Dileptons in Heavy Ion Collisions
A coarse-grained Transport Approach

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GOETHE UNIVERSITÄT FRANKFURT AM MAIN

FIAS Frankfurt Institute for Advanced Studies

DFG

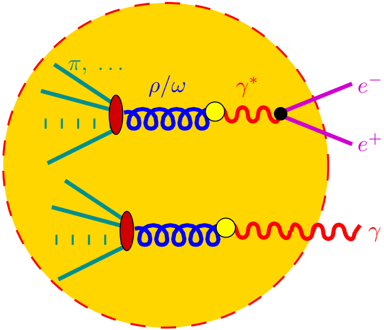
Outline

1. Electromagnetic probes
2. Coarse-grained transport approach (UrQMD with Stephan Endres)
3. Dielectrons at SIS energies (HADES)
4. Dimuons at SPS (NA60)
5. Conclusions

Electromagnetic probes
motivation and general framework

Electromagnetic probes in heavy-ion collisions

- $\gamma, \ell^{\pm}$: no strong interactions
- $\Rightarrow$ fireball transparent medium
- reflect whole "history" of collision:
    - from pre-equilibrium phase
    - from thermalized medium QGP and hot hadron gas
    - from VM decays after thermal freezeout



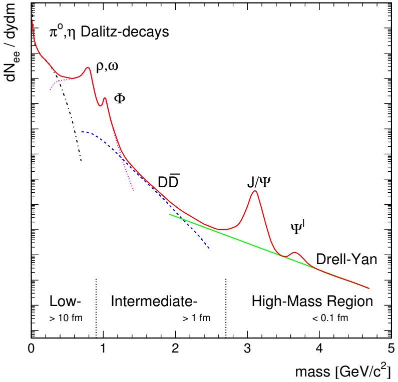


Fig. by A. Drees

Electromagnetic probes from a thermal source

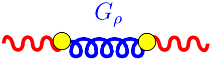
- dilepton thermal emission rates given by electromagnetic-current-correlation function $(J_\mu = \sum_f Q_f \bar{\psi}_f \gamma_\mu \psi_f)$

[McLerran+Toimela (1985), Weldon (1990), Gale+Kapusta (1991),...]

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

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

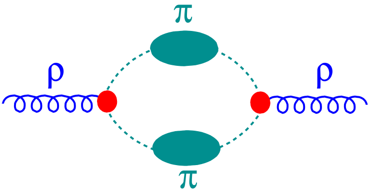
- u: four-velocity of the fluid cell; $p \cdot u = p_0^{\mathrm{hb}}$ energy in “heat-bath frame”
- to lowest order in α: $e^2 \Pi_{\mu\nu} \simeq \Sigma^{(\gamma)}_{\mu\nu}$
- vector-meson dominance model:

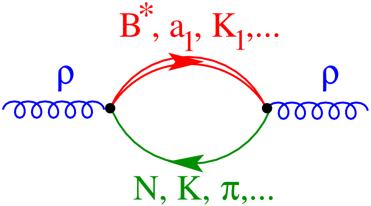
$\Sigma^{\gamma}_{\mu\nu} =$ 

- need in-medium spectral functions of vector bosons
- additional sources: QGP, “multi-pion” processes

Hadronic many-body theory

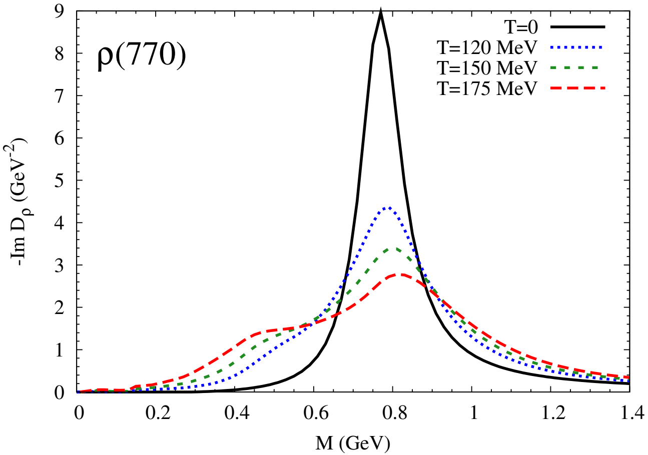
- HMBT for vector mesons [Ko et al, Chanfray et al, Herrmann et al, Rapp et al, ...]
- $\pi\pi$ interactions and baryonic excitations





