Electromagnetic Probes in Heavy-Ion Collisions

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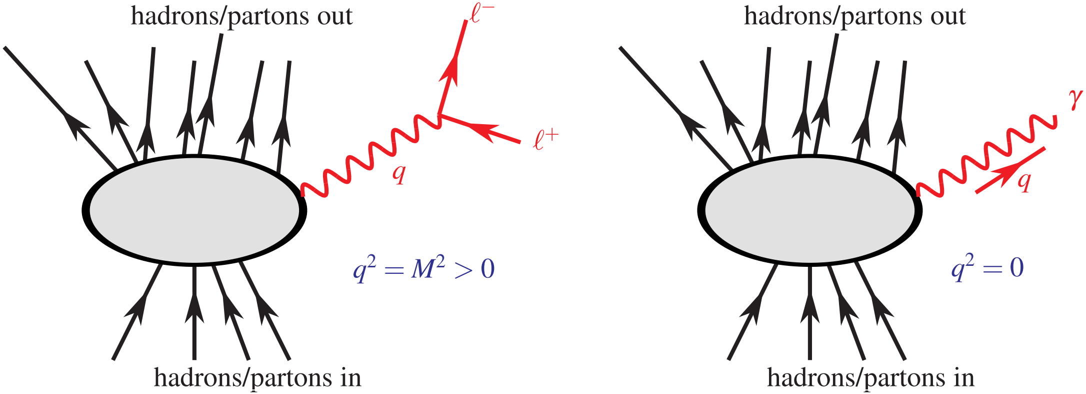
Outline

1. Production rates for dileptons and photons
2. Bulk evolution
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

Production rates for dileptons and photons



- Fermi's golden rule ⇒ transition-matrix element for process $|i\rangle \rightarrow \left|f'\right\rangle = \left|f\right\rangle + |\ell^+\ell^-(k)\rangle$
- QED Feynman rules

The McLerran-Toimela formula

- result (derivation see [GK91], Appendices)

$$\frac{\mathrm{d}N_{\ell^+\ell^-}}{\mathrm{d}^4 x\,\mathrm{d}^4 q} = -\frac{\alpha^2}{3\pi^3}\frac{q^2+2m_\ell^2}{(k^2)^2}\sqrt{1-\frac{4m_\ell^2}{k^2}}\,\eta_{\mu\nu}\mathrm{Im}\,\Pi^{\mu\nu}_{\text{ret}}(M,\vec{q})\,n_{\text{B}}(u\cdot q)$$

- spectral and thermal information!
- $M^2 = q \cdot q$: invariant mass/$\vec{q}$ momentum of dilepton
- u: four-velocity of fluid cell $\Rightarrow$ Doppler effect on $\vec{p}$ and p_T spectra!
- electromagnetic current-current correlator

$$\mathrm{i}\Pi^{\mu\nu}_{\text{ret}}(q) := \int \mathrm{d}^4 x\, \exp(\mathrm{i} q\cdot x)\left\langle \left[\mathbf{J}^{\mu}_{\text{em}}(x), \mathbf{J}^{\nu}_{\text{em}}(0)\right]\right\rangle_{T,\mu_B}\Theta(x^0)$$

- written in (local) restframe of the medium
- probing medium with photons: same correlator for $q \cdot q = M^2 = 0$
- then correlator $\Leftrightarrow$ dielectric function $\epsilon(\omega)$ of electrodynamics!

$$\omega\frac{\mathrm{d}N_\gamma}{d^4 x\,\mathrm{d}^3\vec{q}} = -\frac{\alpha\eta_{\mu\nu}}{2\pi^2}\mathrm{Im}\,\Pi^{\mu\nu}_{\text{ret}}(q^0,\vec{q})\,n_{\text{B}}(u\cdot q), \quad q^0 = \omega = |\vec{k}|$$

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

- General: McLerran-Toimela formula

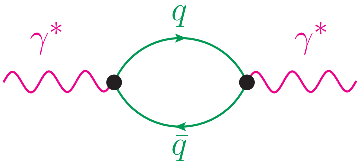
$$\frac{\mathrm{d}N_{\ell^+\ell^-}}{\mathrm{d}^4x\,\mathrm{d}^4q} = -\frac{\alpha^2}{3\pi^3}\frac{q^2+2m_\ell^2}{(k^2)^2}\sqrt{1-\frac{4m_\ell^2}{k^2}}\,\eta_{\mu\nu}\mathrm{Im}\,\Pi^{\mu\nu}_{\mathrm{ret}}(M,\vec{q})\,n_{\mathrm{B}}(u\cdot q)$$

- in-medium em. current-current correlation function

$$\mathrm{i}\Pi^{\mu\nu}_{\mathrm{ret}}(q) := \int \mathrm{d}^4x\;\exp(\mathrm{i}q\cdot x)\left\langle\left[\mathbf{J}^{\mu}_{\mathrm{em}}(x),\,\mathbf{J}^{\nu}_{\mathrm{em}}(0)\right]\right\rangle_{T,\mu_B}\Theta(x^0)$$

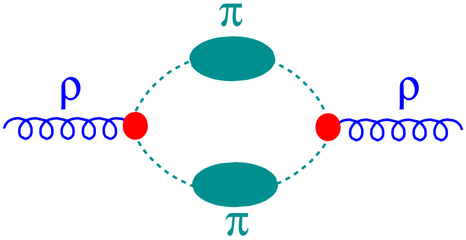
- Feynman diagrams: photon polarization
- in QGP phase: $q\bar{q}$ annihilation
- hard-thermal-loop improved em. current-current correlator

