Dileptons in heavy-ion-collisions

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September 13, 2021

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CRC-TR 211 Strong-interaction matter under extreme conditions

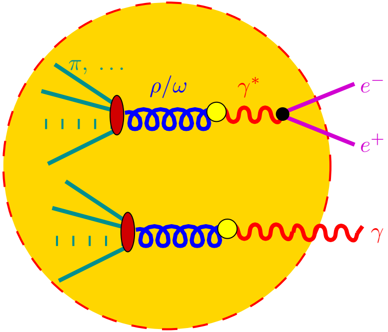
Outline

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

Electromagnetic probes
theory perspective

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



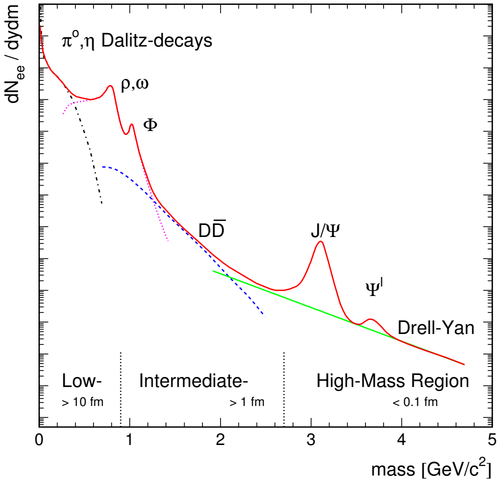


Fig. by A. Drees

Electromagnetic probes from thermal source

- retarded electromagnetic-current-correlation function

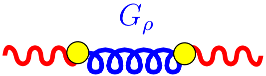
$$\Pi^{\mu\nu}_{\text{em},i} = \mathrm{i} \int \mathrm{d}^4 x \, \exp(\mathrm{i} q x) \Theta(x^0) \left\langle \left[j^{\mu}_{\text{em},i}(x), j^{\nu}_{\text{em},i}(0) \right] \right\rangle$$

- McLerran-Toimela formula [MT85, GK91]

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

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

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

$\Sigma^{\gamma}_{\mu\nu} =$ 

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

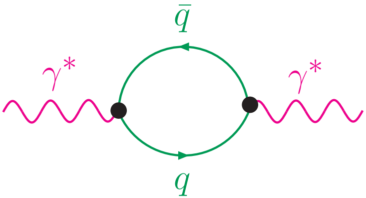
Radiation from thermal QGP: $q\bar{q}$ annihilation

- General: McLerran-Toimela formula

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

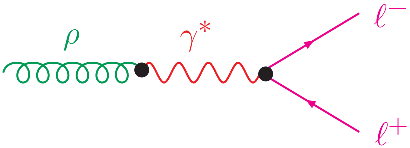
- in QGP phase: $q\bar{q}$ annihilation
- hard-thermal-loop improved em. current-current correlator

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



Radiation from hadronic sources: ρ, ω, ϕ decays

- model assumption: vector-meson dominance

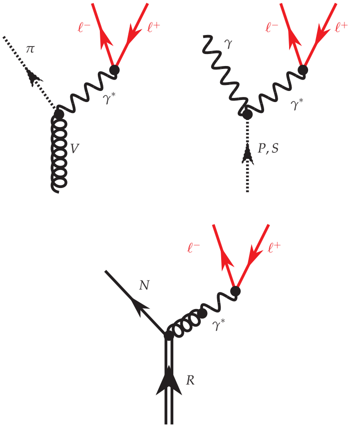


$$\frac{\mathrm{d}N^{(\mathrm{MT})}_{\rho\to l^+ l^-}}{\mathrm{d}^4 x\,\mathrm{d}^4 q} = \frac{M}{q^0}\Gamma_{\rho\to l^+ l^-}(M)\frac{\mathrm{d}N_\rho}{\mathrm{d}^3\vec{x}\,\mathrm{d}^4 q}$$

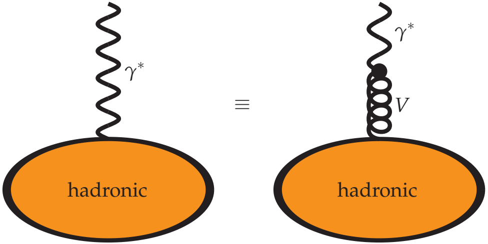
$$= -\frac{\alpha^2}{3\pi^3}\frac{L(M^2)}{M^2}\frac{m_\rho^4}{g_\rho^2} g_{\mu\nu}\,\mathrm{Im}\, D_\rho^{\mu\nu}(M,\vec{q}) f_B\left(\frac{q\cdot u - 2\mu_\pi(t)}{T(t)}\right)$$

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

Transition form factors: "ρ mesons" via VMD

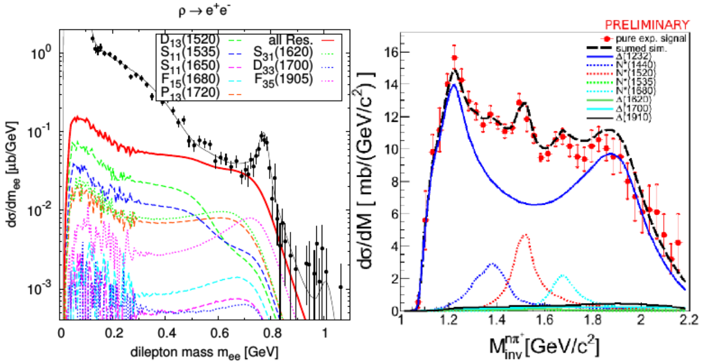


- vector mesons have "vacuum spectral shapes"
- propagated as "on-shell particles" of finite lifetime and variable mass
- Dalitz decay: 1 particle $\rightarrow$ 3 particles
- V: $\omega \rightarrow \pi + \gamma^* \rightarrow \pi + \ell^+ + \ell^-$
- P, S: $\pi, \eta \rightarrow \gamma + \gamma^* \rightarrow \gamma + \ell^+ + \ell^-$
- 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

