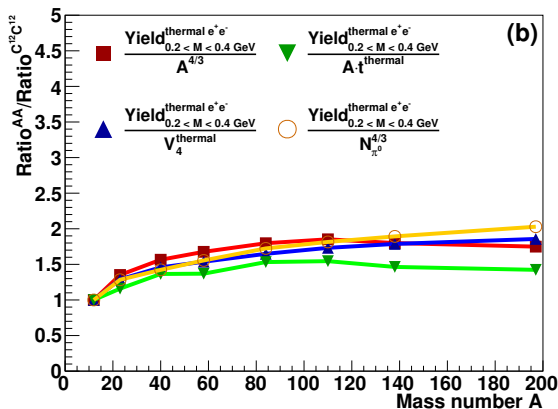
# Signatures of the QCD-phase structure?

# 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  $\gamma$ ) emission vs. beam energy [EHB16b, RH16]  
similar study in [GHR<sup>+</sup>16]
- **caveat**: phase transition not really implemented!!!

# Scaling behavior of thermal-dilepton yield

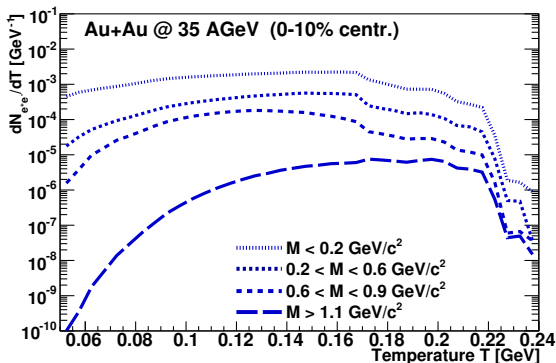
- central collisions from C+C to Au+Au at  $E_{\text{kin}} = 1.76 \text{ AGeV}$



- 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

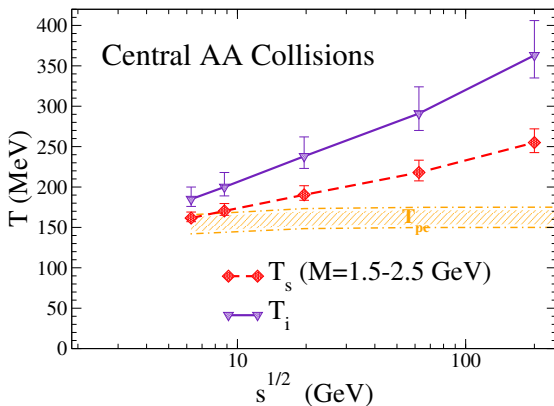
# Mass-temperature relation in dilepton emission

- 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)



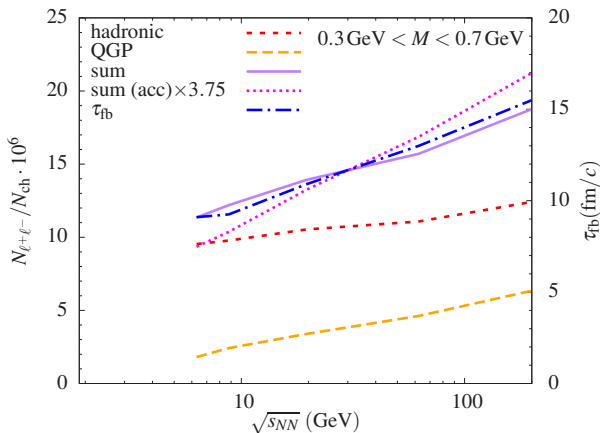
# Dilepton systematics in the beam-energy scan

- 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  $\chi$  symmetry restoration)
- **medium modifications of  $\rho$ ,  $\omega$ ,  $\phi$**
- 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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