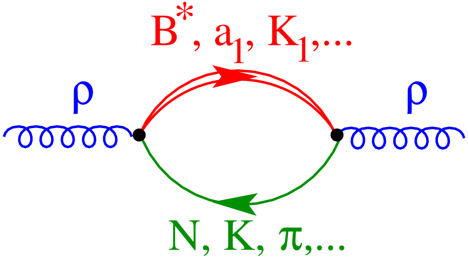
$-\mathrm{i}\Pi_{\mathrm{em,QGP}} =$



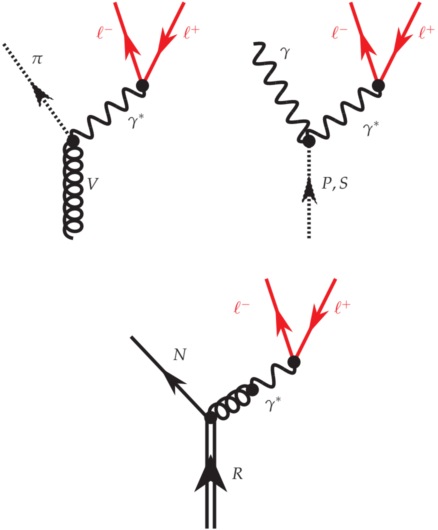
Hadronic many-body theory

- hadronic many-body theory (HMBT) of vector mesons
  [Ko et al, Chanfray et al, Herrmann et al, Rapp et al, …]
- $\pi\pi$ interactions and hadronic excitations
- effective hadronic models, implementing symmetries
- good approximation: vector-meson dominance, $J_{\text{em}}^{\mu} \propto \rho^{\mu}, \omega^{\mu}, \phi^{\mu}$
- dilepton/photon rates then $\propto \operatorname{Im} D_{\text{VM}}$ (VM-spectral functions)
- parameters fixed by phenomenology
  (photon absorption at nucleons and nuclei, $\pi N \rightarrow \rho N$)
- evaluated at finite temperature and density
- self-energies ⇒ mass shift and broadening in the medium

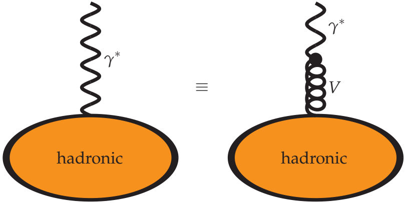




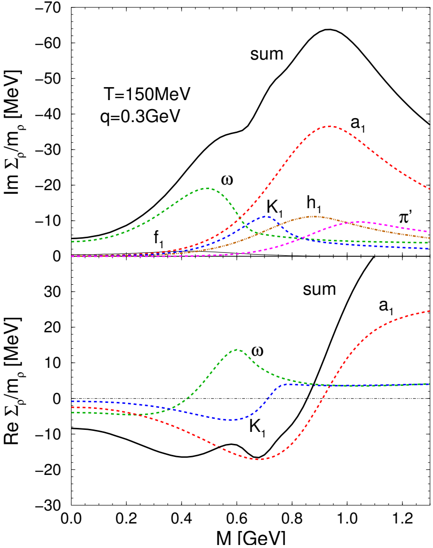
Dalitz decays



- **Dalitz decay**:
  1 particle → 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

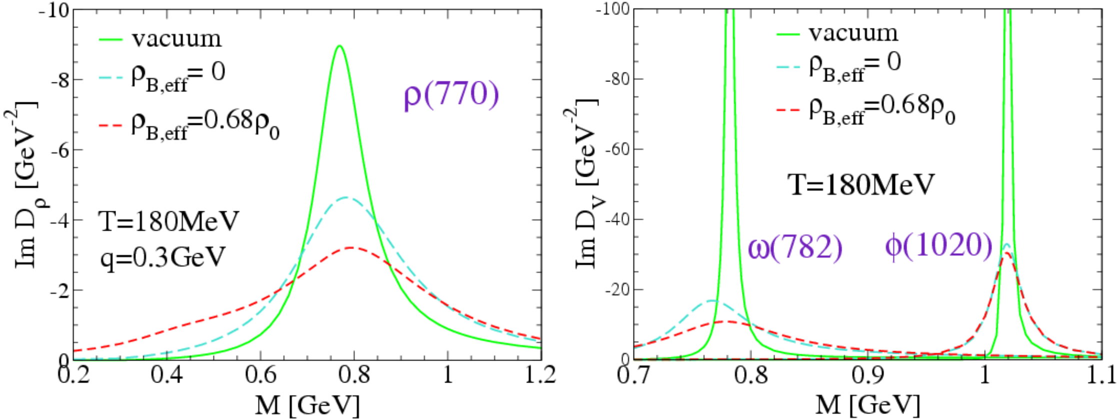


Meson contributions



[RG99]

In-medium spectral functions and baryon effects

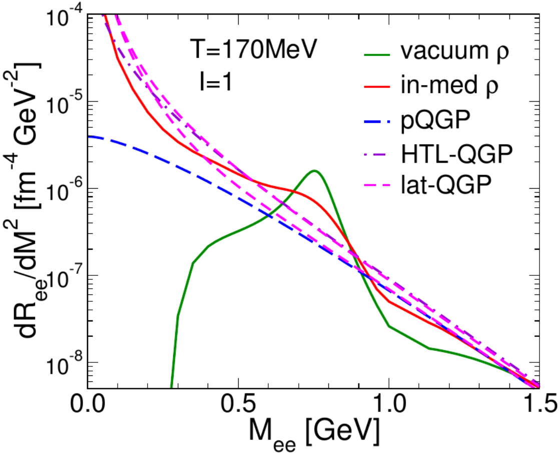


[RW99]

