Electromagnetic Probes in Heavy-Ion Collisions

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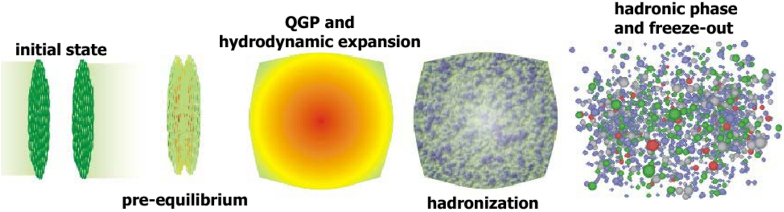
Outline

Heavy-Ion collisions in a Nutshell

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



QCD and ("accidental") symmetries

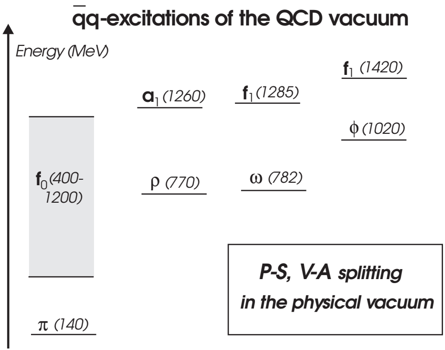
- fundamental theory of strong interactions: QCD

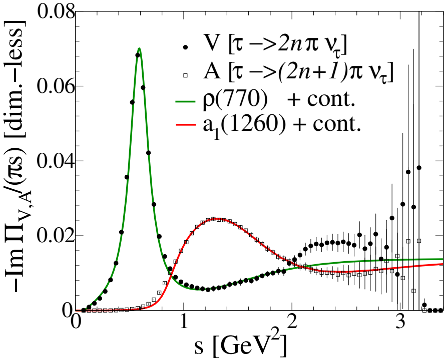
$$\mathscr{L}_{\text{QCD}} = -\frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a + \bar{\psi}(\mathrm{i}\not{D} - \hat{M})\psi$$

- particle content:
  - ψ: Quarks, including flavor- and color degrees of freedom, $\hat{M} = \mathrm{diag}(m_u, m_d, m_s, \ldots) =$ current quark masses
  - A_μ^a: gluons, gauge bosons of $\mathrm{SU}(3)_{\text{color}}$
- symmetries
  - fundamental building block: local $\mathrm{SU}(3)_{\text{color}}$ symmetry
  - in light-quark sector: approximate chiral symmetry
  - chiral symmetry $\Rightarrow$ connection between QCD and effective hadronic models

Phenomenology and Chiral symmetry

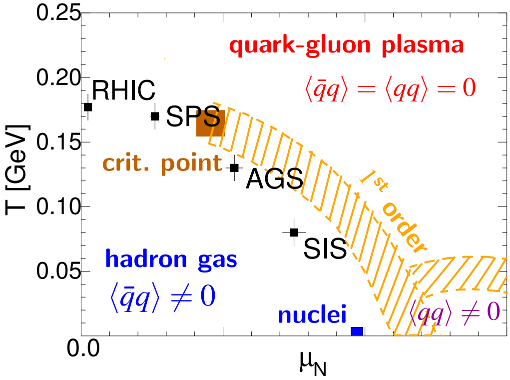
- in vacuum: Spontaneous breaking of chiral symmetry
- ⇒ mass splitting of chiral partners





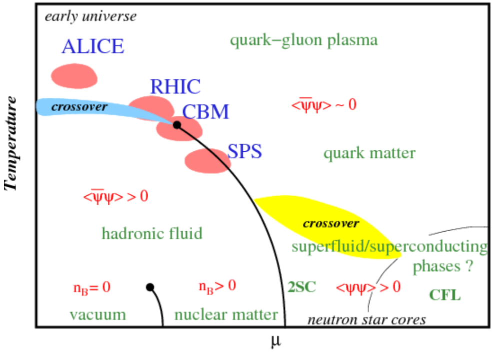
The QCD-phase diagram

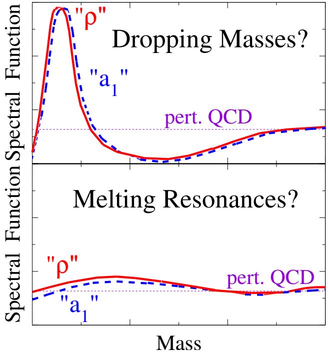
- hot and dense matter: quarks and gluons close together
- highly energetic collisions ⇒ "deconfinement"
- quarks and gluons relevant degrees of freedom ⇒ quark-gluon plasma
- still strongly interacting ⇒ fast thermalization!



The QCD-phase diagram

- at high temperature/density: restoration of chiral symmetry
- lattice QCD: $T_c^{\chi} \simeq T_c^{\text{deconf}}$

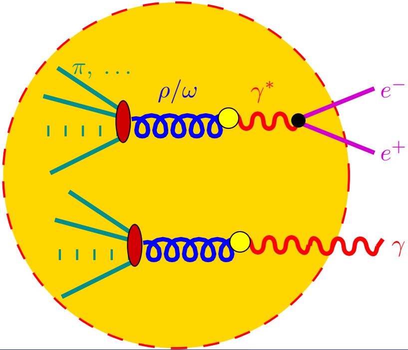




- mechanism of chiral restoration?
- two main theoretical ideas
  - "dropping masses": $m_{\text{had}} \propto \langle \overline{\psi} \psi \rangle$
  - "melting resonances": broadening of spectra through medium effects

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



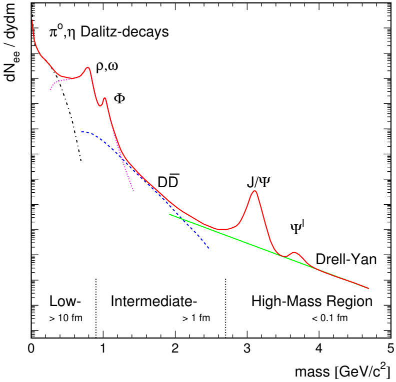


Fig. by A. Drees

Electromagnetic probes from thermal source

- 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 [L. D. McLerran, T. Toimela PRD **31**, 545 (1985); C. Gale, J. I. Kapusta, NPB **357**, 65 (1991)]

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

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

- manifestly Lorentz covariant (dependent on four-velocity of fluid cell, u)
- $q \cdot u = E_{\text{cm}}$: Doppler blue shift of q_T spectra!

