Hadrons in hot and dense matter IV

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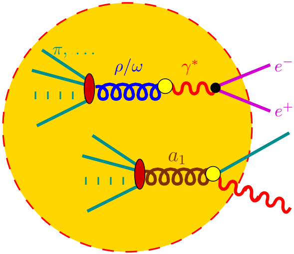
Outline

Em. probes and vector mesons

Why Electromagnetic Probes?

- $\gamma, \ell^{\pm}$: only e. m. interactions
- whole matter evolution



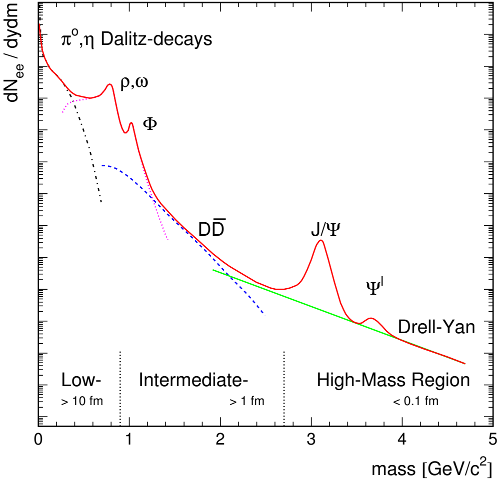


Fig. by A. Drees (from [RW00])

Vector Mesons and electromagnetic Probes

- photon and dilepton thermal emission rates given by same electromagnetic-current-correlation function ($J_\mu = \sum_f Q_f \overline{\psi_f} \gamma_\mu \psi_f$)
- McLerran-Toimela formula (cf. Lecture II)

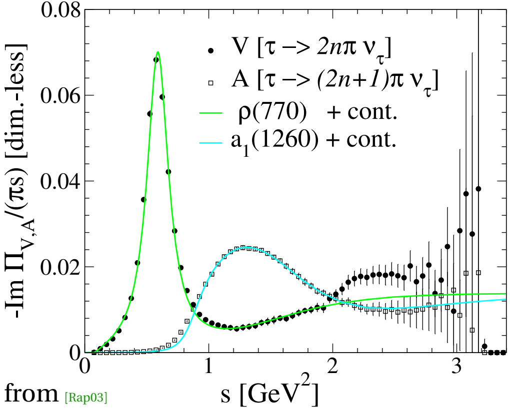
$$\Pi^{<}_{\mu\nu}(q) = \int \mathrm{d}^4 x \exp(\mathrm{i} q \cdot x) \left\langle J_\mu(0) J_\nu(x) \right\rangle_T = -2 n_B(q_0) \operatorname{Im} \Pi^{(\text{ret})}_{\mu\nu}(q)$$

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

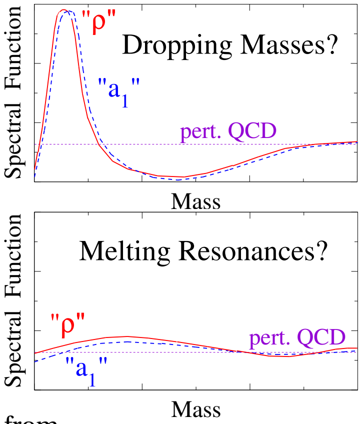
$$\frac{\mathrm{d}N_{e^+e^-}}{\mathrm{d}^4 x \mathrm{d}^4 k} = -g^{\mu\nu} \frac{\alpha^2}{3 q^2 \pi^3} \operatorname{Im} \Pi^{(\text{ret})}_{\mu\nu}(q,u) \Big|_{q^2 = M^2_{e^+e^-}} f_B(p \cdot u)$$

- manifestly Lorentz covariant (dependent on four-velocity of fluid cell, u)
- to lowest order in α: $4\pi\alpha \Pi_{\mu\nu} \simeq \Sigma^{(\gamma)}_{\mu\nu}$
- derivable from underlying thermodynamic potential, Ω!

Vector Mesons and chiral symmetry



from [Rap03]



from [Rap05]

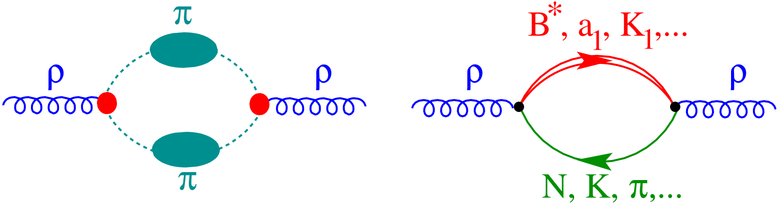
Hadronic models for light vector mesons

Realistic hadronic models for light vector mesons

- many approaches
  - gauged linear σ-model + vector-meson dominance [Pis95, UBW02]
    gauge-symmetry breaking $\Rightarrow$ pions still in physical spectrum!
  - massive Yang-Mills model; gauged non-linear chiral model with explicitly broken gauge symmetry [Mei88, LSY95]
  - hidden local symmetry: Higgs-like chiral model [BKU+85, HY03]
    allows for vector manifestation or usual manifestation (with a_1)
- here we concentrate on the phenomenological model by Rapp, Wambach, et al [RW99a, RG99, RW00]

Hadronic many-body theory

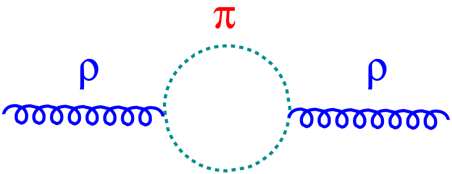
- Phenomenological HMBT [RW99a, RG99] for vector mesons
- $\pi\pi$ interactions and baryonic excitations

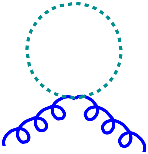


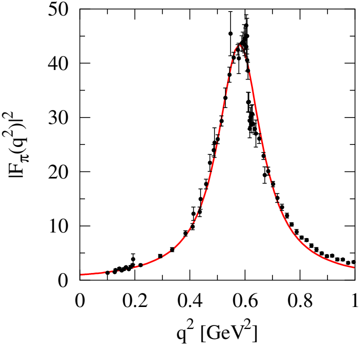
- Baryon (resonances) important, even at RHIC with low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

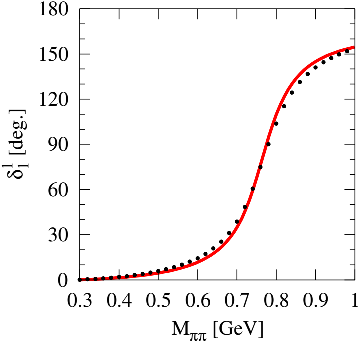
The meson sector (vacuum)

- most important for ρ-meson: pions



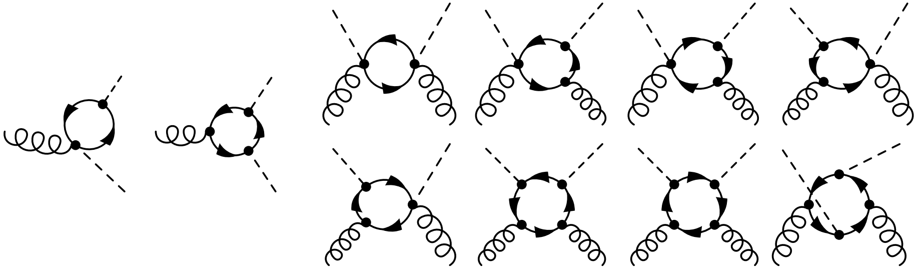




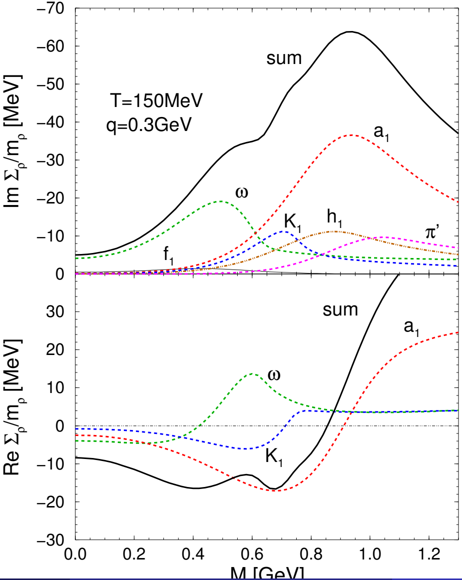


The meson sector (matter)

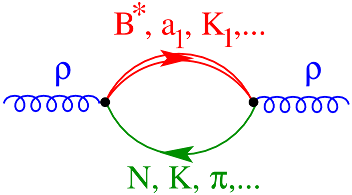
- Pions dressed with N-hole-, Δ-hole bubbles
- Ward-Takahashi ⇒ vertex corrections mandatory!