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

Dilepton rates: Hadron gas ⟷ QGP

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



Bulk evolution with transport and coarse graining

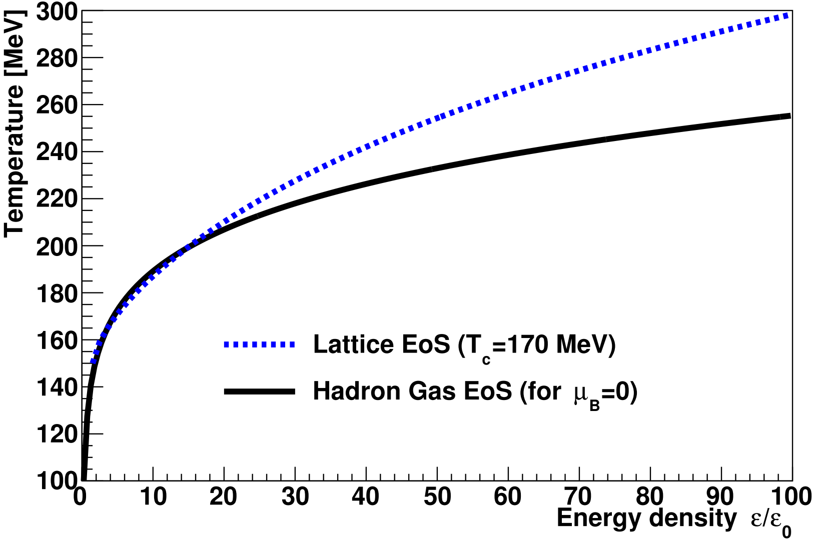
- established transport models for bulk evolution
  - e.g., UrQMD, GiBUU, BAMPS, (p)HSD,...
  - solve Boltzmann equation for hadrons and/or partons
- dilemma: need medium-modified dilepton/photon emission rates
- usually available only in equilibrium QFT calculations
- one way out:
  - UrQMD transport for entire bulk evolution
    ⇒ use coarse graining in space-time cells ⇒ extract $T, \mu_B, \mu_\pi, \ldots$
    ⇒ use equilibrium rates locally
  - 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

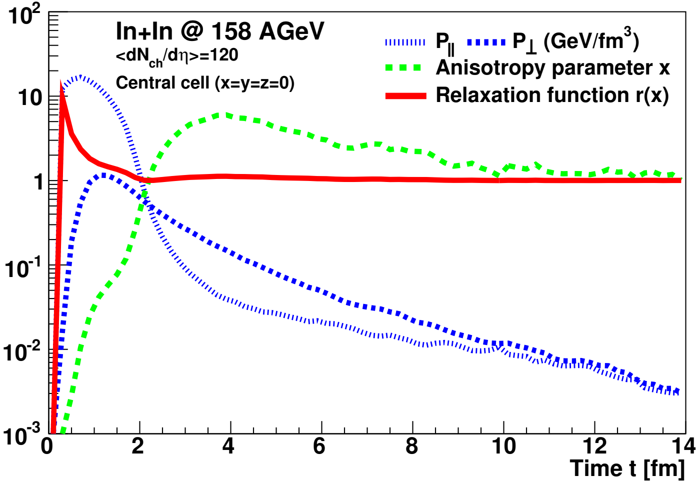
Coarse-grained UrQMD (CGUrQMD)

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



Coarse-grained UrQMD (CGUrQMD)

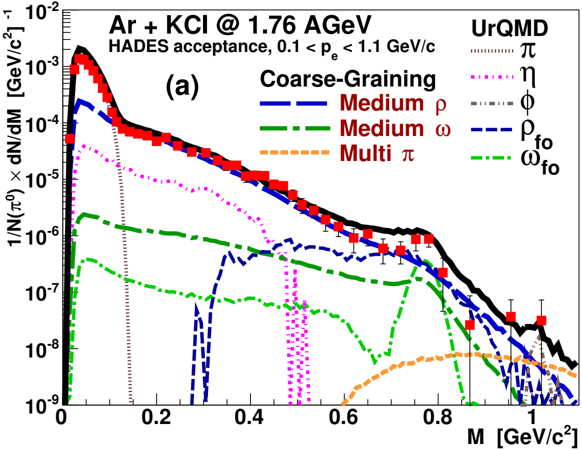
- pressure anisotropy (for In+In @ SPS; NA60)



Dielectrons (SIS/HADES)

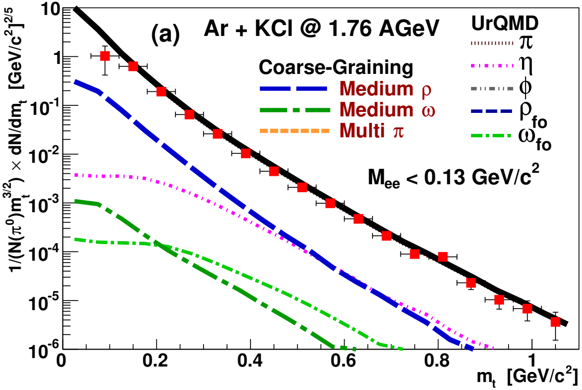
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



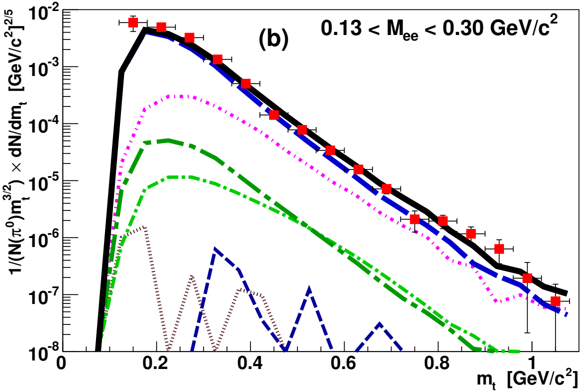
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