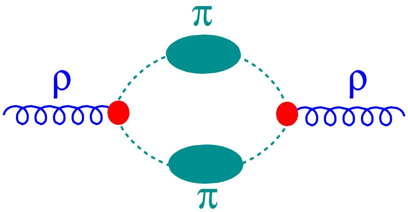
- production through hadron resonances
  $NN \rightarrow NR \rightarrow NN\rho$, $NN \rightarrow N\Delta \rightarrow NN\pi\rho$

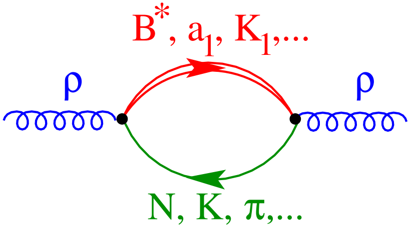


- plots: J. Weil et al [WHM12, ABB+14]
- VMD model ⟺ em. transition form factors of baryon resonances!
- “ρ”-line shape “modified” already in elementary hadronic reactions
- due to production mechanism via resonances

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

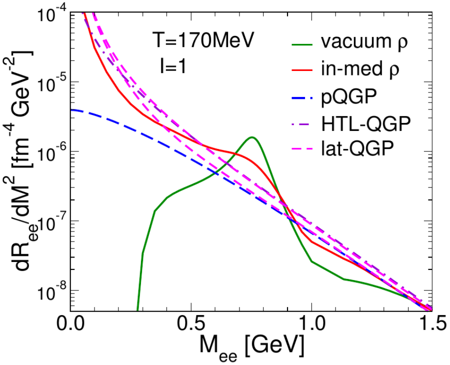




- Baryons important, even at low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

Dilepton rates: Hadron gas ⟷ QGP

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



[Rap13]

Bulk-medium evolution

Bulk evolution with transport and coarse graining

- established transport models for bulk evolution
  - e.g., UrQMD, GiBUU, BAMPS, (p)HSD,...
  - solve Boltzmann equation for hadrons and/or partons
- dilemma: need medium-modified dilepton/photon emission rates
- usually available only in equilibrium QFT calculations
- ways out:
  - (ideal) hydrodynamics ⇒ local thermal equilibrium ⇒ use equilibrium rates
  - transport-hydro hybrid model: treat early stage with transport, then coarse grain ⇒ switch to hydro ⇒ switch back to transport (Cooper-Frye "particlization")
- here: UrQMD transport for entire bulk evolution
  ⇒ use coarse graining in space-time cells ⇒ extract $T, \mu_B, \mu_\pi, \ldots$ ⇒ use equilibrium rates locally

Coarse-grained UrQMD (CGUrQMD)

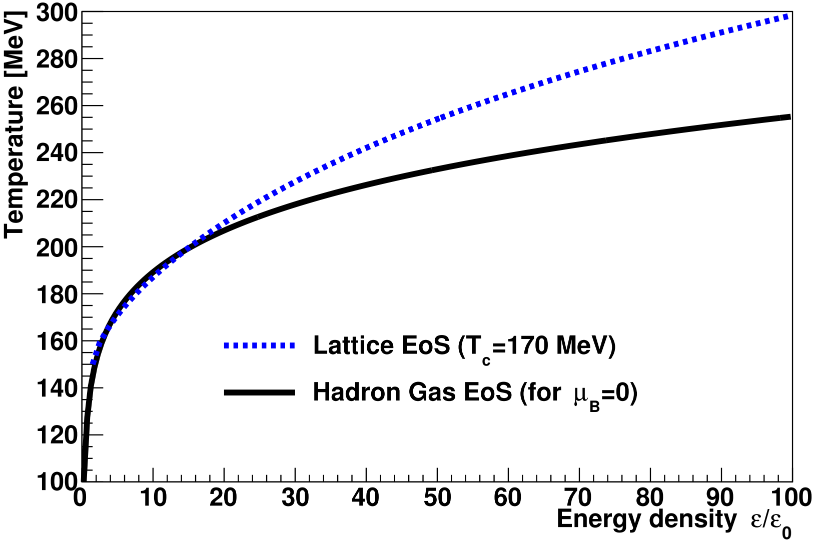
- problem with medium modifications of spectral functions/interactions
- only available in equilibrium many-body QFT models
- use "in-medium cross sections" naively: double counting?!?
- way out: map transport to local-equilibrium fluid
- use ensemble of UrQMD runs with an equation of state
- space-time grid with $\Delta t = 0.2\,\text{fm}/c$, $\Delta x = 0.8\,\text{fm}$
- fit temperature, chemical potentials, flow-velocity field
  from anisotropic energy-momentum tensor [FMRS13]

$$T^{\mu\nu} = (\epsilon + P_{\perp}) u^{\mu} u^{\nu} - P_{\perp} g^{\mu\nu} - (P_{\parallel} - P_{\perp}) V^{\mu} V^{\nu}$$

- thermal rates from partonic/hadronic QFT become applicable
- here: extrapolated lattice QGP and Rapp-Wambach HMBT
- caveat: consistency between EoS, matter content of QFT model/UrQMD!

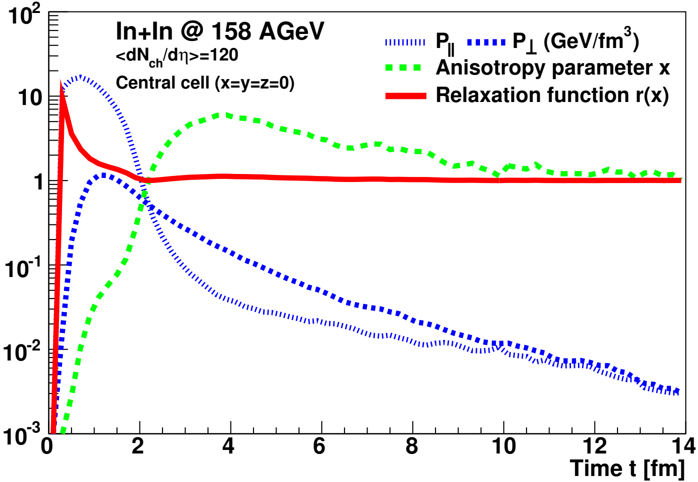
Coarse-grained UrQMD (CGUrQMD)