The meson sector (contributions from higher resonances)

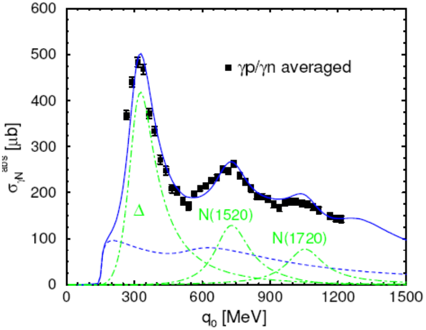


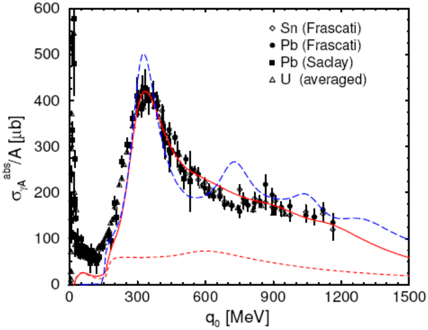
The baryon sector (vacuum)



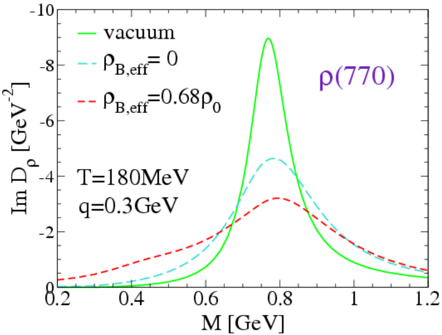
- $P = 1$-baryons: p-wave coupling to ρ:
  N(939), Δ(1232), N(1720), Δ(1905)
- $P = -1$-baryons: s-wave coupling to ρ:
  N(1520), Δ(1620), Δ(1700)

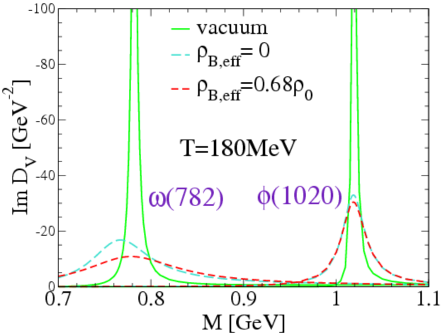
Photoabsorption on nucleons and nuclei





In-medium spectral functions and baryon effects

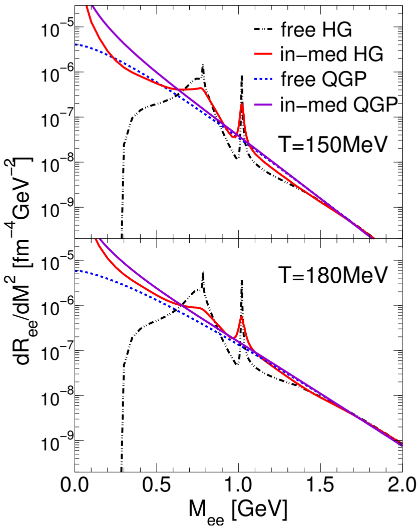




[RW99b]

- baryon effects important
  - large contribution to broadening of the peak
  - responsible for most of the strength at small M
  - important even at RHIC and LHC although $n_{\text{net B}} = n_{\text{B}} - n_{\bar{\text{B}}} \simeq 0$ ($\mu_{\text{B}} \simeq 0$)
  - reason: C-invariance of strong interactions ⇒ $n_{\text{B}} + n_{\bar{\text{B}}}$ relevant!

Dilepton rates: Hadron gas ⟷ QGP



- in-medium hadron gas matches with QGP
- similar results also for γ rates
- "quark-hadron duality"?
- does it work with chiral model?
- hidden local symm.+baryons? [Harada, Yamawaki et al.]

Dileptons in AA collisions

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 ⇒ local thermal equilibrium
    ⇒ use equilibrium rates
  - use 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)

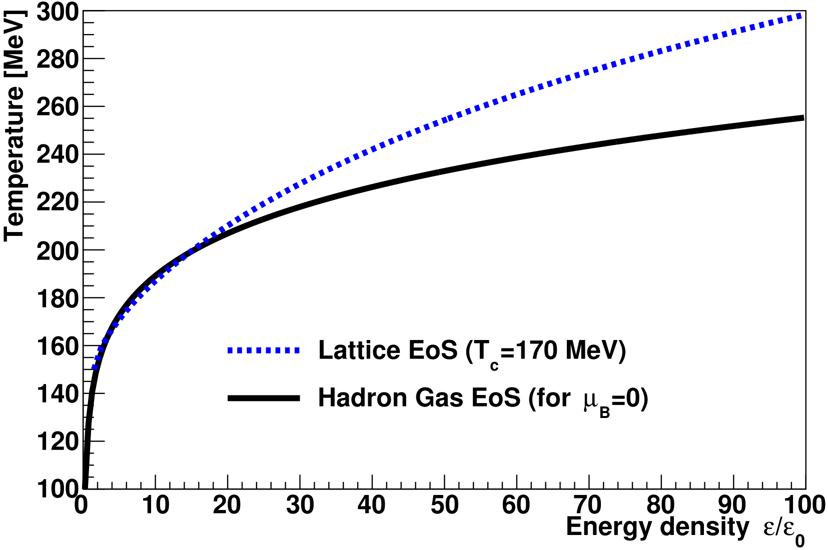
- problem with medium modifications of spectral functions/interactions
- only available in equilibrium many-body QFT models
- use "in-medium cross sections" naively: double counting?!?
- way out: map transport to local-equilibrium fluid
- use ensemble of UrQMD runs with an equation of state
- space-time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

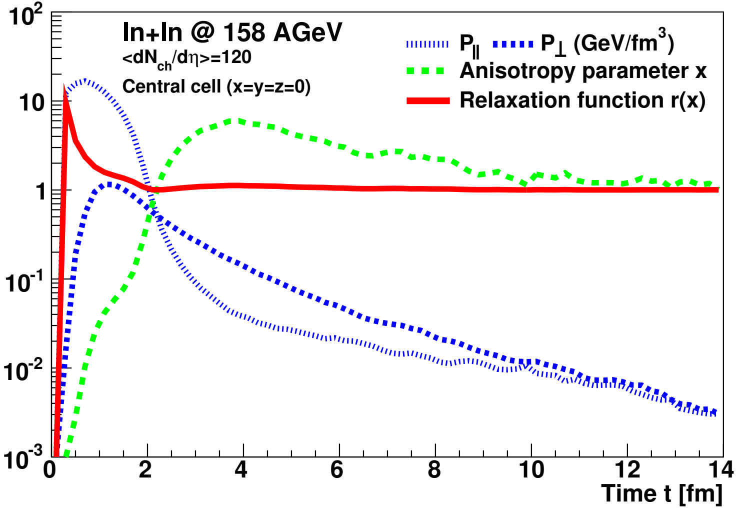
Coarse-grained UrQMD (CGUrQMD)