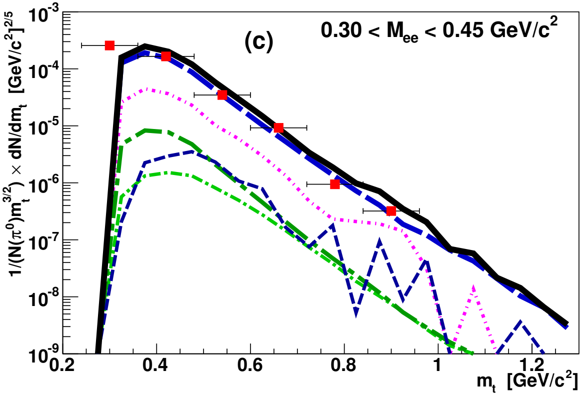
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



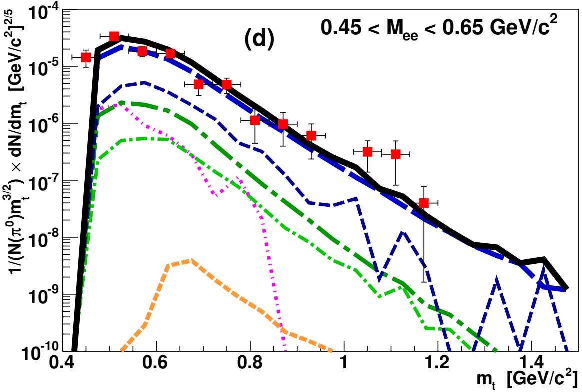
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



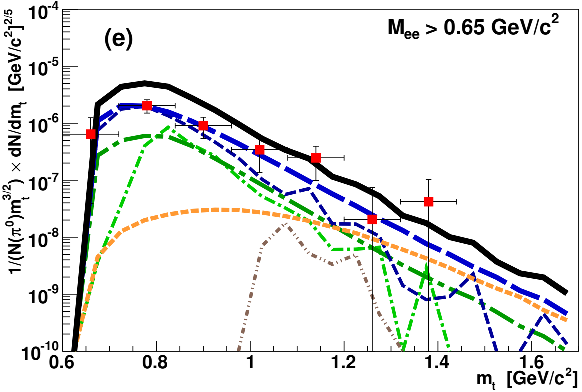
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



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

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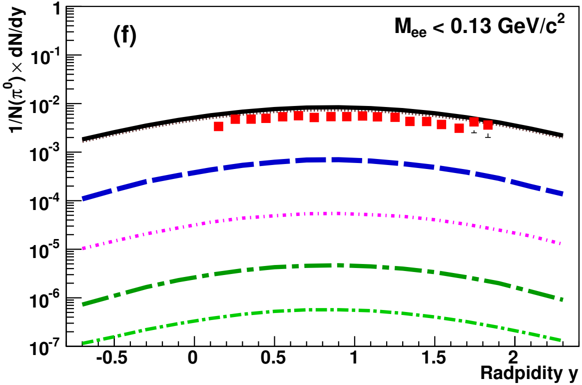
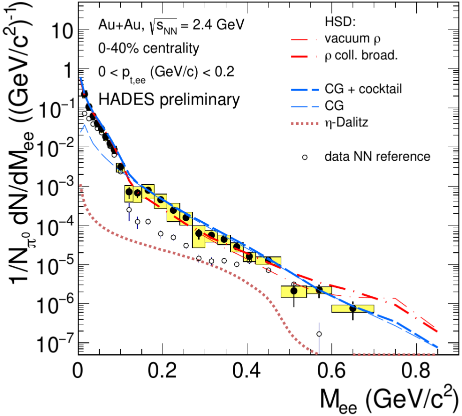
- m_t spectra
- rapidity spectrum ($M_{\mathrm{ee}} < 0.13$ GeV)



CGUrQMD: Au+Au (1.24 *A*GeV) (SIS/HADES)



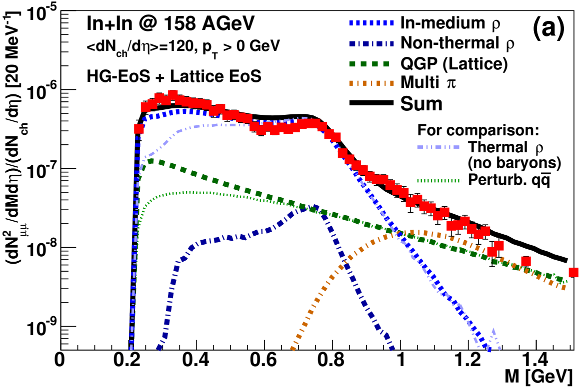
[Gal20]

- excellent agreement between models and data

Dimuons (SPS/NA60)

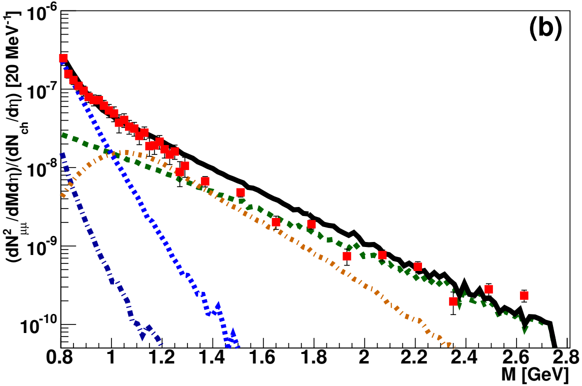
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