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



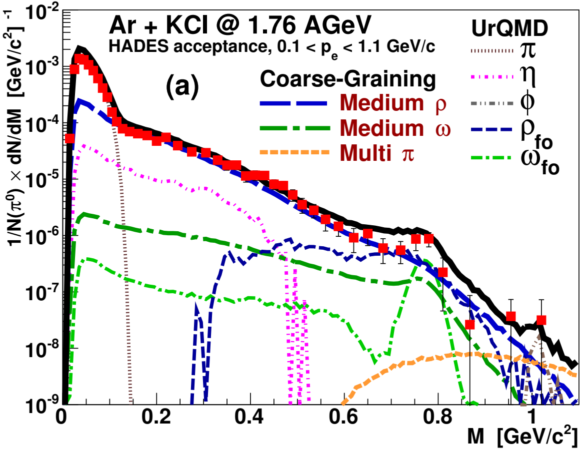
Coarse-grained UrQMD (CGUrQMD)

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



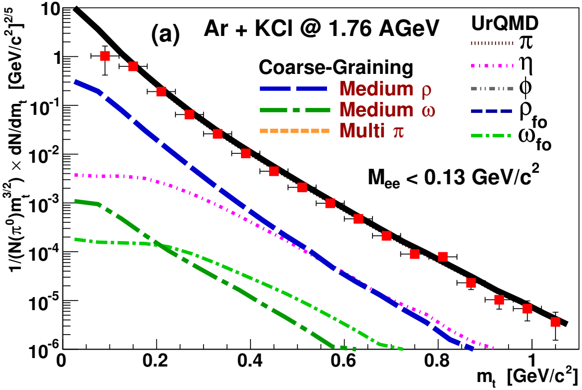
Dielectrons (SIS/HADES)

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



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

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



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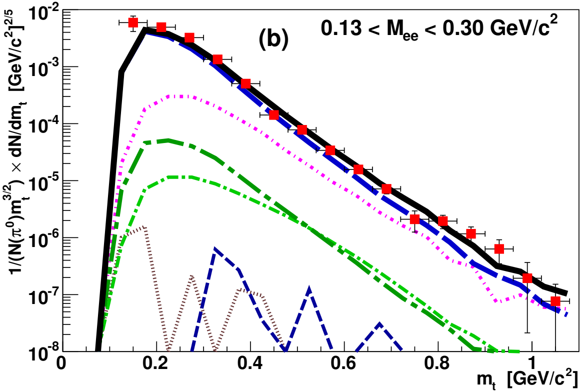
- dielectron spectra from $\text{Ar}+\text{KCl}(1.76\,A\text{GeV}) \rightarrow e^+e^-$ (SIS/HADES)
- m_t spectra
- $0.13\,\text{GeV} M_{\text{ee}} < 0.3\,\text{GeV}$



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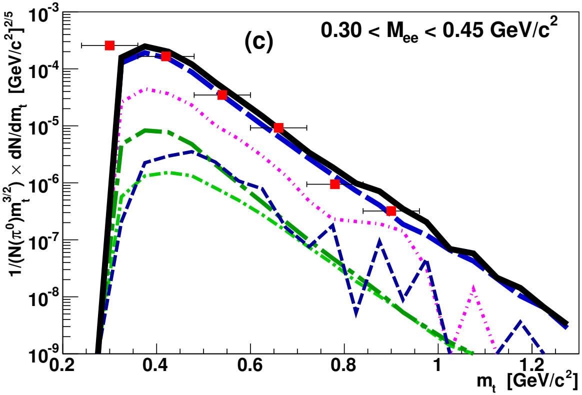
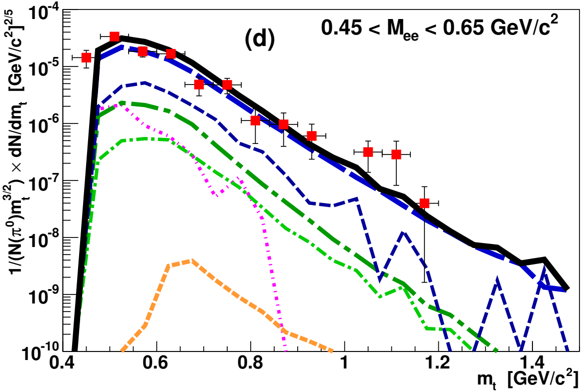
- m_t spectra
- $0.3\,\text{GeV} M_{ee} < 0.45\,\text{GeV}$



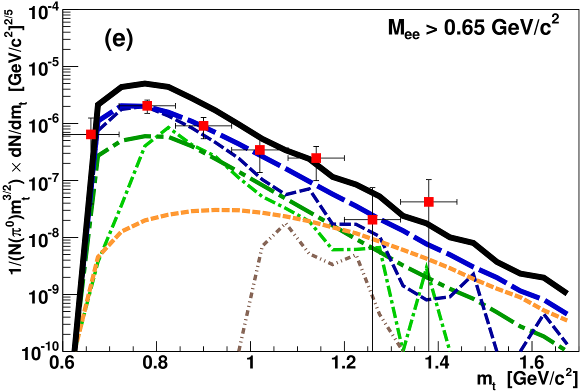
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