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

- General: McLerran-Toimela formula

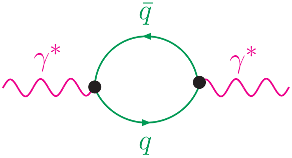
$$\frac{\mathrm{d}N^{(\mathrm{MT})}_{l^+l^-}}{\mathrm{d}^4x\,\mathrm{d}^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M^2)}{M^2} g_{\mu\nu} \mathrm{Im} \sum_i \Pi^{\mu\nu}_{\mathrm{em},i}(M,\vec{q}) f_B(q\cdot u)$$

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

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

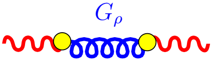
- in QGP phase: $q\bar{q}$ annihilation
- hard-thermal-loop improved electromagnetic current-current correlator

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



Radiation from thermal sources: ρ decays

- model assumption: vector-meson dominance

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

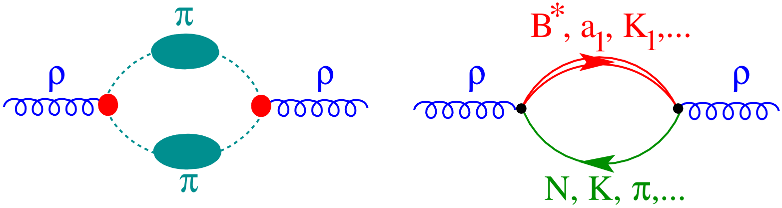
$$\frac{\mathrm{d}N^{(\mathrm{MT})}_{\rho\to l^+l^-}}{\mathrm{d}^4x\,\mathrm{d}^4q} = \frac{M}{q^0}\Gamma_{\rho\to l^+l^-}(M)\frac{\mathrm{d}N_\rho}{\mathrm{d}^3\vec{x}\,\mathrm{d}^4q}$$

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

- 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 $T(t)$, $\mu_{\text{meson/baryon}}(t)$
- $-\mathrm{Im}\,D_\rho$ in-medium ρ-meson spectral function!
- analogous for ω and ϕ

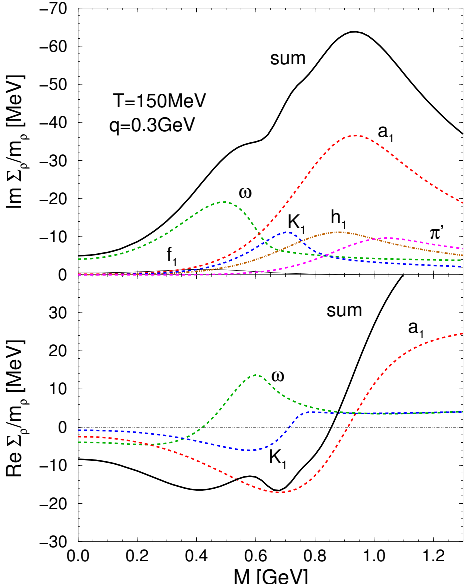
Hadronic many-body theory

- 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 ⇒ mass shift and broadening of particle/resonance in the medium



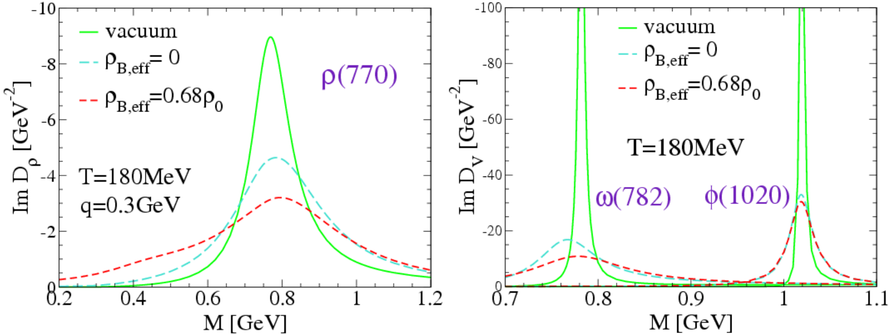
- Baryon (resonances) important, even at low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

Meson contributions



[C. Gale, R. Rapp, PRC **60**, 024903 (1999)]

In-medium spectral functions and baryon effects



[R. Rapp, J. Wambach, EJPA **6**, 415 (1999)]

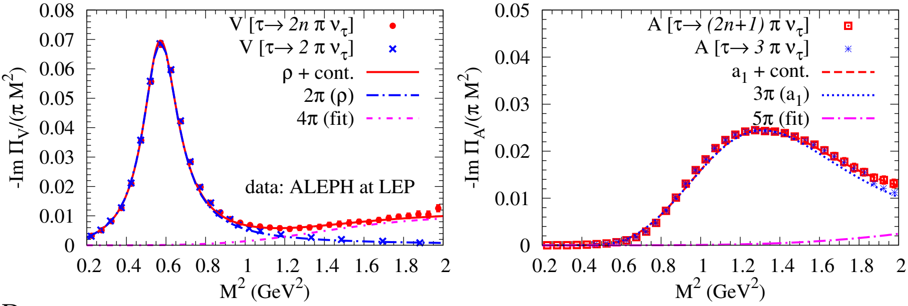
- baryon effects important
  - large contribution to broadening of the peak
  - responsible for most of the strength at small M

Radiation from thermal sources: multi-π processes

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

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

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



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

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
- fit temperature, chemical potentials, flow-velocity field from anisotropic energy-momentum tensor [W. Florkowski et al NPA **904-905**, 803c (2013)]

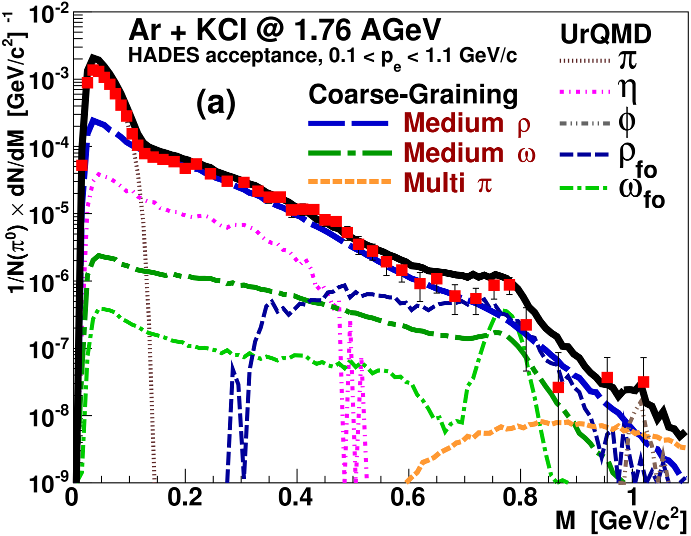
$$T^{\mu\nu} = (\epsilon + P_\perp) u^\mu u^\nu - P_\perp g^{\mu\nu} - (P_\parallel - P_\perp) V^\mu V^\nu$$