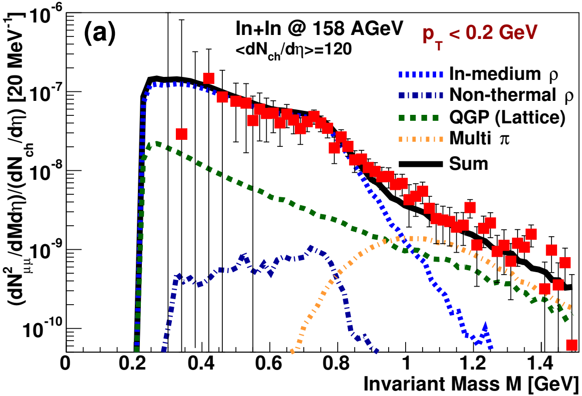
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



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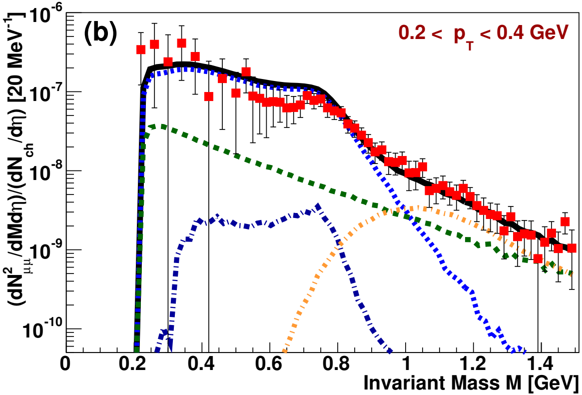
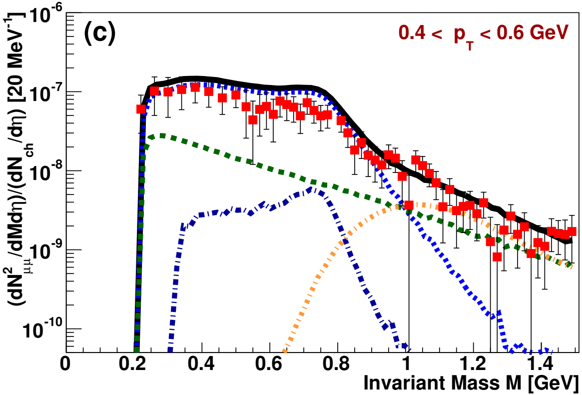
- min-bias data $(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120)$
- $0.2\,\mathrm{GeV} < p_T < 0.4\,\mathrm{GeV}$



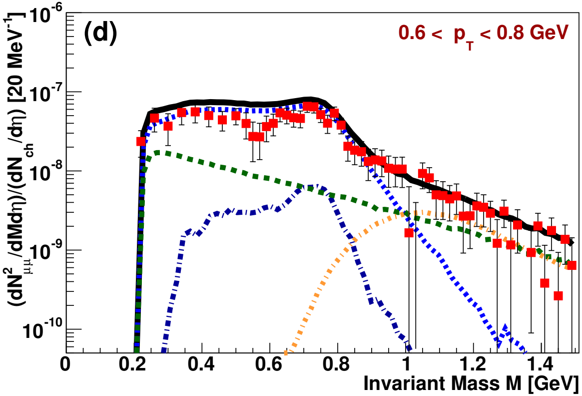
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



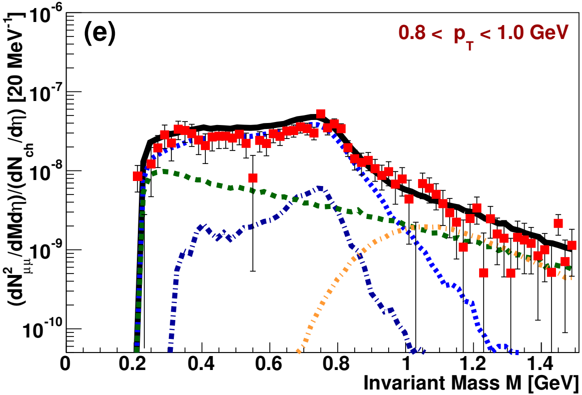
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



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)

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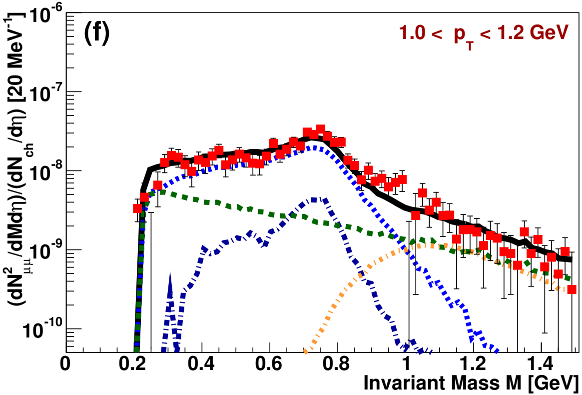
- min-bias data $(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120)$
- $1.0\,\mathrm{GeV} < p_T < 1.2\,\mathrm{GeV}$