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

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



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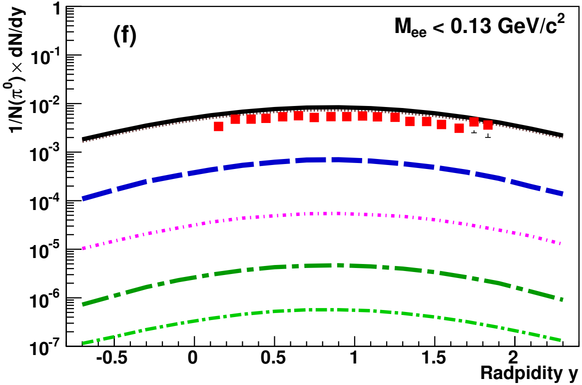
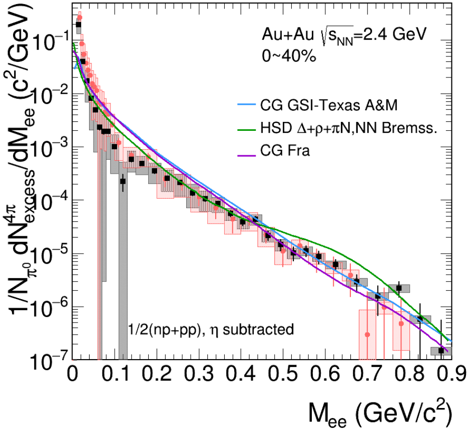
- dielectron spectra from $\mathrm{Ar}+\mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow \mathrm{e}^+\mathrm{e}^-$ (SIS/HADES)
- m_t spectra
- rapidity spectrum ($M_{\mathrm{ee}} < 0.13$ GeV)



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



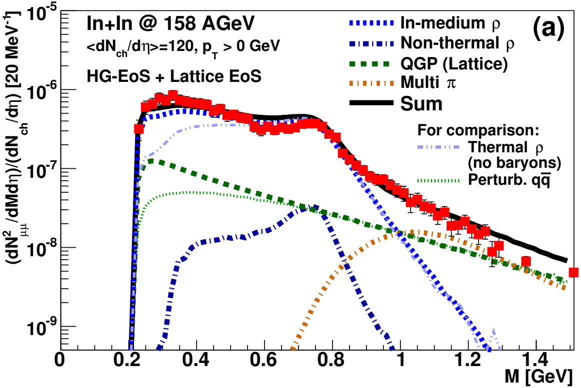
[T. Galtyuk, Quark Matter 2017 talk]

- 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)

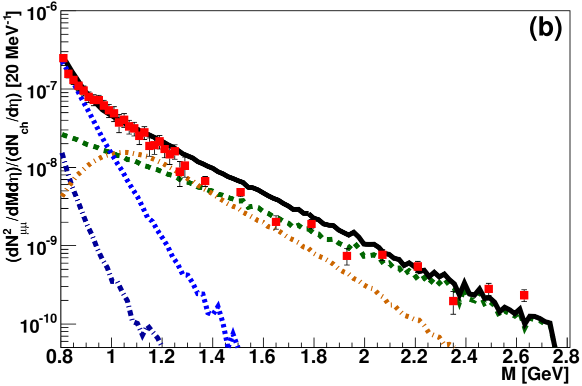
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



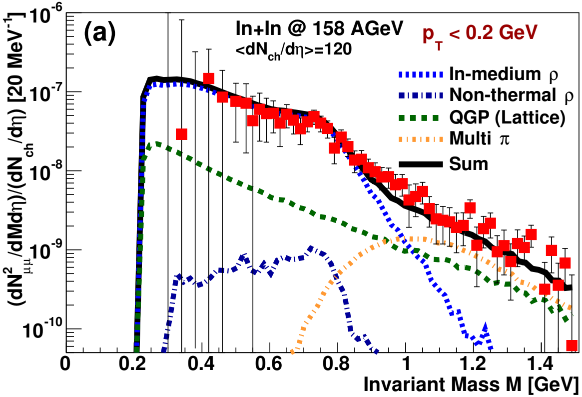
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



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

- dimuon spectra from In + In(158 *A*GeV) $\rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $p_T < 0.2$ GeV



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

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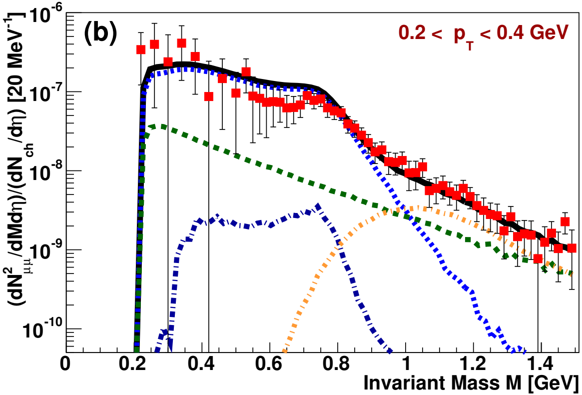
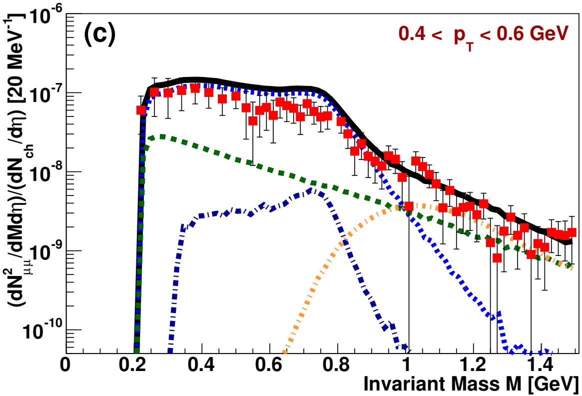
- min-bias data ($\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120$)
- $0.2\,\text{GeV} < p_T < 0.4\,\text{GeV}$



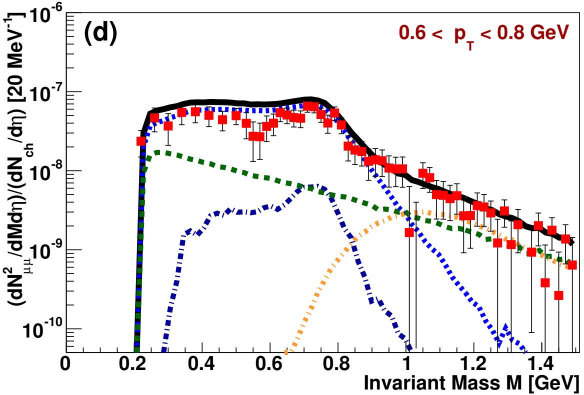
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