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

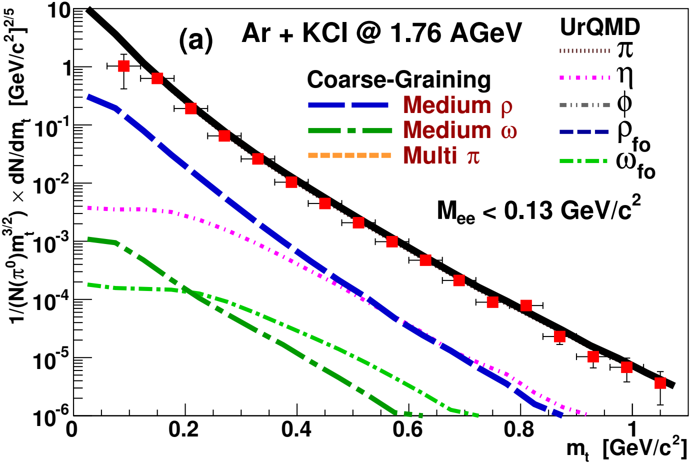
Dielectrons (SIS/HADES)

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

- coarse-graining method works at low energies!
- UrQMD-medium evolution + RW-QFT rates [S. Endres, HvH, J. Weil, M. Bleicher, arXiv: 1505.06131 [nucl-th]]



- dielectron spectra from $\mathrm{Ar}+\mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow e^+e^-$ (SIS/HADES)
- m_t spectra [S. Endres, HvH, J. Weil, M. Bleicher, arXiv: 1505.06131 [nucl-th]]
- $M_{ee} < 0.13$ GeV



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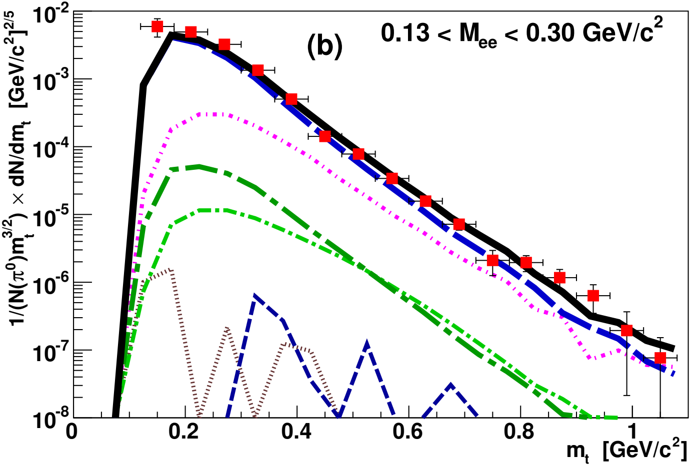
- m_t spectra [S. Endres, HvH, J. Weil, M. Bleicher, arXiv: 1505.06131 [nucl-th]]
- $0.13\,\mathrm{GeV} M_{\mathrm{ee}} < 0.3\,\mathrm{GeV}$



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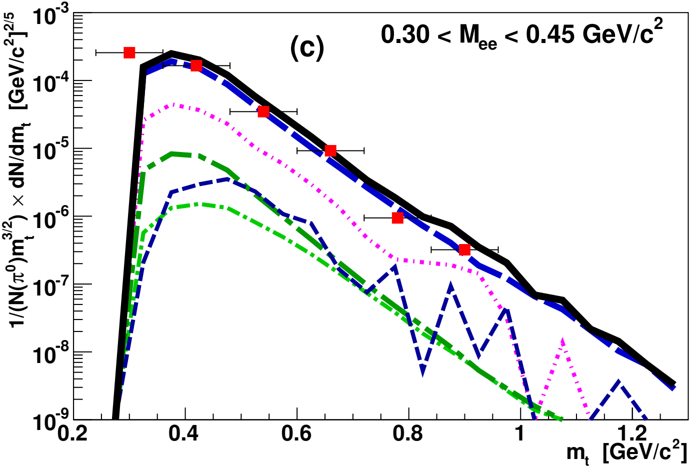
- dielectron spectra from $\mathrm{Ar} + \mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow \mathrm{e}^{+}\mathrm{e}^{-}$ (SIS/HADES)
- m_t spectra [S. Endres, HvH, J. Weil, M. Bleicher, arXiv: 1505.06131 [nucl-th]]
- $0.3\,\mathrm{GeV} M_{\mathrm{ee}} < 0.45\,\mathrm{GeV}$



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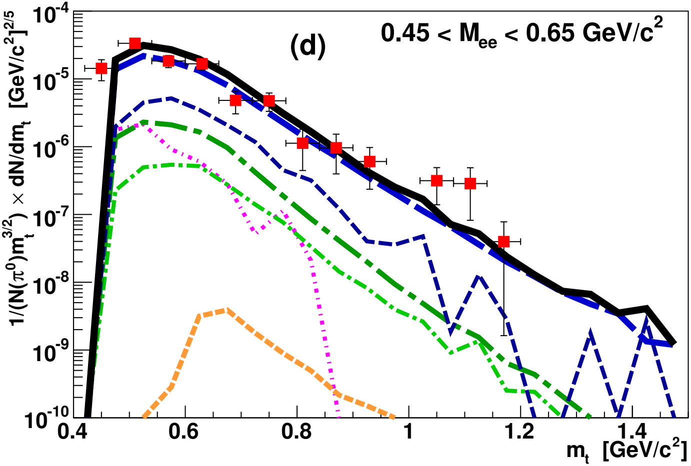
- m_t spectra [S. Endres, HvH, J. Weil, M. Bleicher, arXiv: 1505.06131 [nucl-th]]
- $0.45\,\mathrm{GeV} M_{\mathrm{ee}} < 0.65\,\mathrm{GeV}$