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

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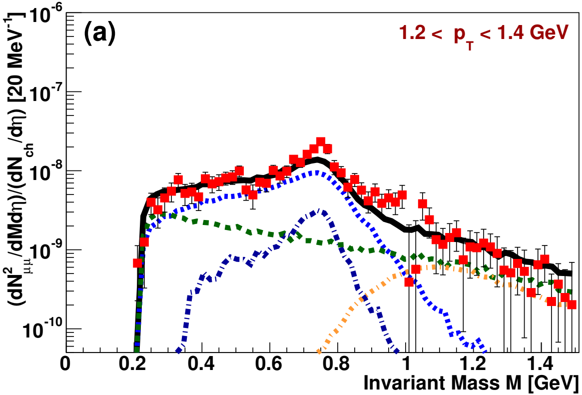
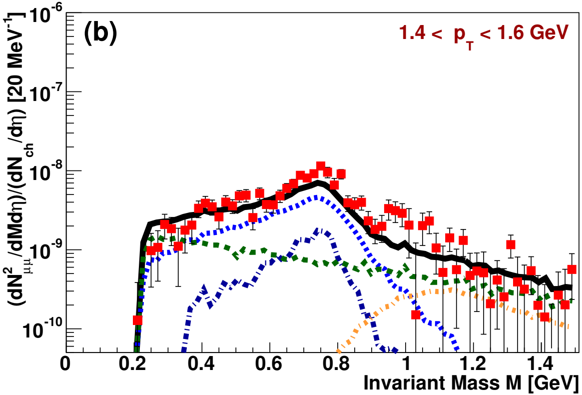
- min-bias data ($\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120$)
- $1.2\,\text{GeV} < p_T < 1.4\,\text{GeV}$



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

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



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

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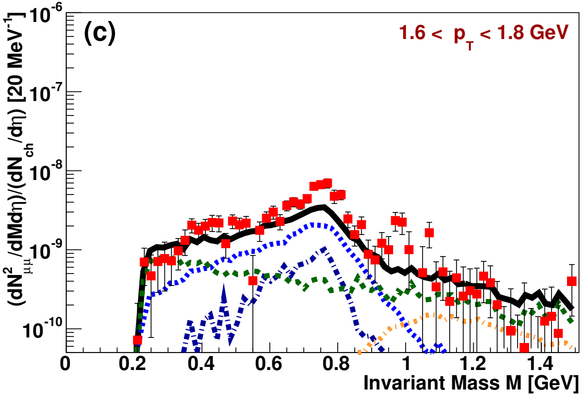

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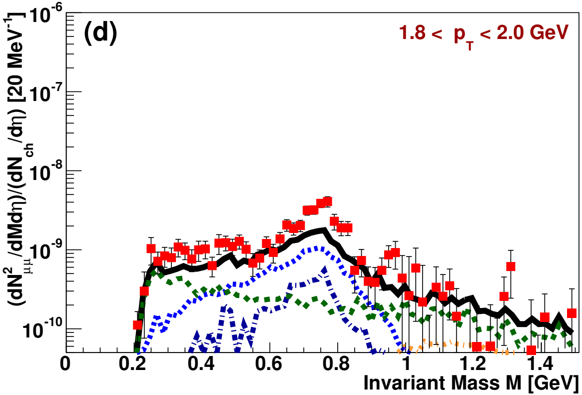
- min-bias data $(\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120)$
- $1.8\,\text{GeV} < p_T < 2.0\,\text{GeV}$



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

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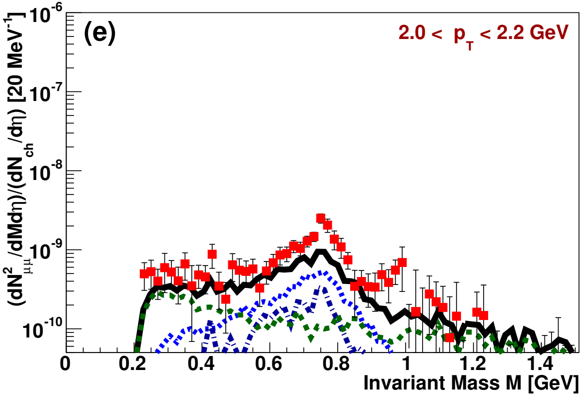
- min-bias data $(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120)$
- $2.0\,\mathrm{GeV} < p_T < 2.2\,\mathrm{GeV}$



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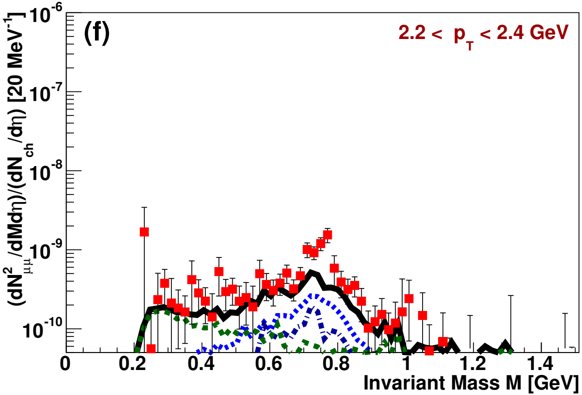
- dimuon spectra from $\text{In}+\text{In}(158\,A\text{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data $(\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120)$
- $2.2\,\text{GeV} < p_T < 2.4\,\text{GeV}$



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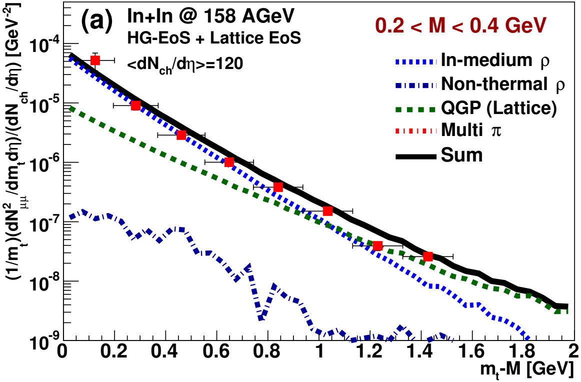