- +corresponding vertex corrections ⇔ gauge invariance
- 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)

In-medium spectral functions and baryon effects



[R. Rapp, J. Wambach Adv. Nucl. Phys **25**, 1 (2000), R. Rapp, J. Wambach, HvH ,Landolt-Börnstein I/23, 4-1 (2009), arXiv: 0901.3289 [hep-ph]]

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

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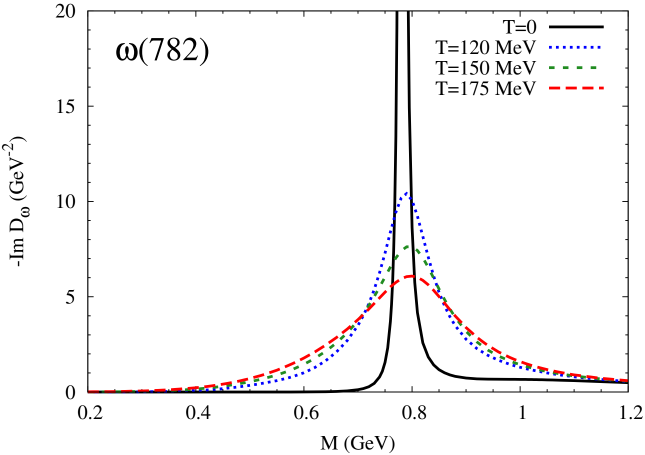

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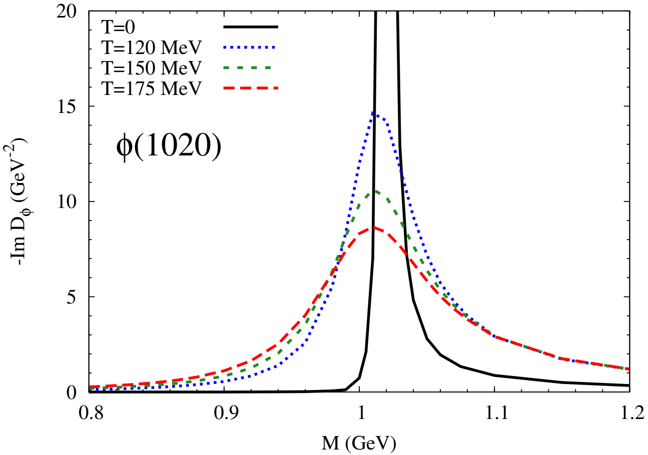

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Coarse-grained UrQMD

(with S. Endres, J. Weil, M. Bleicher)

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)]

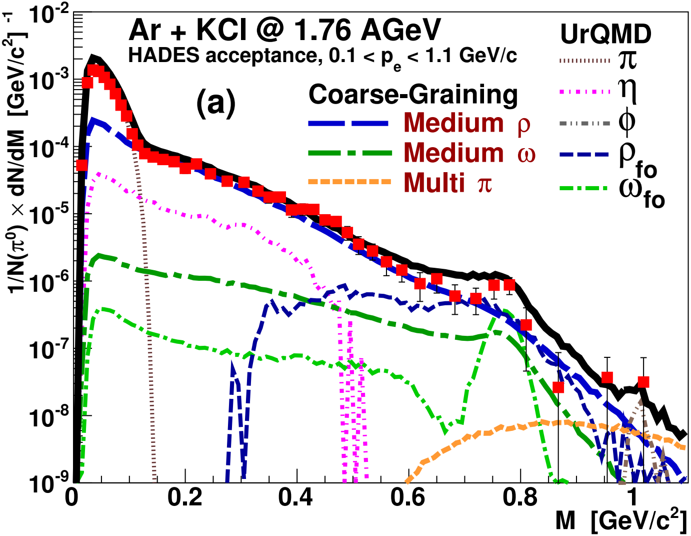
$$T^{\mu\nu} = (\epsilon + P_\perp) u^\mu u^\nu - P_\perp g^{\mu\nu} - (P_\parallel - P_\perp) V^\mu V^\nu$$