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



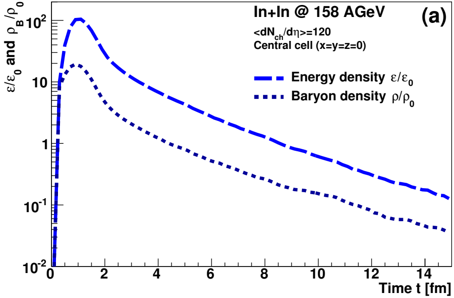
Coarse-grained UrQMD (CGUrQMD)

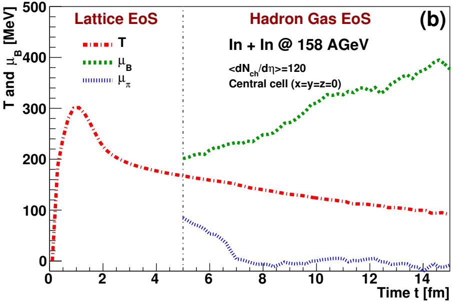
- pressure anisotropy (for In+In @ SPS; NA60)



Coarse-grained UrQMD (CGUrQMD)

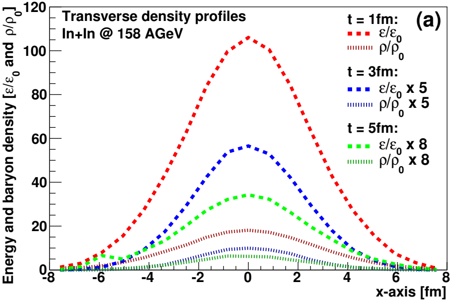
- energy/baryon density ⇒ T, μ_B (for In+In @ SPS; NA60)
- central "fluid" cell!

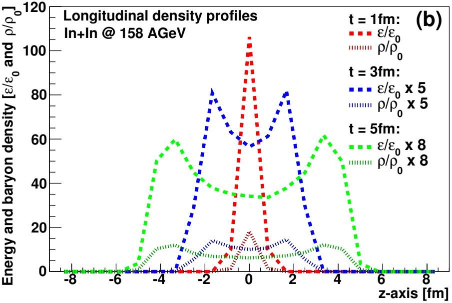




Coarse-grained UrQMD (CGUrQMD)

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

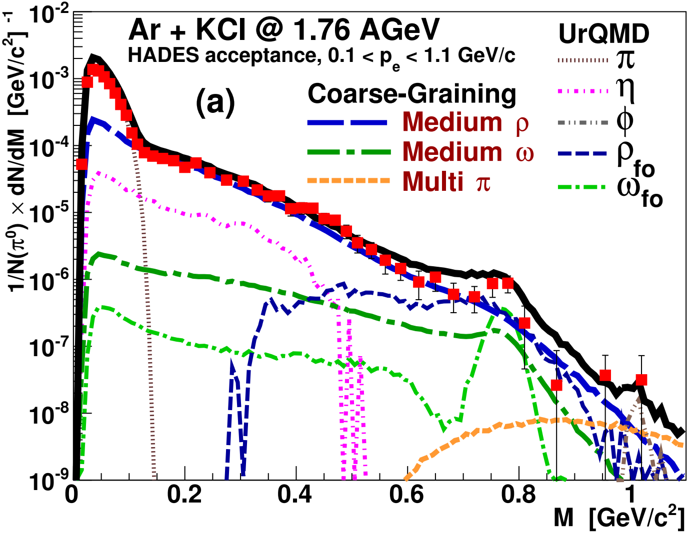




Dielectrons (SIS/HADES)

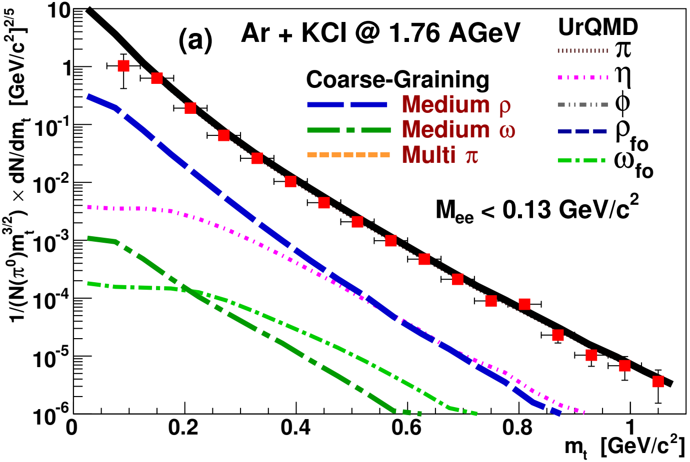
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



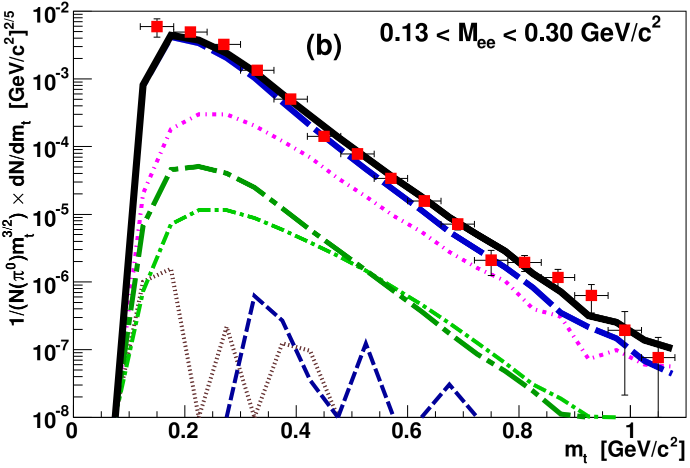
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



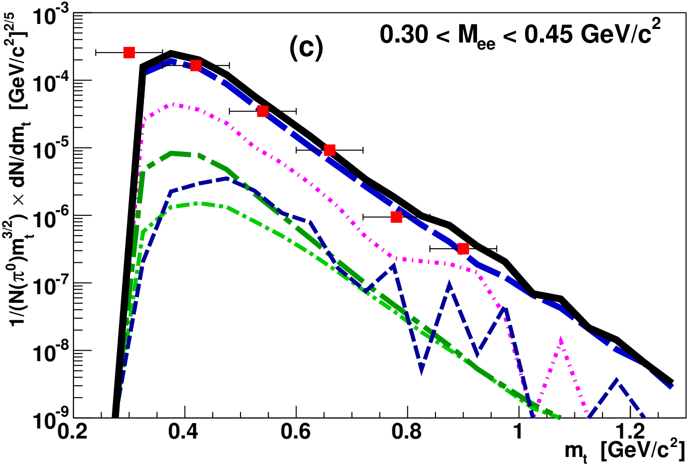
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



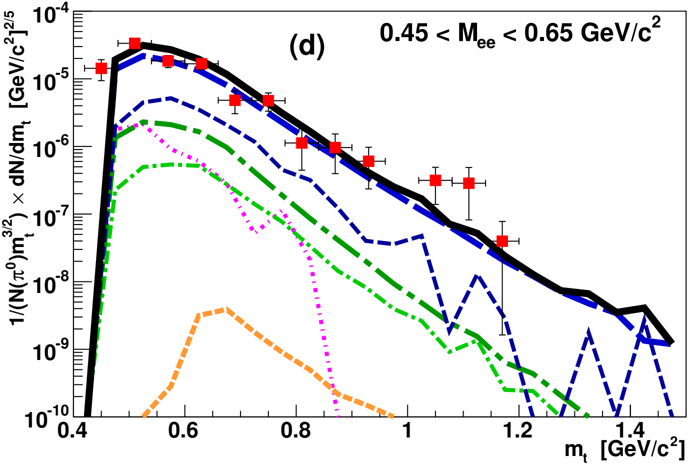
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