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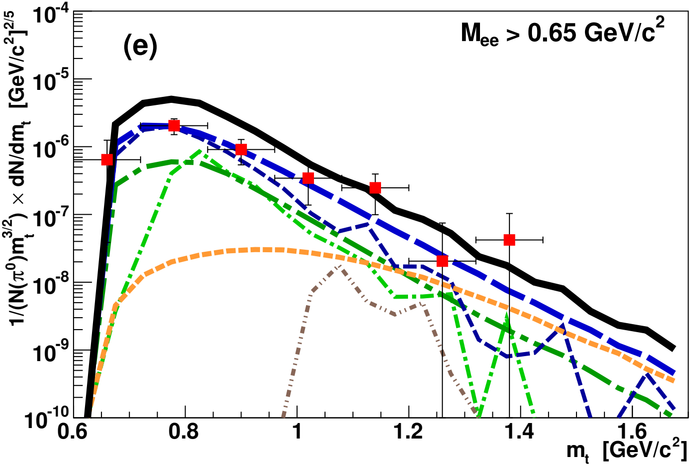
- m_t spectra [S. Endres, HvH, J. Weil, M. Bleicher, arXiv: 1505.06131 [nucl-th]]
- $M_{ee} > 0.65$ GeV



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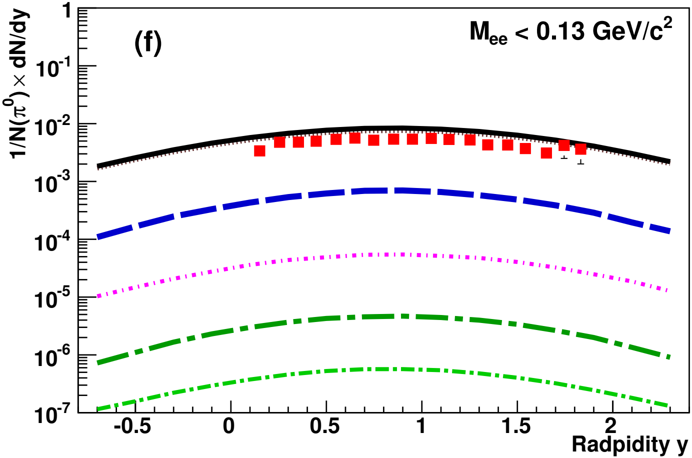
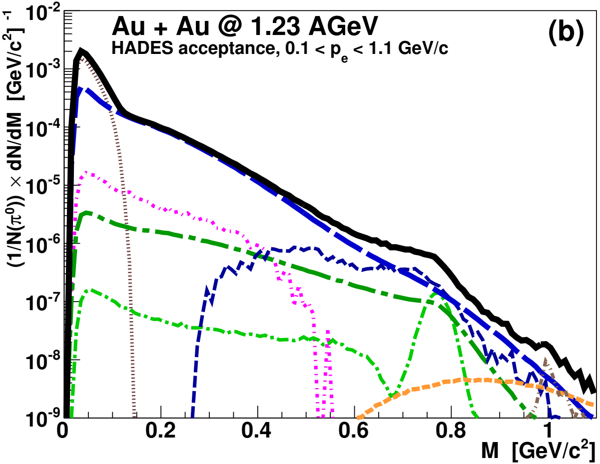
- m_t spectra [S. Endres, HvH, J. Weil, M. Bleicher, arXiv: 1505.06131 [nucl-th]]
- rapidity spectrum ($M_{\mathrm{ee}} < 0.13$ GeV)



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



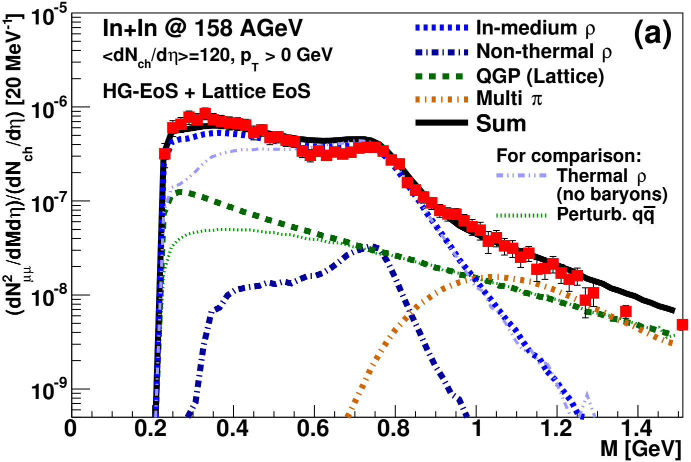
- caveat: pp/np acceptance filter with single-e cut, $p_t < 100$ MeV
- correct filter urgently needed!
- excellent agreement with preliminary HADES data (data points not shown here on request of the HADES collaboration)

Dimuons (SPS/NA60)

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

- dimuon spectra from $\text{In} + \text{In}(158\,A\text{GeV}) \rightarrow \mu^+\mu^-$ (NA60)

  [S. Endres, HvH, J. Weil, M. Bleicher, PRC **91**, 054911 (2015)]
- min-bias data ($\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120$)
- note the importance of baryon effects!



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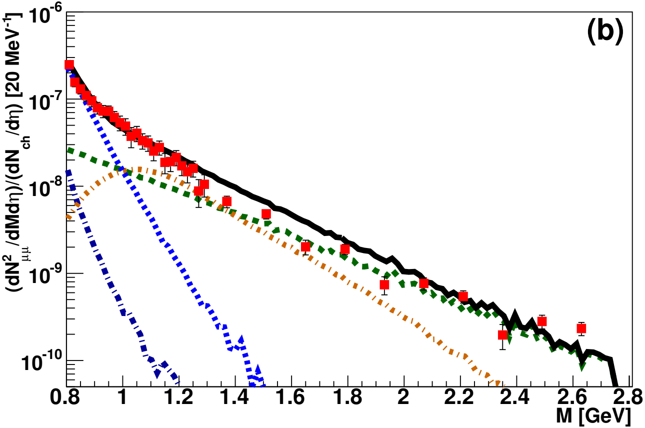
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- higher IMR: provides averaged true temperature
  (no blueshifts in the invariant-mass spectra!)