- thermal rates from partonic/hadronic QFT become applicable
- extrapolated lattice QGP and Rapp-Wambach hadronic many-body theory

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]]



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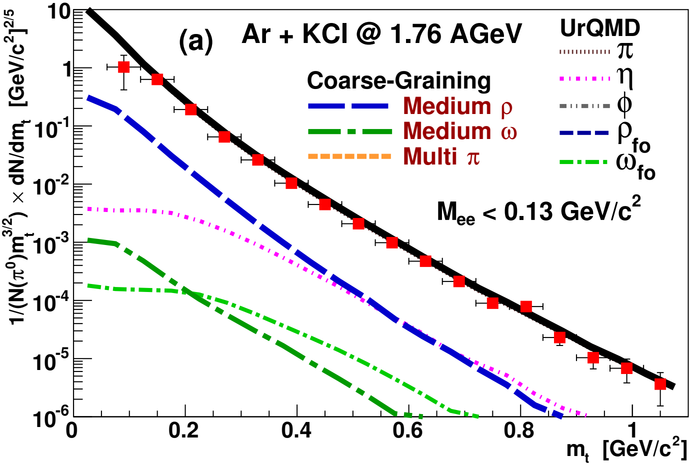
- m_t spectra [S. Endres, HvH, J. Weil, M. Bleicher, arXiv: 1505.06131 [nucl-th]]
- $M_{ee} < 0.13$ GeV



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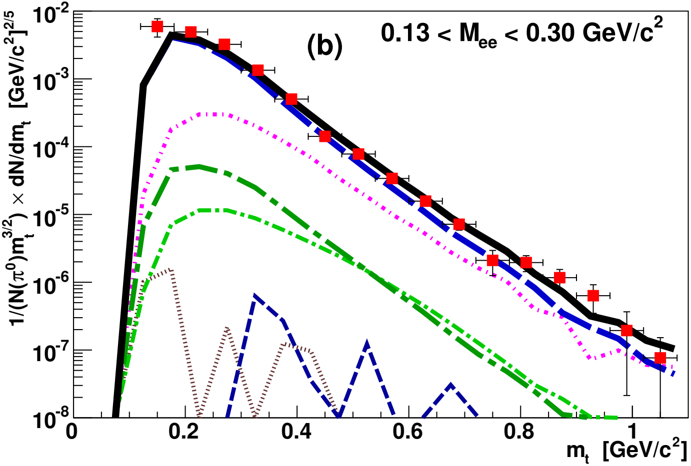
- m_t spectra [S. Endres, HvH, J. Weil, M. Bleicher, arXiv: 1505.06131 [nucl-th]]
- $0.13\,\mathrm{GeV} M_{\mathrm{ee}} < 0.3\,\mathrm{GeV}$



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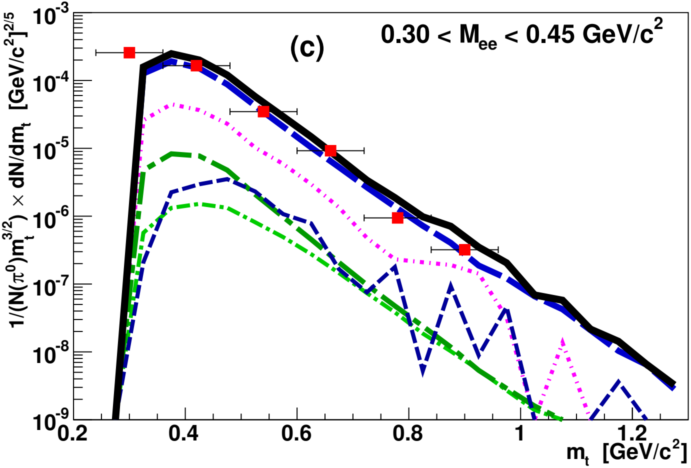
- m_t spectra [S. Endres, HvH, J. Weil, M. Bleicher, arXiv: 1505.06131 [nucl-th]]
- 0.3 GeV M_{ee} < 0.45 GeV