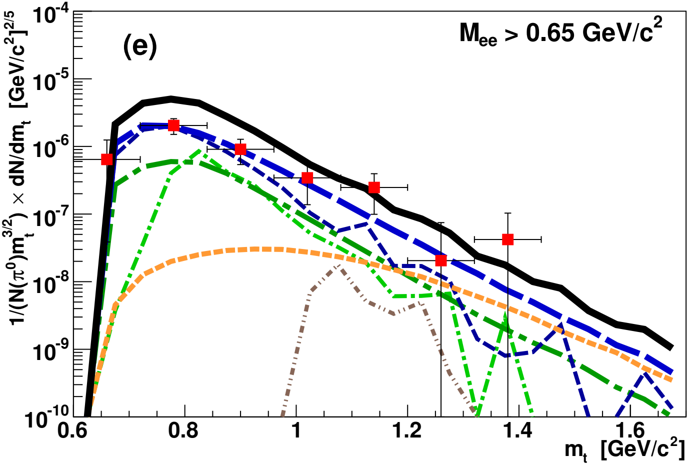
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- dielectron spectra from Ar + KCl(1.76 *A*GeV) → e^+e^- (SIS/HADES)
- m_t spectra
- 0.45 GeV M_{ee} < 0.65 GeV



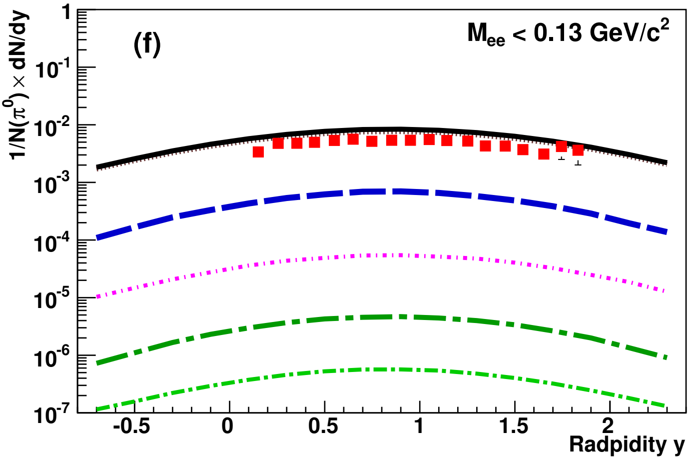
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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

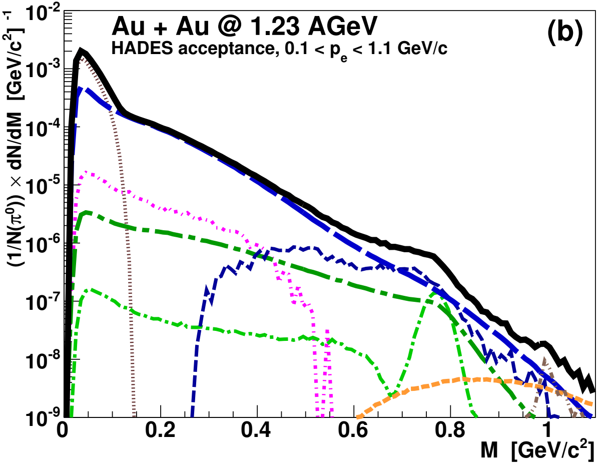


CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

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



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

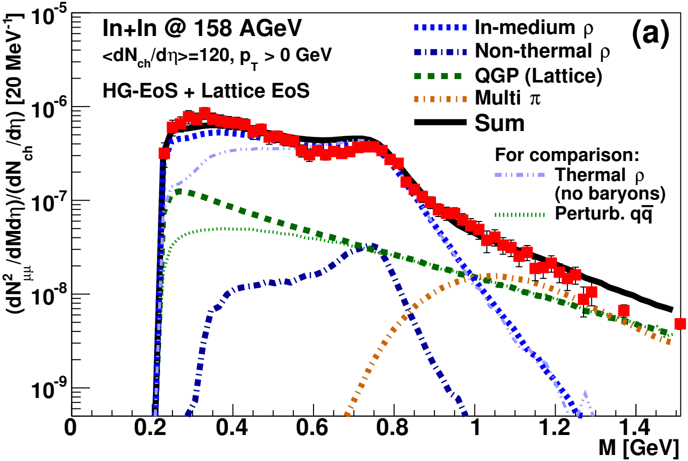


- caveat: pp/np acceptance filter with single-e cut, $p_t < 100$ MeV
- correct filter urgently needed!
- excellent agreement with preliminary HADES data

Dimuons (SPS/NA60)

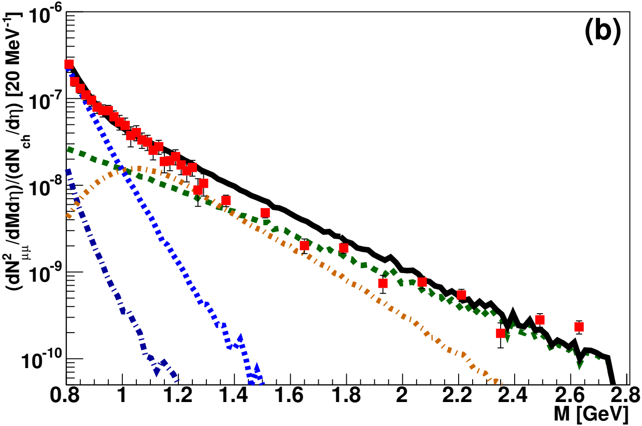
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



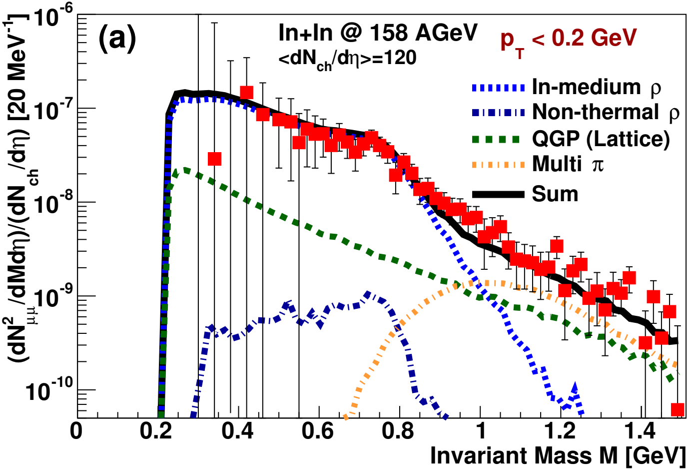
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



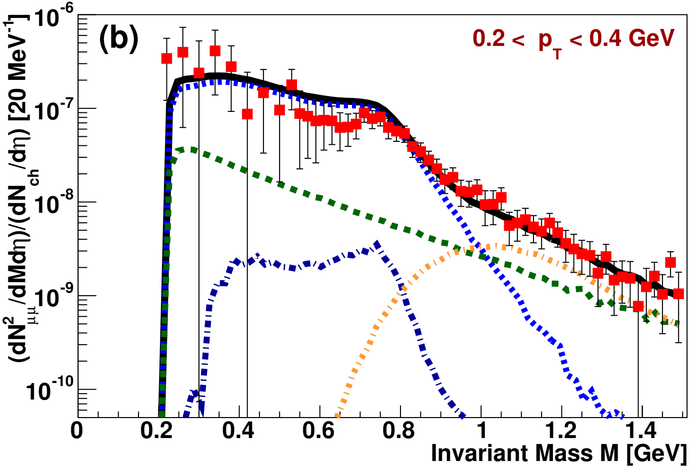
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