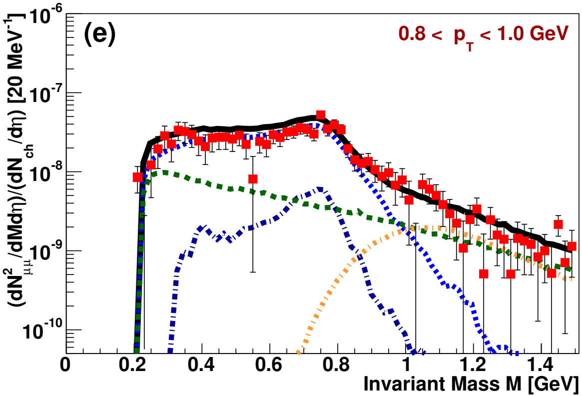
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



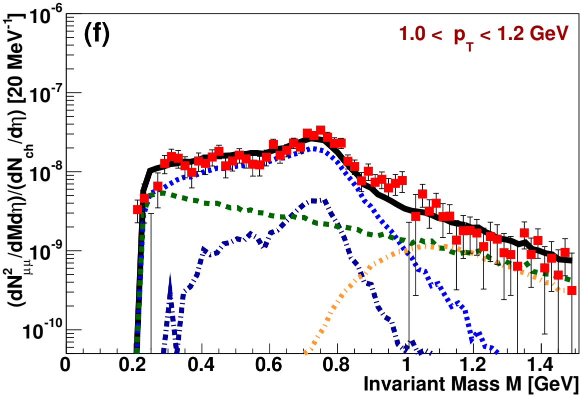
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



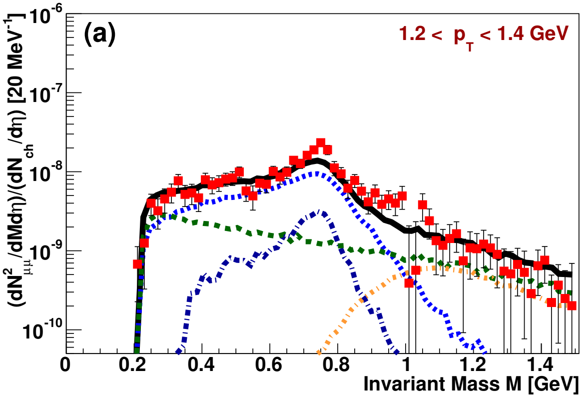
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



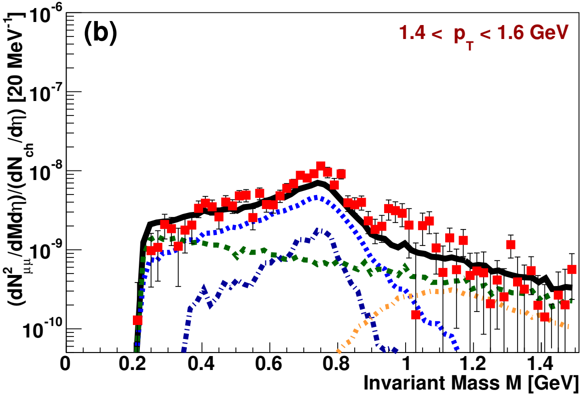
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



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

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



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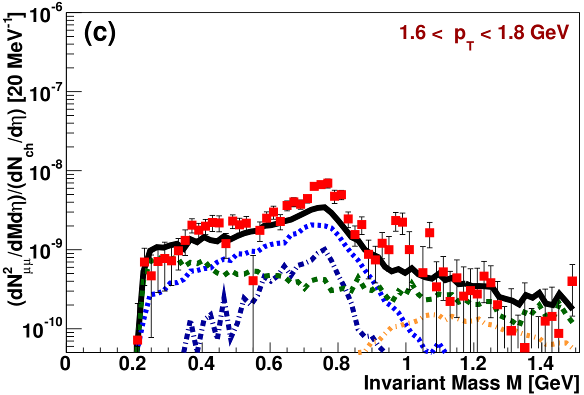
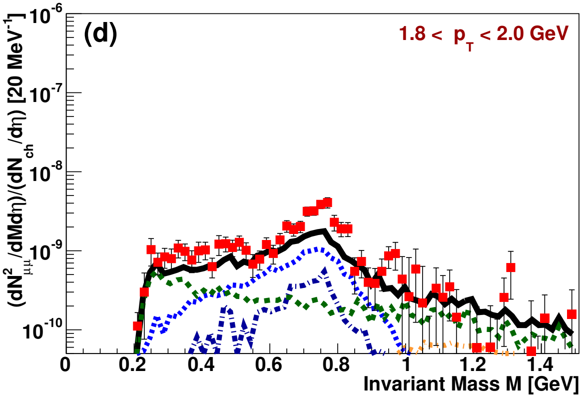
- min-bias data $(\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120)$
- $1.6\,\text{GeV} < p_T < 1.8\,\text{GeV}$



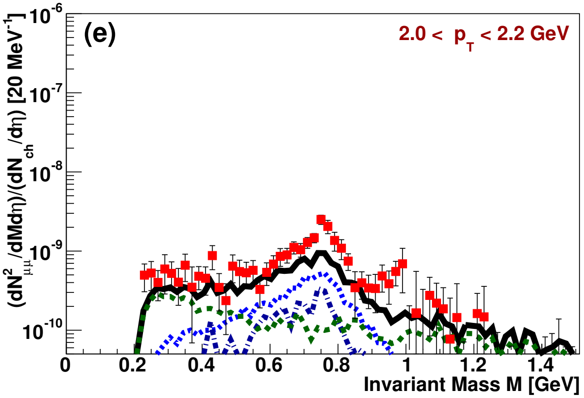
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