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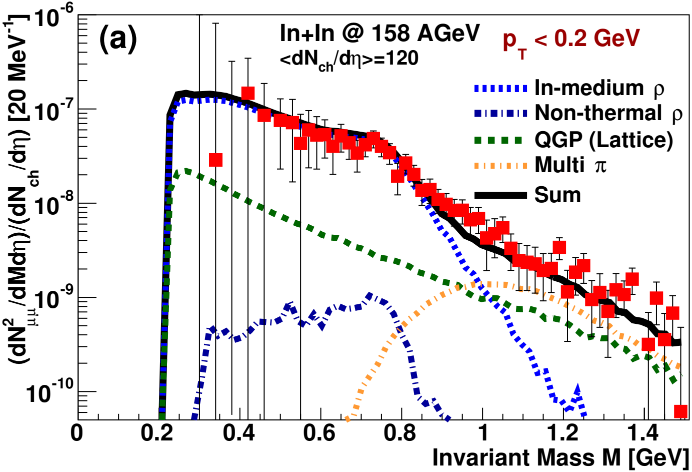
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $p_T < 0.2$ GeV



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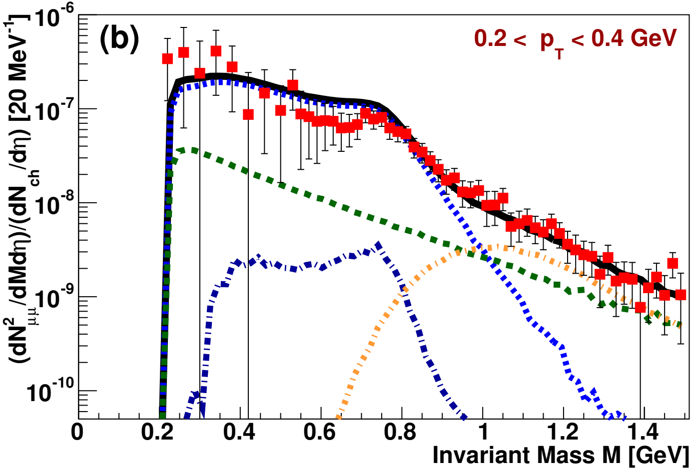
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $0.2\,\mathrm{GeV} < p_T < 0.4\,\mathrm{GeV}$



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

- dimuon spectra from In + In(158 *A*GeV) $\rightarrow \mu^+\mu^-$ (NA60)

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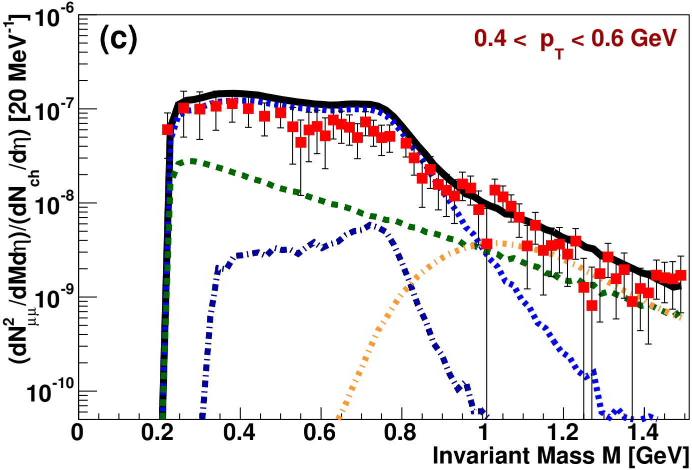
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $0.4\ \mathrm{GeV} < p_T < 0.6\ \mathrm{GeV}$



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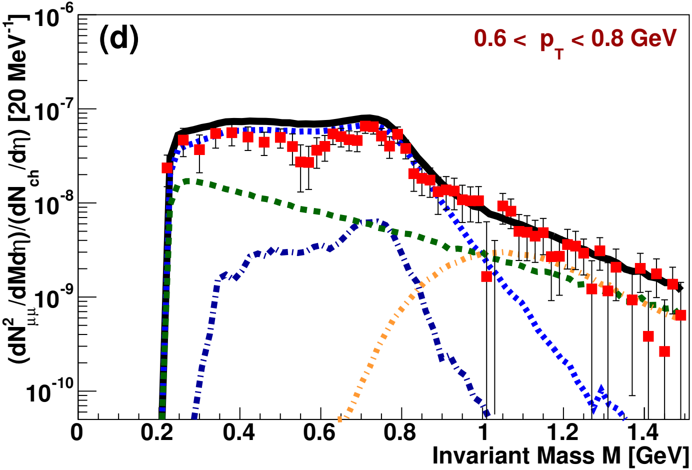
- min-bias data ($\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120$)
- $0.6\,\text{GeV} < p_T < 0.8\,\text{GeV}$



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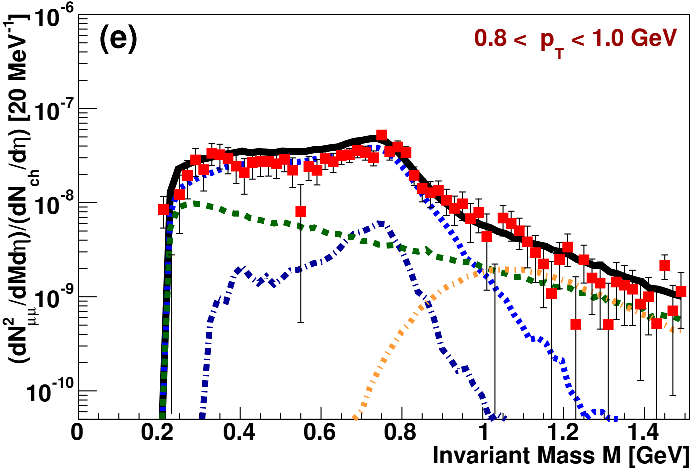
- min-bias data ($\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120$)
- $0.8\,\text{GeV} < p_T < 1.0\,\text{GeV}$



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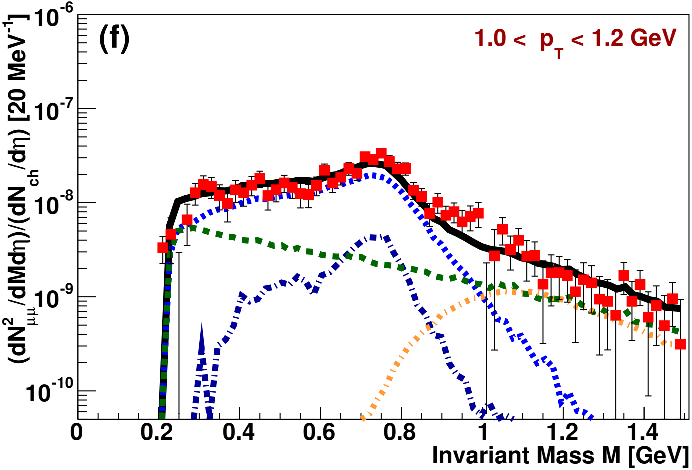
- min-bias data $(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120)$
- $1.0\,\mathrm{GeV} < p_T < 1.2\,\mathrm{GeV}$