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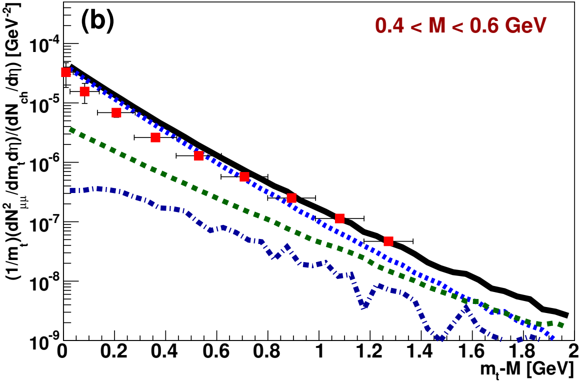
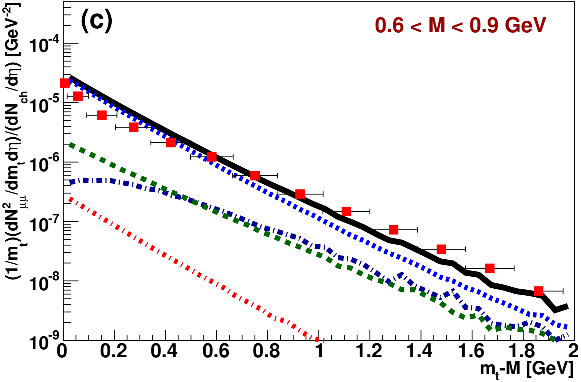


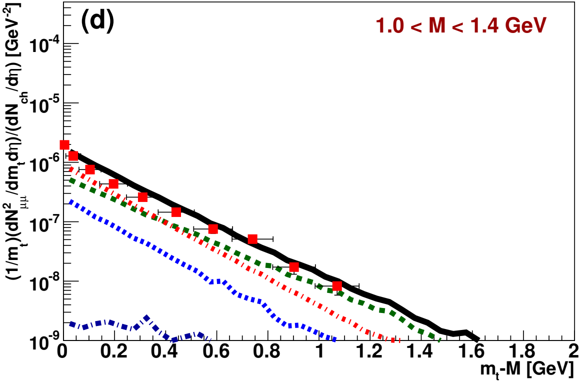
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



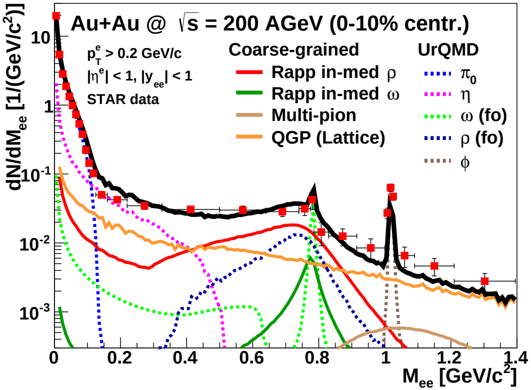
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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

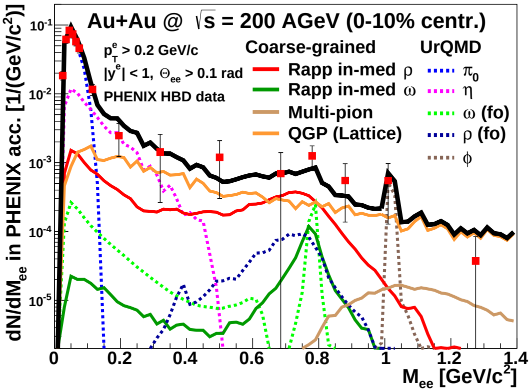


Dielectrons at RHIC

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

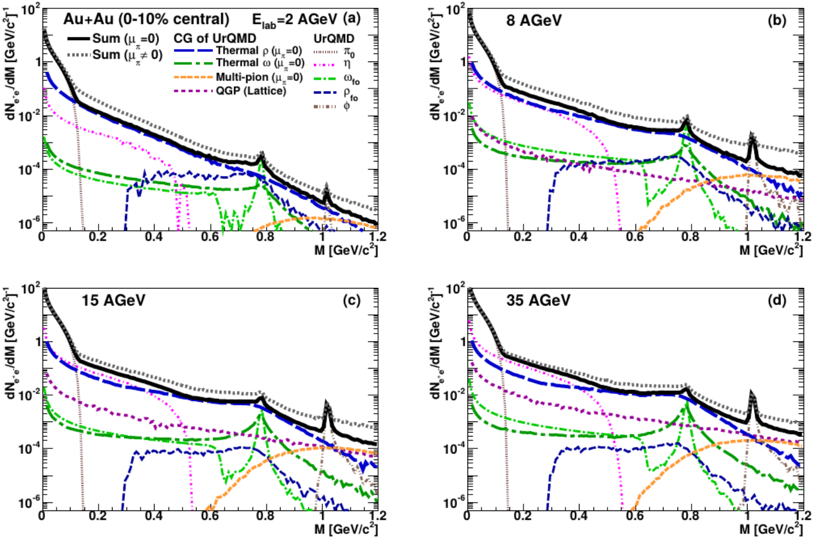


CGUrQMD: Au+Au ($\sqrt{s_{NN}} = 200\,\mathrm{GeV}$) (RHIC/PHENIX)



Dielectrons at RHIC-BES/FAIR/NICA

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

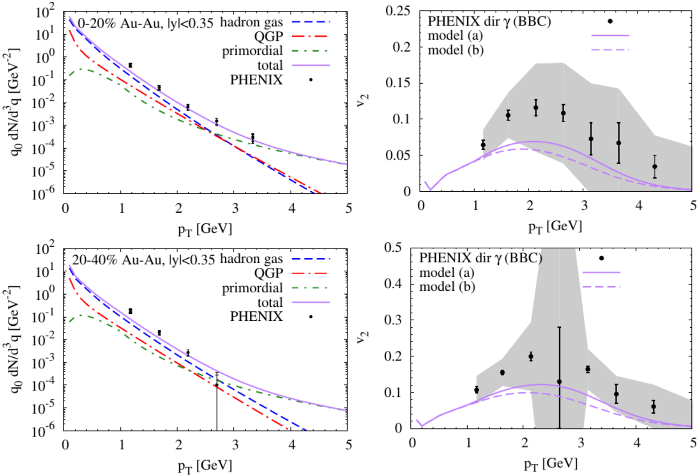


NB: also photon spectra [EHB16b]