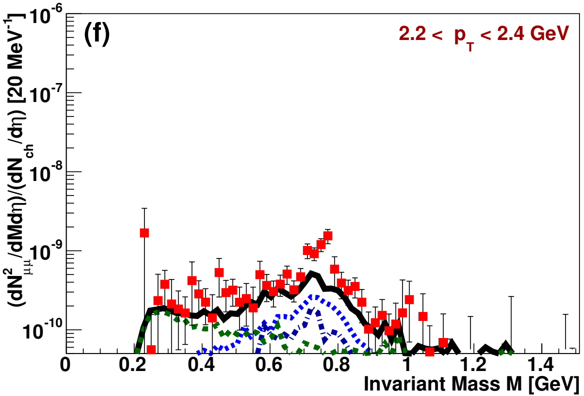
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



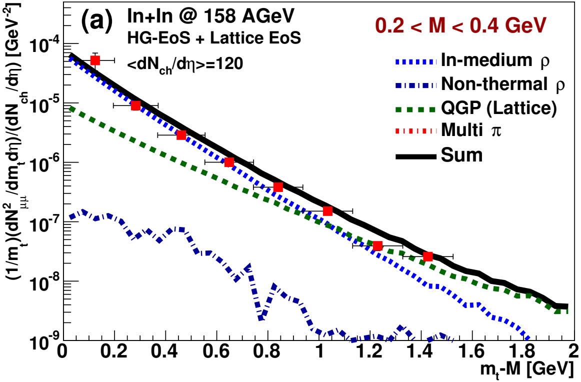
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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

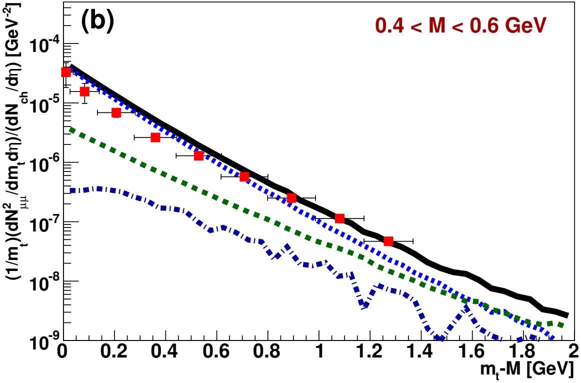


CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

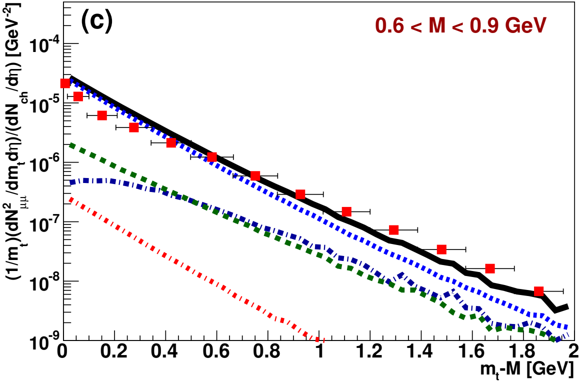
- dimuon spectra from In + In(158 *A*GeV) $\rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)



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

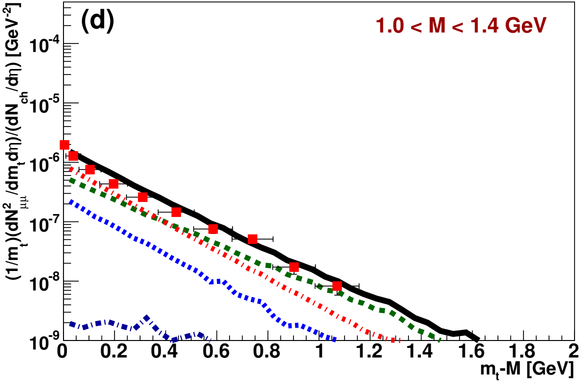


- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)



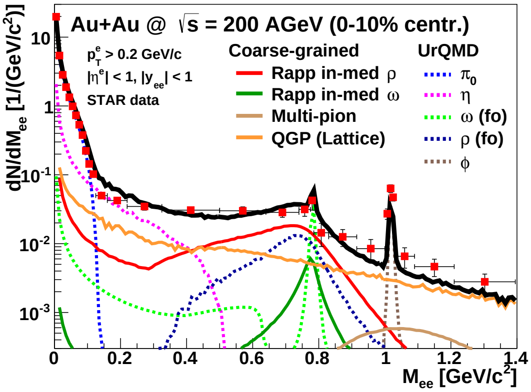
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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

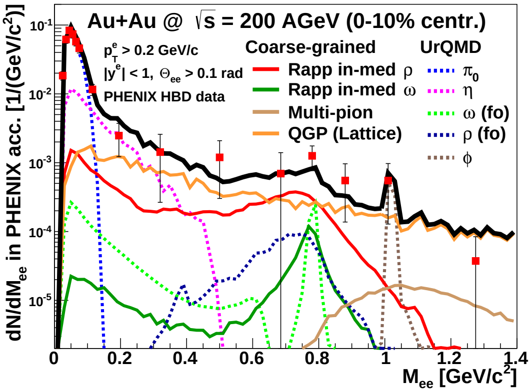


Dielectrons at RHIC

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

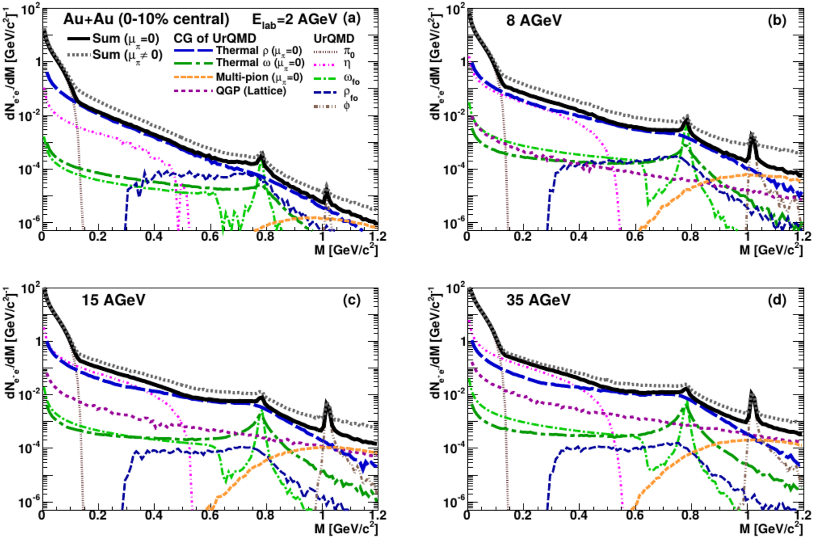


CGUrQMD: Au+Au ($\sqrt{s_{NN}} = 200\,\text{GeV}$) (RHIC/PHENIX)