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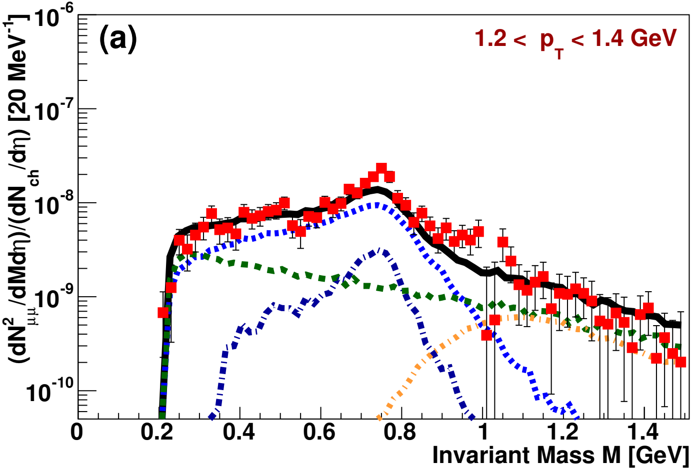
- $1.2\,\mathrm{GeV} < p_T < 1.4\,\mathrm{GeV}$

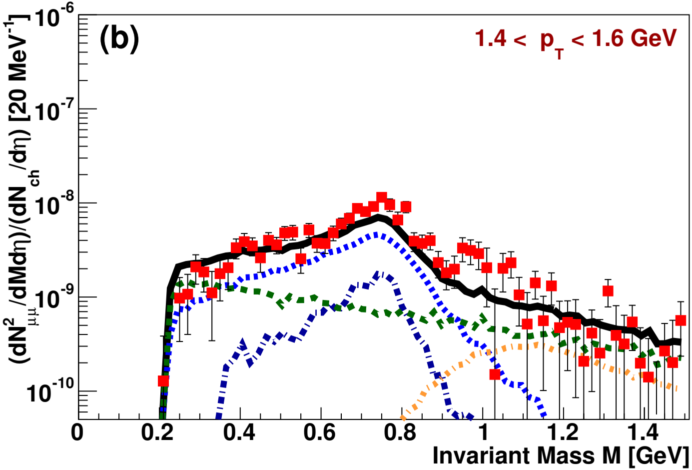


CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

- dimuon spectra from In + In(158 *A*GeV) → $\mu^+\mu^-$ (NA60)

  [S. Endres, HvH, J. Weil, M. Bleicher, PRC **91**, 054911 (2015)]

- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $1.4\ \mathrm{GeV} < p_T < 1.6\ \mathrm{GeV}$

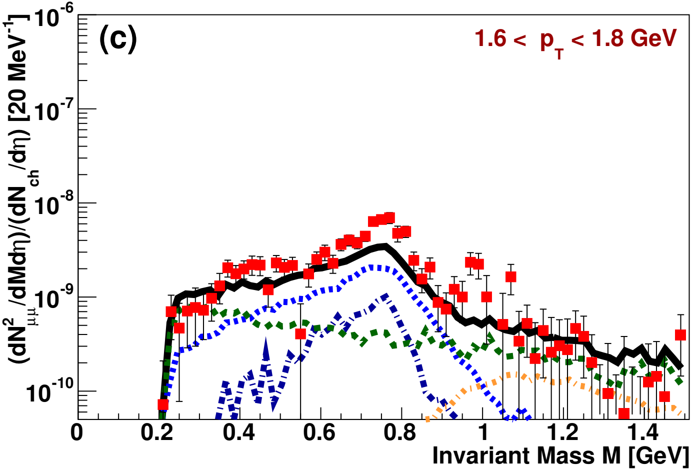


CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

- dimuon spectra from $\text{In} + \text{In}(158\,A\text{GeV}) \to \mu^+\mu^-$ (NA60)

[S. Endres, HvH, J. Weil, M. Bleicher, PRC **91**, 054911 (2015)]

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

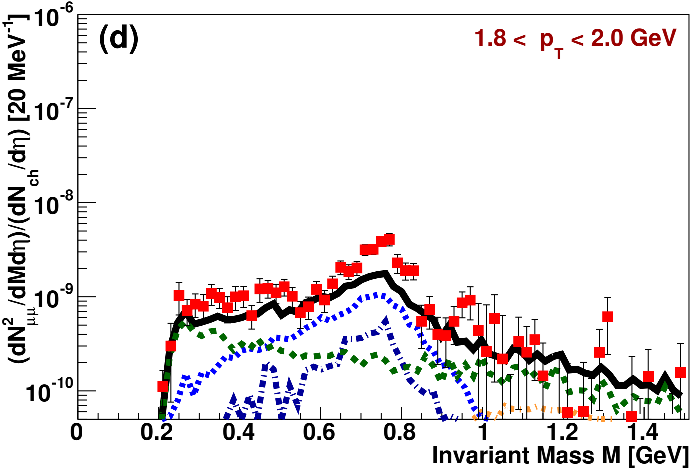


CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\text{In} + \text{In}(158\,A\text{GeV}) \rightarrow \mu^+\mu^-$ (NA60)

[S. Endres, HvH, J. Weil, M. Bleicher, PRC **91**, 054911 (2015)]

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

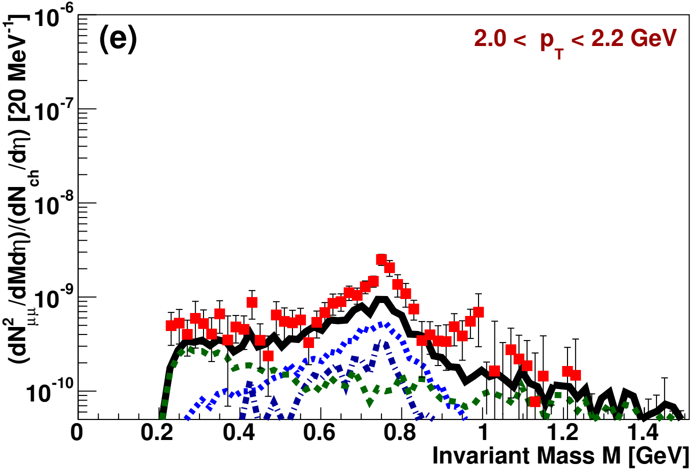


CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\text{In} + \text{In}(158\,A\text{GeV}) \rightarrow \mu^+\mu^-$ (NA60)