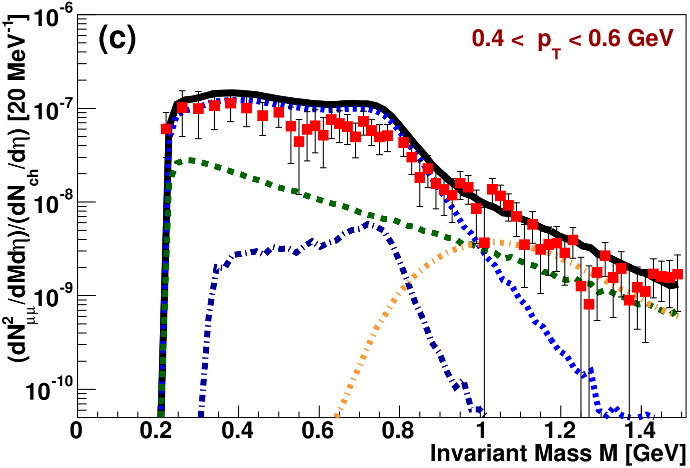
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In} + \mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $0.2\ \mathrm{GeV} < p_T < 0.4\ \mathrm{GeV}$



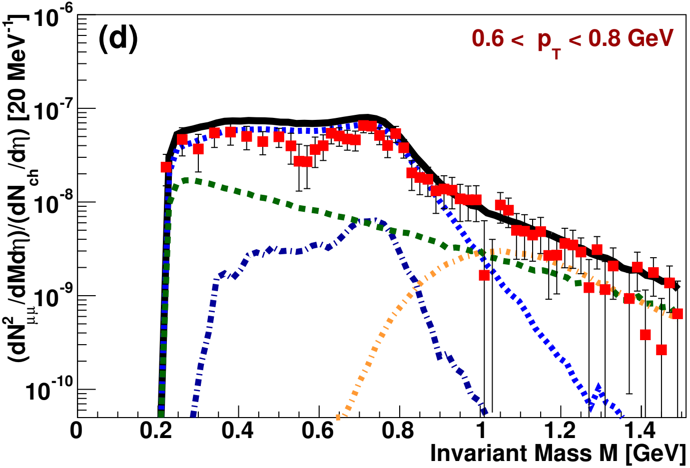
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



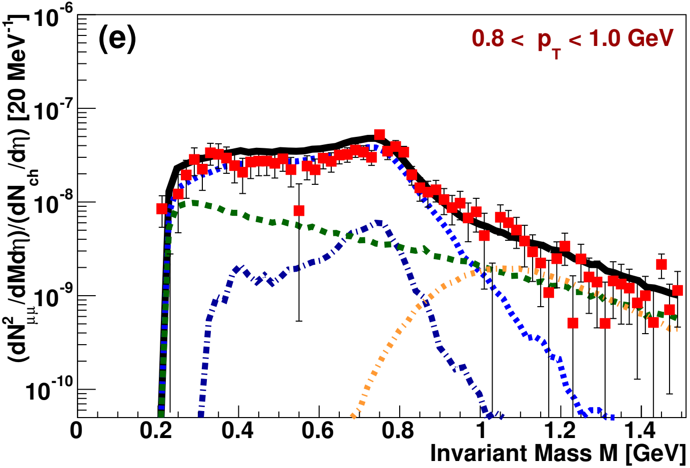
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



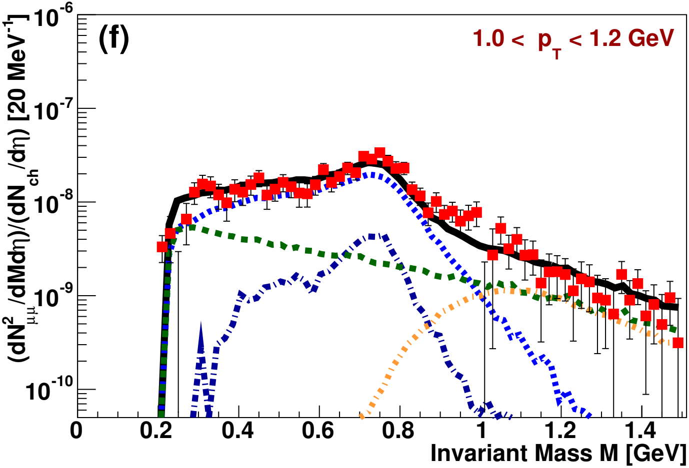
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



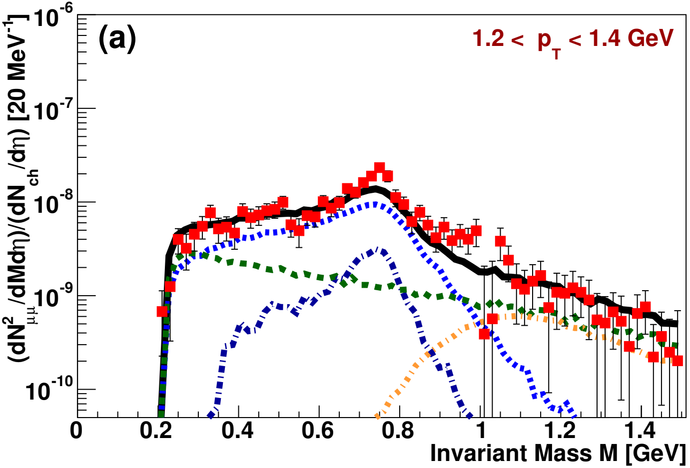
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



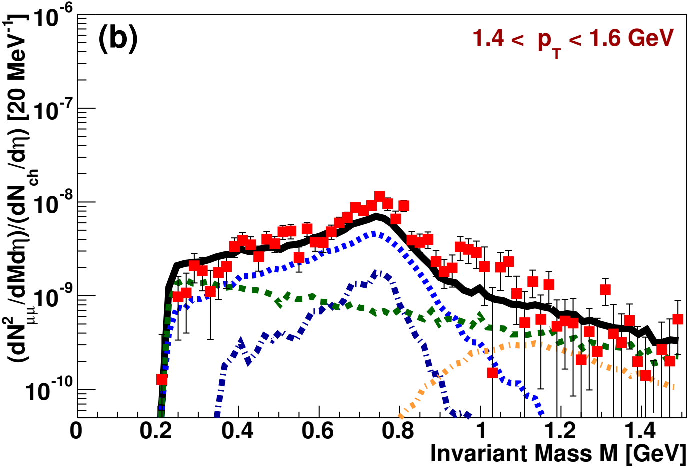
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



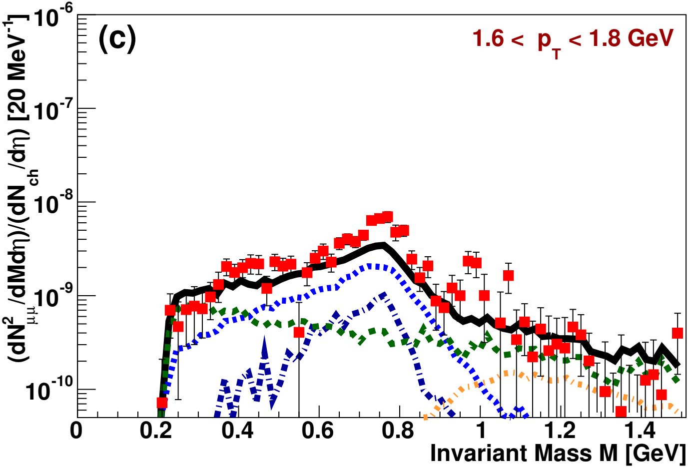
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