Dielectrons at RHIC-BES/FAIR/NICA

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

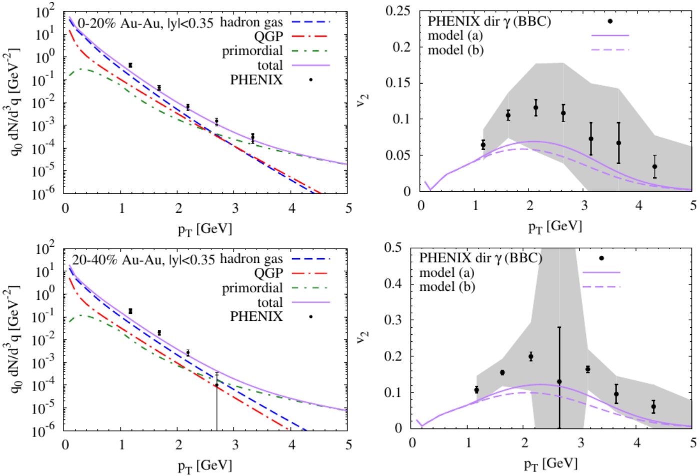


NB: also photon spectra [EHB16b]

Direct photons (RHIC/LHC)

Direct Photons at RHIC

- same model [TRG04] for rates as for dileptons
- photons inherit v_2 from hadronic sources

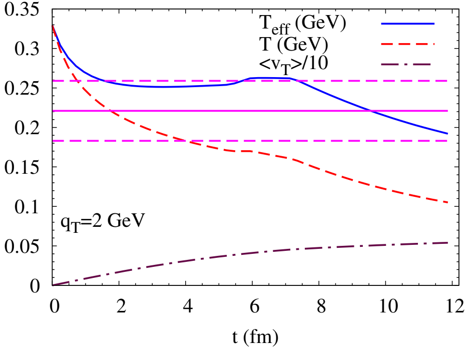


[HGR11, RHH14, HHR15]

Effective slopes vs. temperatures

- effective slopes of photon p_T spectra are NOT temperatures!
- emission from a flowing medium ⇒ Doppler effect

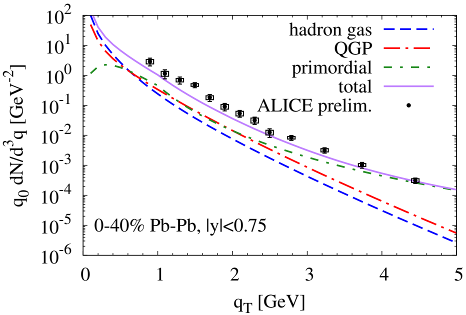
$$T_{\text{eff}} \simeq \sqrt{\frac{1+\langle v_T \rangle}{1-\langle v_T \rangle}}\, T$$

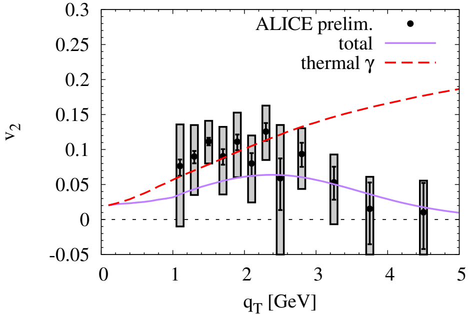


[RHH14]

Direct Photons at the LHC

same model, fireball adapted to hadron data from ALICE [HHR15]





- large direct-photon v_2
- early buildup of v_2; here developed already at end of QGP phase
- emission mostly around T_c (dual rates!) ⇒
- ⇒ source has already developed radial flow and v_2
- large effective slopes include blueshift from radial flow!
- still additional (hadronic?) sources (bremsstrahlung?) missing?!?

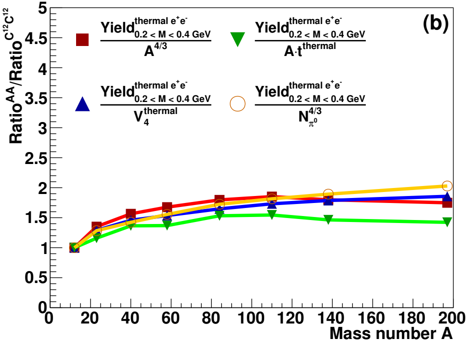
Signatures of the QCD-phase structure?

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

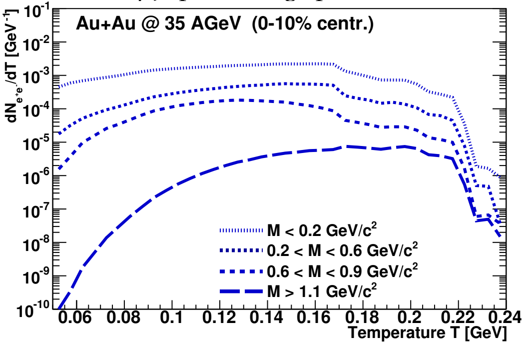
- central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76\,A\text{GeV}$