  [S. Endres, HvH, J. Weil, M. Bleicher, PRC **91**, 054911 (2015)]

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

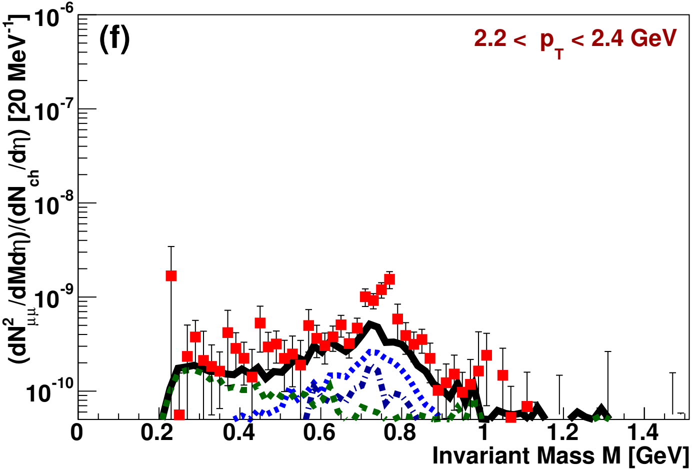


CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

- dimuon spectra from $\text{In} + \text{In}(158\,A\text{GeV}) \rightarrow \mu^+\mu^-$ (NA60)

  [S. Endres, HvH, J. Weil, M. Bleicher, PRC **91**, 054911 (2015)]

- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $2.2\,\text{GeV} < p_T < 2.4\,\text{GeV}$



- dimuon spectra from In + In(158 *A*GeV) → $\mu^+\mu^-$ (NA60) [S. Endres, HvH, J. Weil, M. Bleicher, PRC **91**, 054911 (2015)]
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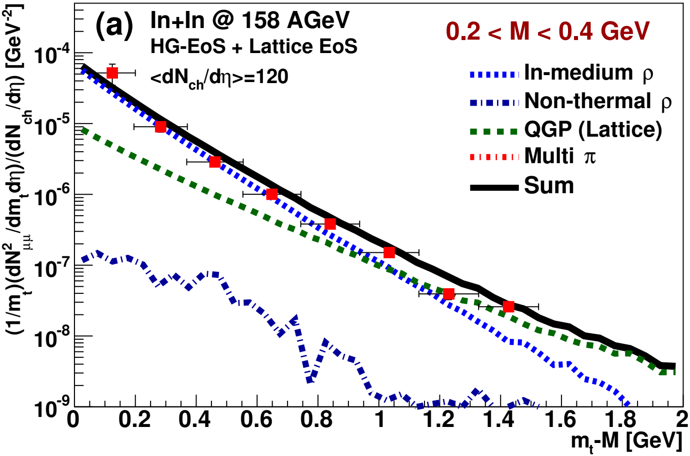
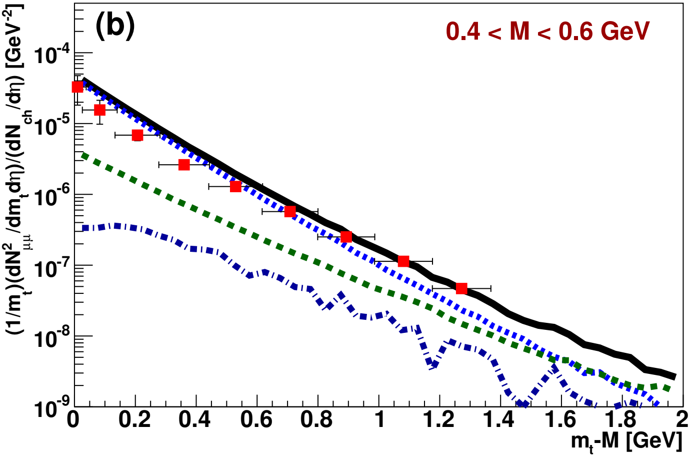


CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [S. Endres, HvH, J. Weil, M. Bleicher, PRC **91**, 054911 (2015)]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)



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

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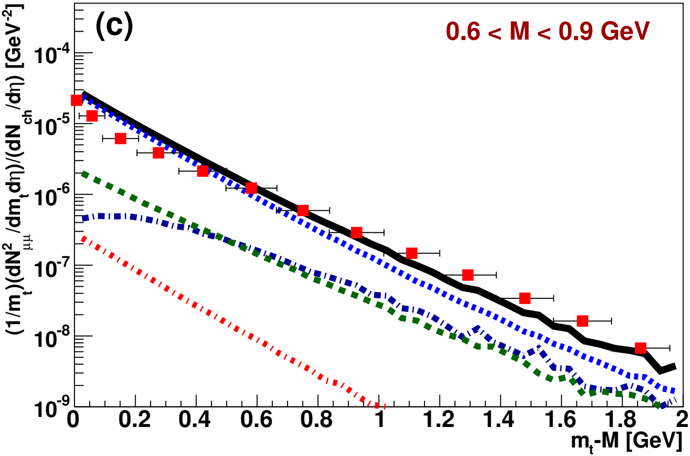
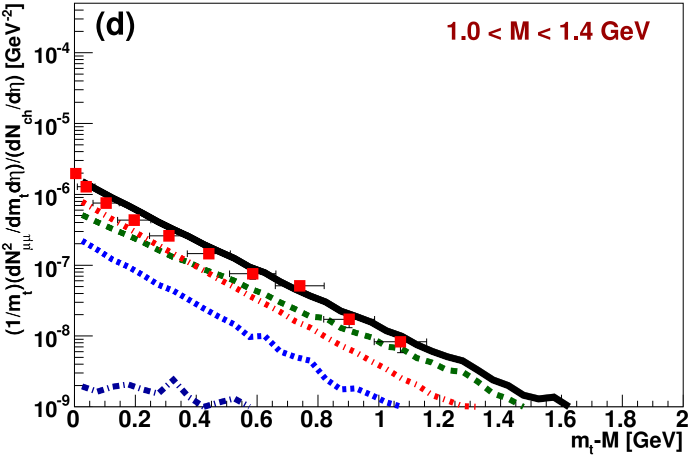
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)