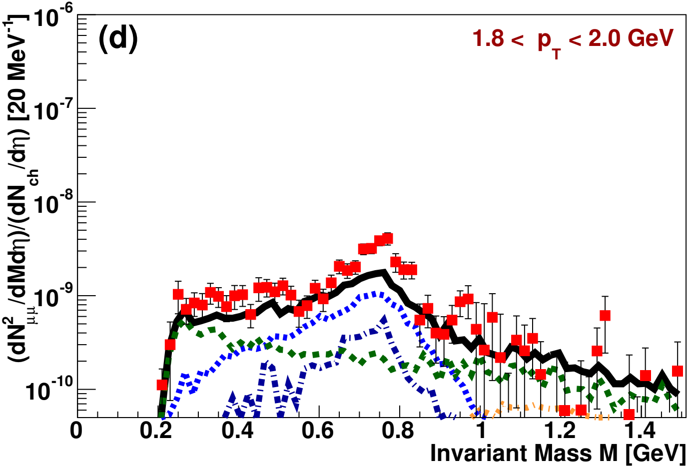
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

- dimuon spectra from $\text{In} + \text{In}(158\,A\text{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120$)
- $1.6\,\text{GeV} < p_T < 1.8\,\text{GeV}$



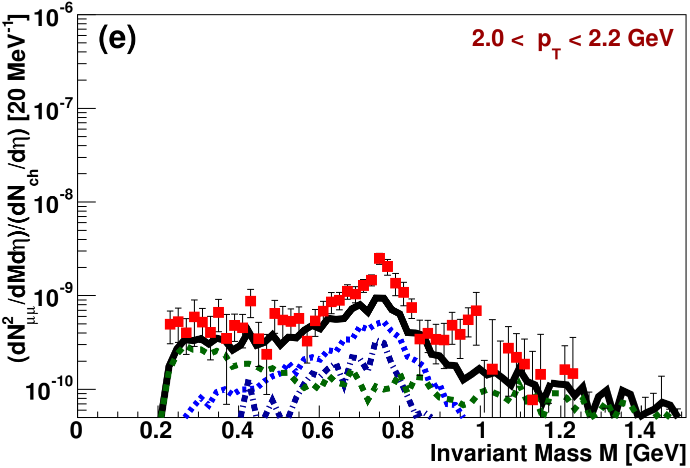
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



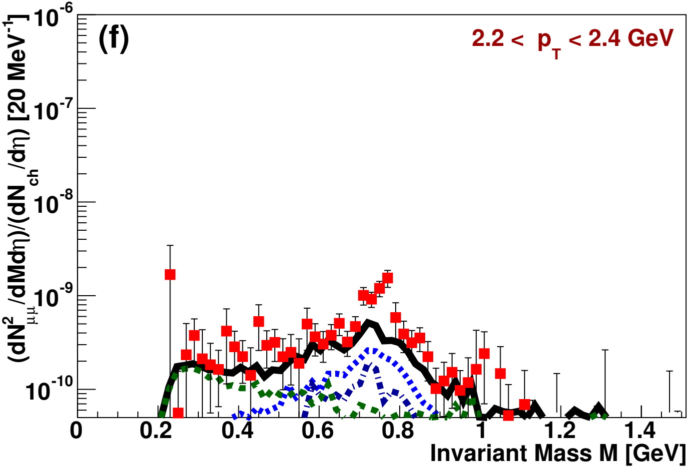
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



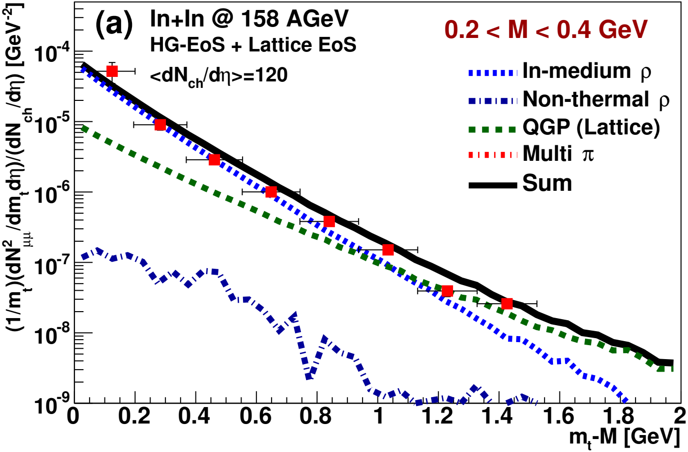
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



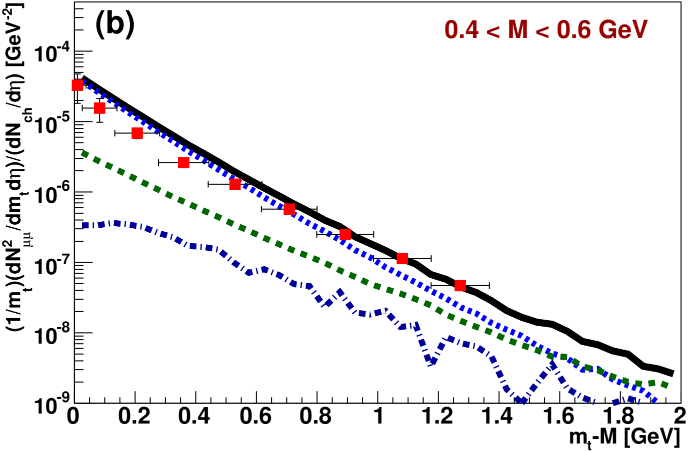
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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



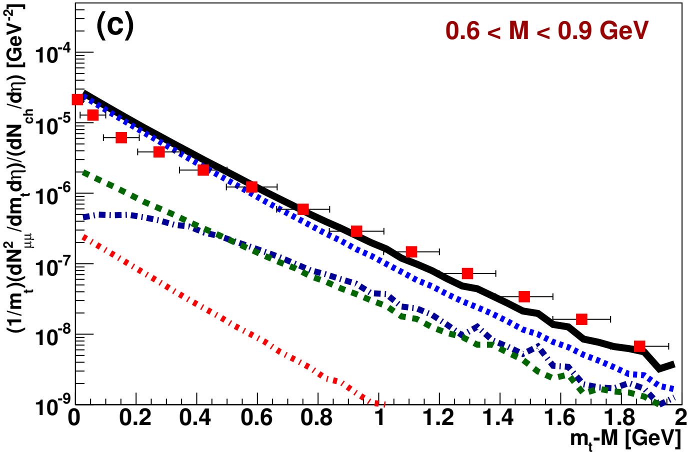
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



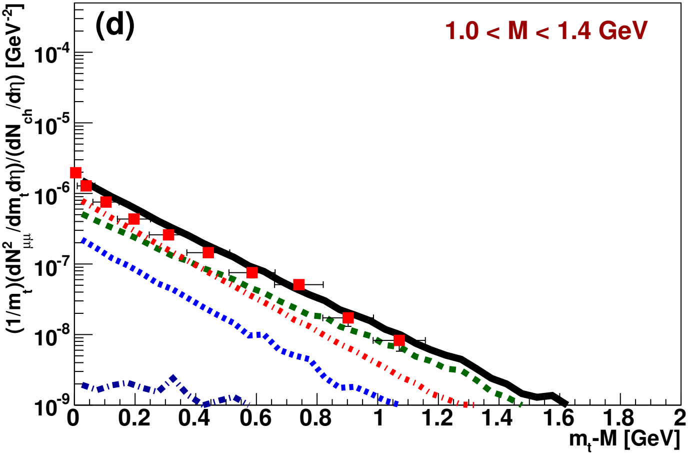
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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