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

Mass-temperature relation in dilepton emission

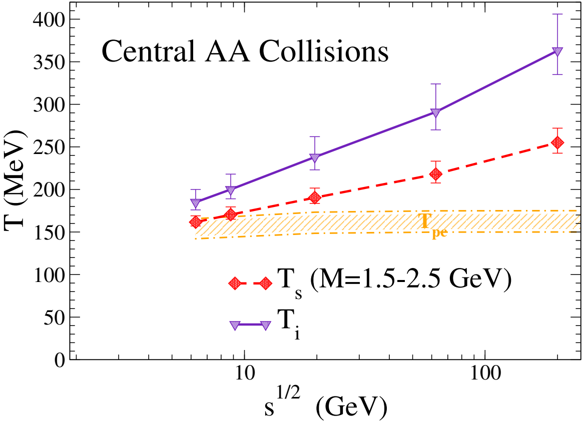
- interplay between increasing volume and decreasing temperature of fireball
- in IMR ($T < m_\phi < M_{\ell^+\ell^-} < m_{J/\psi}$) biased towards early hot stages
- only "background": correlated $D\overline{D}$ decays, some Drell-Yan
- otherwise emission from thermal QGP and hadronic sources
- invariant-mass slope $\Leftrightarrow$ true invariant space-time averaged temperature
- no blueshift due to radial flow as in p_t spectra (e.g., photons)



[EHB16b, EHB16a]

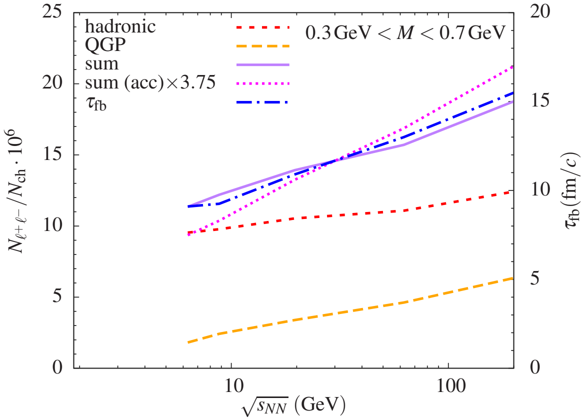
Dilepton systematics in the beam-energy scan

- thermal-fireball model [RH16, EHB16a]
- invariant-mass slope in IMR ⇒ true temperature!
- no blue shift from radial flow as in p_T/m_T spectra



Dilepton systematics in the beam-energy scan

- thermal-fireball model [RH16]
- beam-energy scan at RHIC and lower energies at 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???

Bibliography I

[ABB+14] G. Agakishiev, et al., Baryon resonance production and dielectron decays in proton-proton collisions at 3.5 GeV, Eur. Phys. J. A **50** (2014) 82.
`https://doi.org/10.1140/epja/i2014-14082-1`

[EHB16a] S. Endres, H. van Hees, M. Bleicher, Energy, centrality and momentum dependence of dielectron production at collider energies in a coarse-grained transport approach, Phys. Rev. C **94** (2016) 024912.
`https://doi.org/10.1103/PhysRevC.94.024912`

[EHB16b] S. Endres, H. van Hees, M. Bleicher, Photon and dilepton production at the Facility for Proton and Anti-Proton Research and beam-energy scan at the Relativistic Heavy-Ion Collider using coarse-grained microscopic transport simulations, Phys. Rev. C **93** (2016) 054901.
`https://doi.org/10.1103/PhysRevC.93.054901`

Bibliography II

[EHWB15] S. Endres, H. van Hees, J. Weil, M. Bleicher, Dilepton production and reaction dynamics in heavy-ion collisions at SIS energies from coarse-grained transport simulations, Phys. Rev. C **92** (2015) 014911.
https://doi.org/10.1103/PhysRevC.92.014911

[FMRS13] W. Florkowski, M. Martinez, R. Ryblewski, M. Strickland, Anisotropic hydrodynamics, Nucl. Phys. A **904-905** (2013) 803c.
https://doi.org/10.1016/j.nuclphysa.2013.02.138

[GHR+16] T. Galatyuk, P. M. Hohler, R. Rapp, F. Seck, J. Stroth, Thermal Dileptons from Coarse-Grained Transport as Fireball Probes at SIS Energies, Eur. Phys. J. A **52** (2016) 131.
https://doi.org/10.1140/epja/i2016-16131-1

[GK91] C. Gale, J. I. Kapusta, Vector dominance model at finite temperature, Nucl. Phys. B **357** (1991) 65.
https://doi.org/10.1016/0550-3213(91)90459-B

Bibliography III

[HGR11] H. van Hees, C. Gale, R. Rapp, Thermal Photons and Collective Flow at the Relativistic Heavy-Ion Collider, Phys. Rev. C **84** (2011) 054906.
https://doi.org/10.1103/PhysRevC.84.054906

[HHR15] H. van Hees, M. He, R. Rapp, Pseudo-Critical Enhancement of Thermal Photons in Relativistic Heavy-Ion Collisions, Nucl. Phys. A **933** (2015) 256.
https://doi.org/10.1016/j.nuclphysa.2014.09.009

[MT85] L. D. McLerran, T. Toimela, Photon and Dilepton Emission from the Quark-Gluon Plasma: Some General Considerations, Phys. Rev. D **31** (1985) 545.
https://doi.org/10.1103/PhysRevD.31.545

[Rap13] R. Rapp, Dilepton Spectroscopy of QCD Matter at Collider Energies, Adv. High Energy Phys. **2013** (2013) 148253.
https://doi.org/10.1155/2013/148253

Bibliography IV

[RH16] R. Rapp, H. van Hees, Thermal Dileptons as Fireball Thermometer and Chronometer, Phys. Lett. B **753** (2016) 586.
https://doi.org/10.1016/j.physletb.2015.12.065

[RHH14] R. Rapp, H. van Hees, M. He, Properties of Thermal Photons at RHIC and LHC, Nucl. Phys. A **931** (2014) 696.
https://doi.org/10.1016/j.nuclphysa.2014.08.008

[TRG04] S. Turbide, R. Rapp, C. Gale, Hadronic production of thermal photons, Phys. Rev. C **69** (2004) 014903.
https://doi.org/10.1103/PhysRevC.69.014903

[WHM12] J. Weil, H. van Hees, U. Mosel, Dilepton production in proton-induced reactions at SIS energies with the GiBUU transport model, Eur. Phys. J. A **48** (2012) 111.
https://doi.org/10.1140/epja/i2012-12111-9