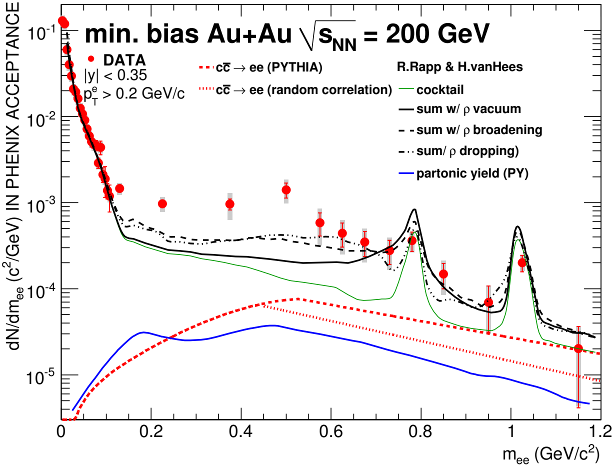


CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60) [S. Endres, HvH, J. Weil, M. Bleicher, PRC **91**, 054911 (2015)]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)

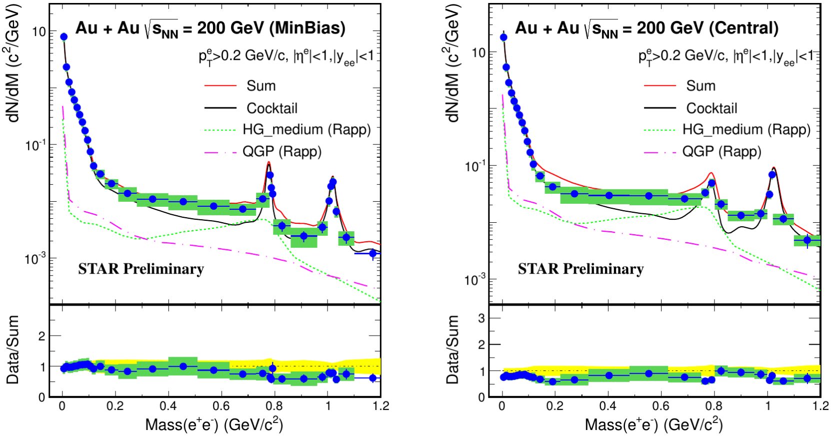


Dileptons@RHIC: PHENIX (2007)



model: Rapp, HvH, data [A. Adare et al, PRC **81**, 034911 (2010)]

- here: thermal-fireball evolution instead of CGUrQMD (work in progress)
- huge enhancement in the LMR unexplained yet!



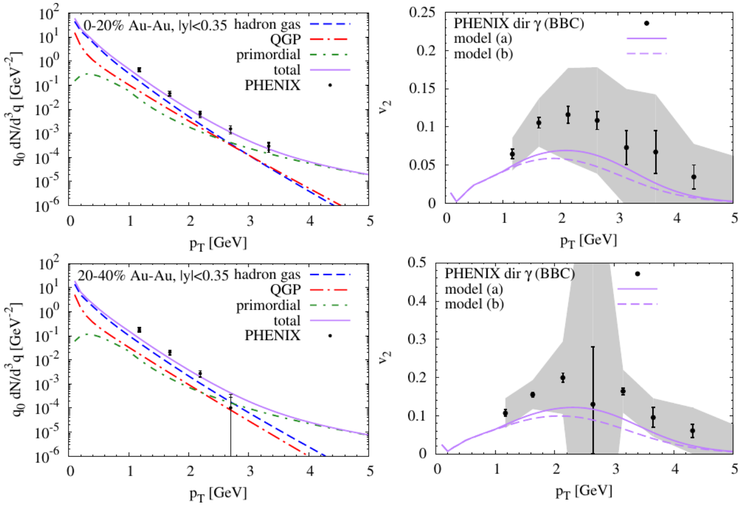
[R. Rapp, Adv. HEP **2013**, 148253 (2013)], data from [J. P. Zhao, JPG **38**, 124134 (2011)]

- compatible with medium modifications in model calculation

Direct photons (RHIC/LHC)

Direct Photons at RHIC

- same model [S. Turbide, R. Rapp, C. Gale, PRC **69**, 014903 (2004)] for rates as for dileptons
- photons inherit v_2 from hadronic sources

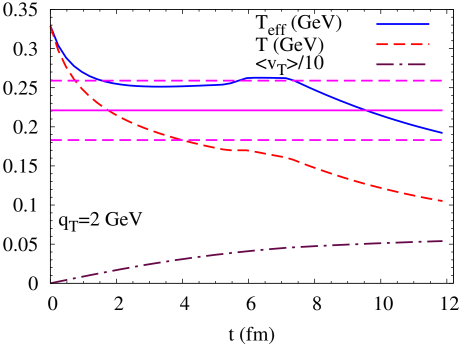


[HvH, C. Gale, R. Rapp, PRC **84**, 054906 (2011); HvH, M. He, R. Rapp, NPA **933**, 256 (2015)]

Effective slopes vs. temperatures

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

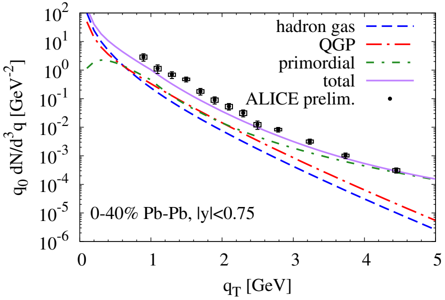
$$T_{\text{eff}} \simeq \sqrt{\frac{1+\langle v_T \rangle}{1-\langle v_T \rangle}}\, T$$

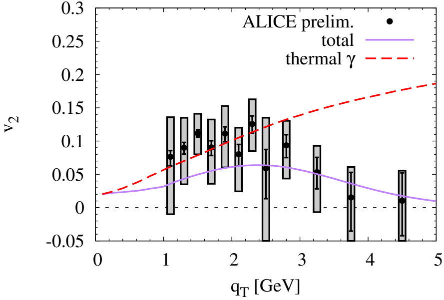


[R. Rapp, HvH, NPA **931**, 696 (2014)]

Direct Photons at the LHC

same model, fireball adapted to hadron data from ALICE [HvH, M. He, R. Rapp, PRC **84**, 054906 (2015)]





- 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?!?

Summary

- em. probes, $\ell^+\ell^-$ and γ: neglible final-state interactions
- probe in-medium electromagnetic current-current correlator over entire history of fireball evolution
- provide insight into fundamental properties of QCD matter
- needs models for electromagnetic radiation from QGP and hadron gas
- medium effects on vector mesons in hot and dense matter
- hint at chiral-symmetry restoration
  $\Rightarrow$ melting resonances rather than dropping mass
- for more details, see website of the HQM Lecture Week spring 2014
  http://fias.uni-frankfurt.de/~hees/hqm-lectweek14/index.html