Direct photons (RHIC/LHC)

Direct Photons at RHIC

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

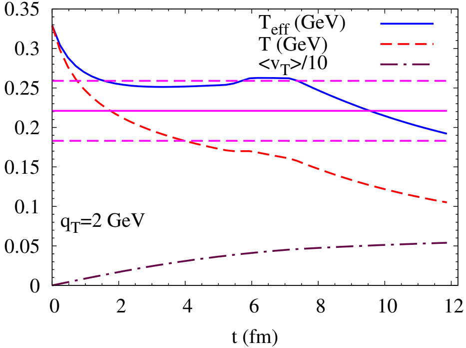


[HGR11, RHH14, HHR15]

Effective slopes vs. temperatures

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

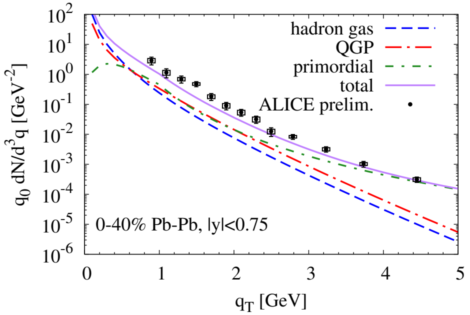
$$T_{\text{eff}} \simeq \sqrt{\frac{1+\langle v_T \rangle}{1-\langle v_T \rangle}}\, T$$

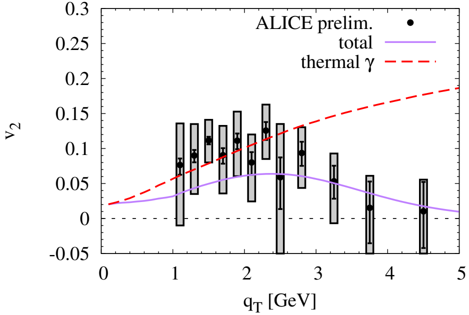


[RHH14]

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?!?

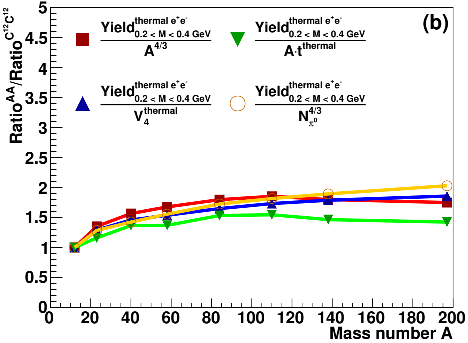
Signatures of the QCD-phase structure?

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 ⇒ “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

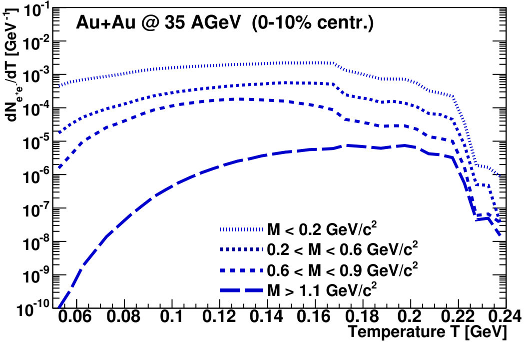
- central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76\,A\text{GeV}$



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

Mass-temperature relation in dilepton emission

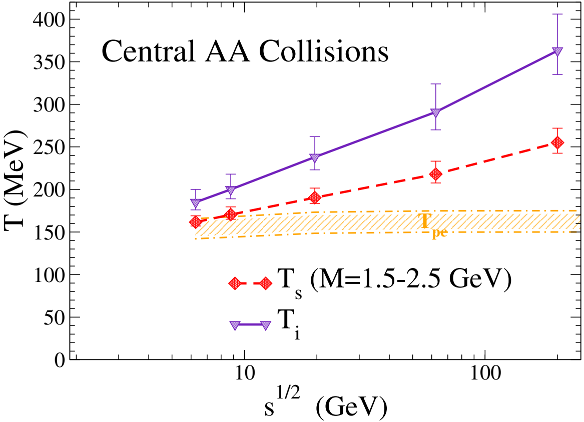
- interplay between increasing volume and decreasing temperature of fireball
- in IMR ($T < m_\phi < M_{\ell^+\ell^-} < m_{J/\psi}$) biased towards early hot stages
- only "background": correlated $D\overline{D}$ decays, some Drell-Yan
- otherwise emission from thermal QGP and hadronic sources
- invariant-mass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



[EHB16b, EHB16a]

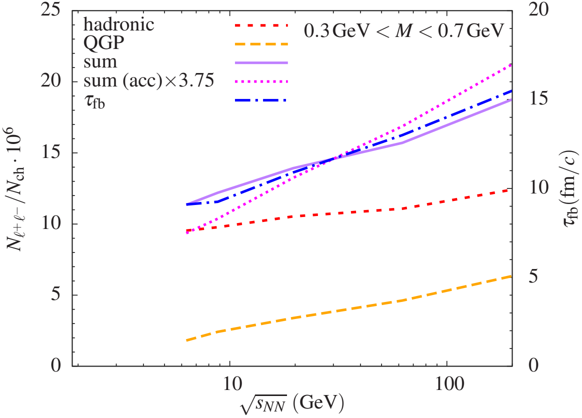
Dilepton systematics in the beam-energy scan

- 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 ⇔ 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 ⇒ 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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