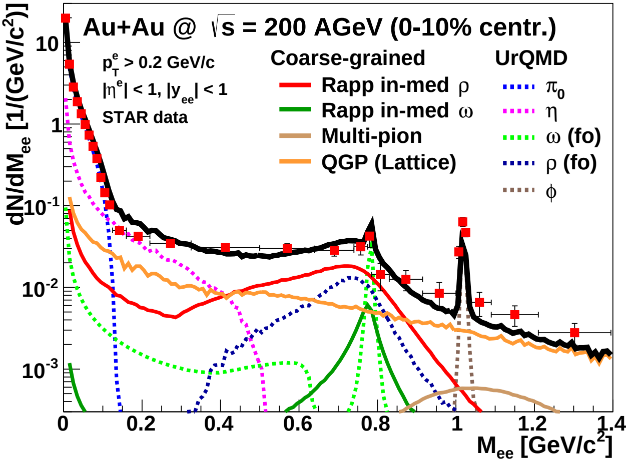
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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

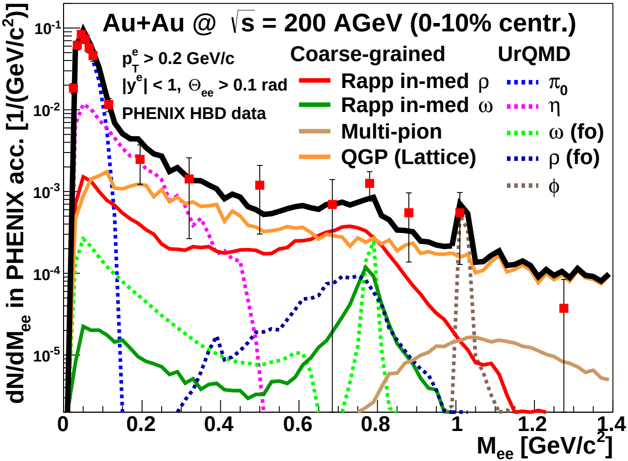


Dielectrons at RHIC

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

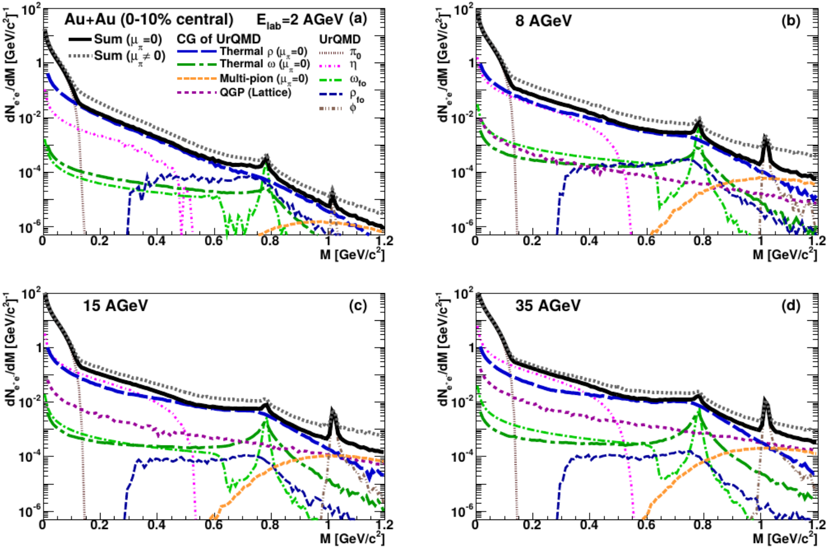


CGUrQMD: Au+Au ($\sqrt{s_{NN}} = 200$ GeV) (RHIC/PHENIX)



Dielectrons at RHIC-BES/FAIR/NICA

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



NB: also photon spectra [EHB16b]

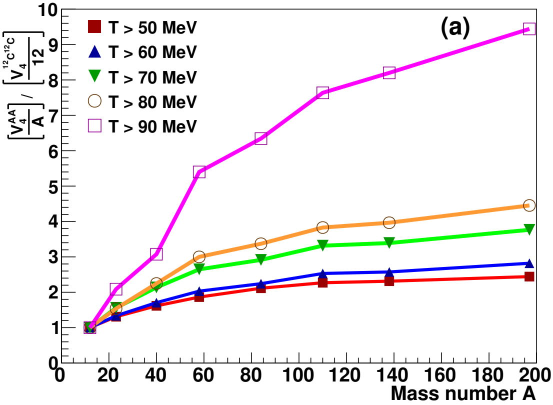
Signatures of the QCD-phase structure?

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!!!

Four Volume

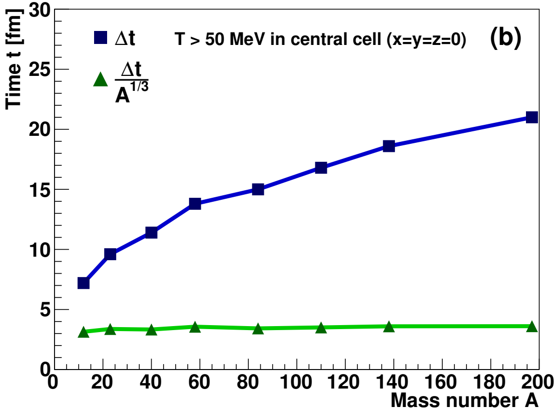
- central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76\,A\text{GeV}$
- $\dfrac{V_{AA}^{(4)}/A}{V_{\text{CC}}^{(4)}/12}$ of cells larger than various T



- how to explain “scaling behavior”?

Lifetime of the central cell

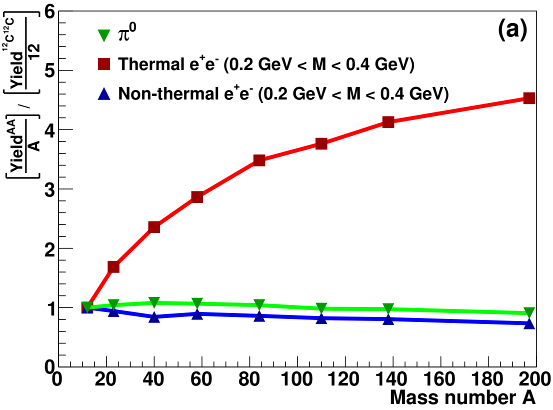
- central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76\,A\text{GeV}$



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

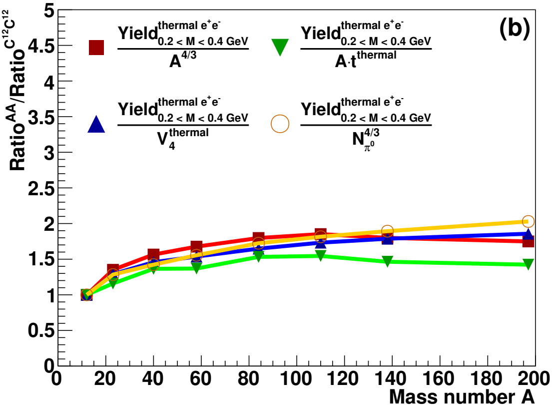
- central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76\, A\text{GeV}$
- $\frac{\text{yield}_{AA}/A}{\text{yield}_{\text{CC}}/12}$



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

Scaling behavior of thermal-dilepton yield

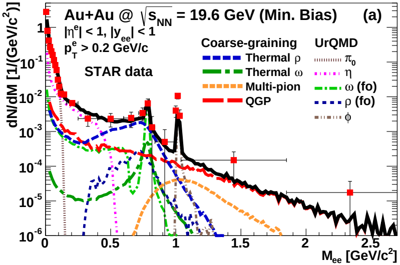
- central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76\,A\text{GeV}$

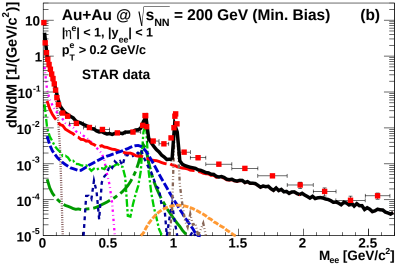


- thermal-dilepton yield roughly $\propto V_{\text{therm}}^{(4)} \propto A^{4/3} \propto A t_{\text{therm}} \propto N_{\pi^0}^{4/3}$
- at low(est) beam energies:
  lifetime of "medium" $\hat{=}$ time nuclei pass through each other

Dilepton systematics in the beam-energy scan

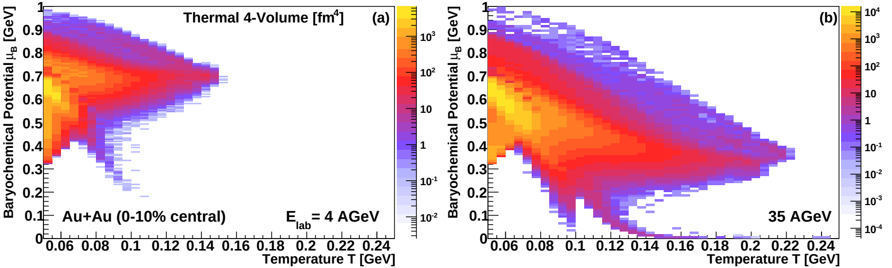
- T and μ_B vs. t [EHB16b, EHB16a]





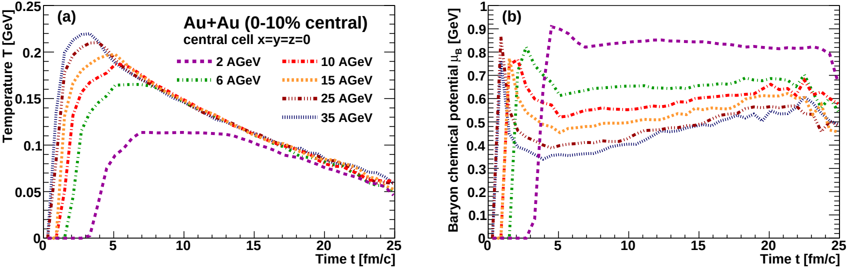
Dilepton systematics in the beam-energy scan

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



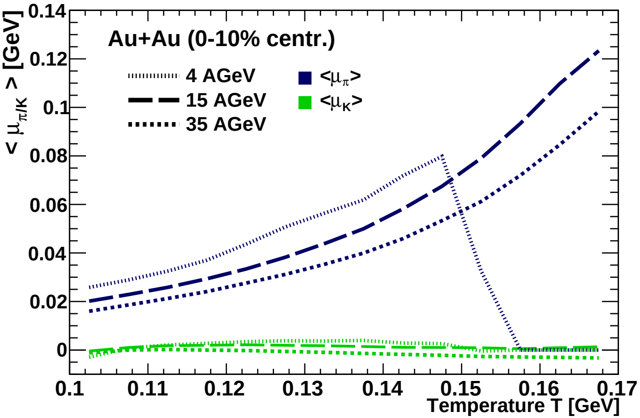
Dilepton systematics in the beam-energy scan

- T and μ_B vs. t [EHB16b, EHB16a]



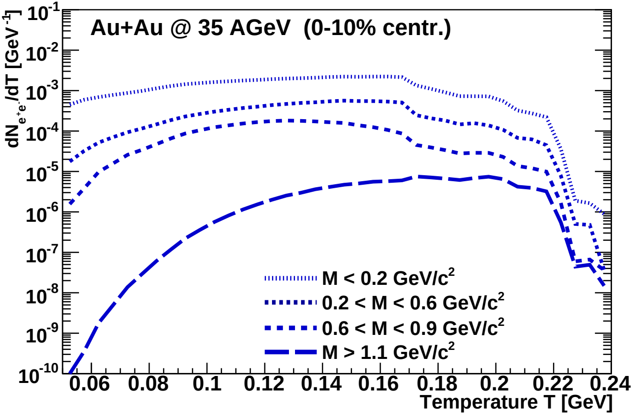
Dilepton systematics in the beam-energy scan

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



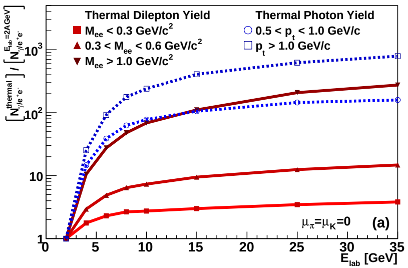
Dilepton systematics in the beam-energy scan

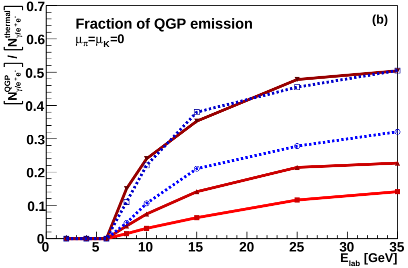
- mass-temperature relation in dilepton emission [EHB16b, EHB16a]



Dilepton systematics in the beam-energy scan

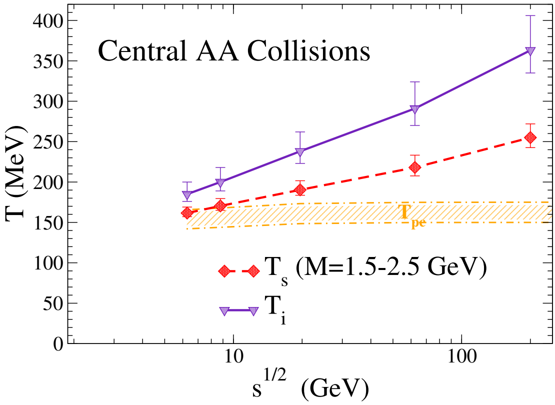
- excitation function e^+e^-/γ yield and QGP fraction [EHB16b, EHB16a]





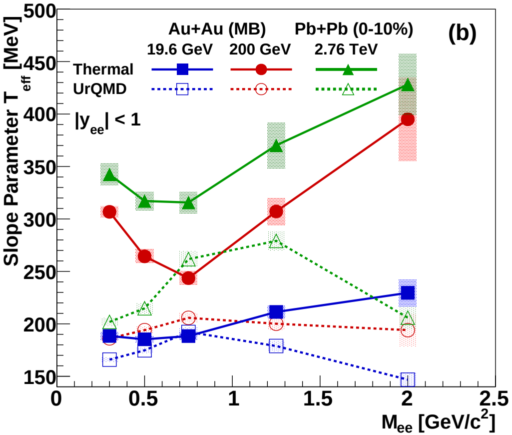
Dilepton systematics in the beam-energy scan

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



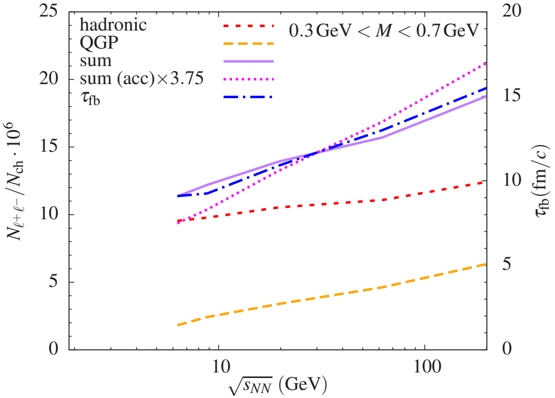
Dilepton systematics in the beam-energy scan

- 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



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Quiz

Quiz

1. Why do we need effective hadronic models to theoretically study electromagnetic probes in HICs?
2. How do we constrain effective hadronic models theoretically?
3. How do we determine all the parameters (couplings, masses, form factors) of the models?
4. What is left to be predicted from such models?
5. What are the most important processes leading to medium modifications of the vector mesons' spectral functions?
6. What are the different dilepton sources that are important in UHICs?
7. What fundamental properties about the hot and dense medium produced in HICs have we inferred from $\ell^+\ell^-$ data so far?