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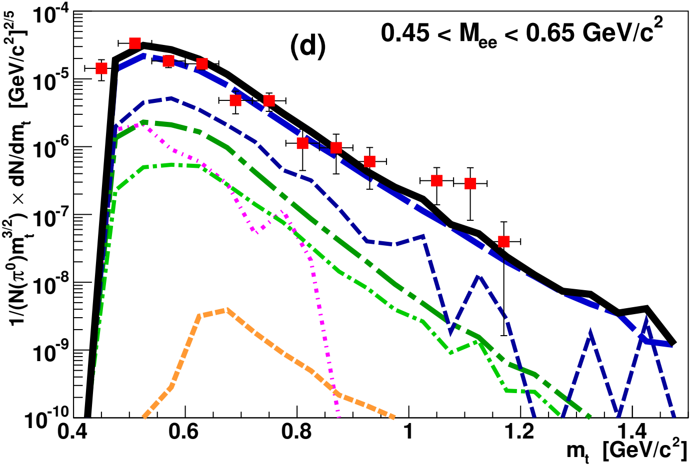
- m_t spectra [S. Endres, HvH, J. Weil, M. Bleicher, arXiv: 1505.06131 [nucl-th]]
- $0.45\,\text{GeV} M_{ee} < 0.65\,\text{GeV}$



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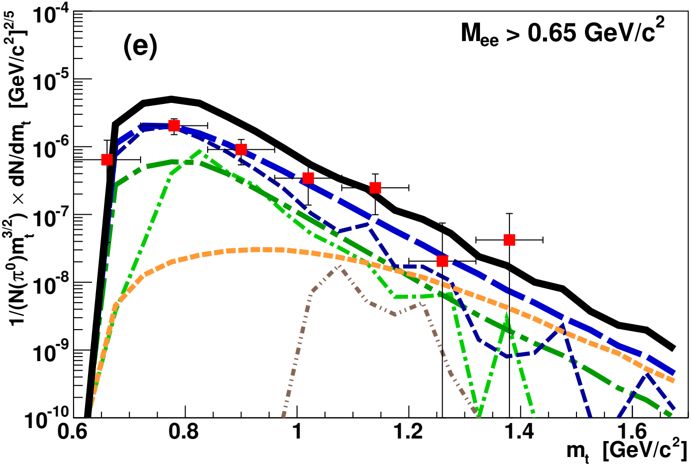
- $M_{\mathrm{ee}} > 0.65$ GeV



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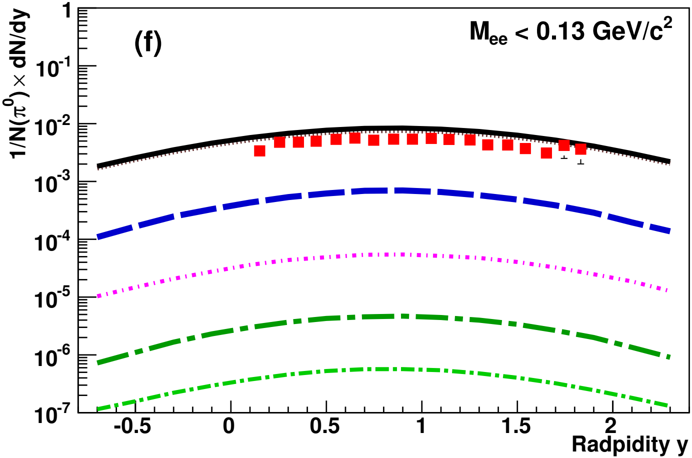
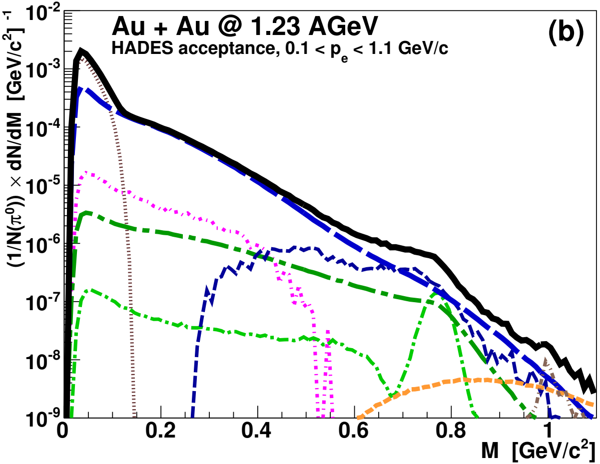
- rapidity spectrum ($M_{\mathrm{ee}} < 0.13$ GeV)



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



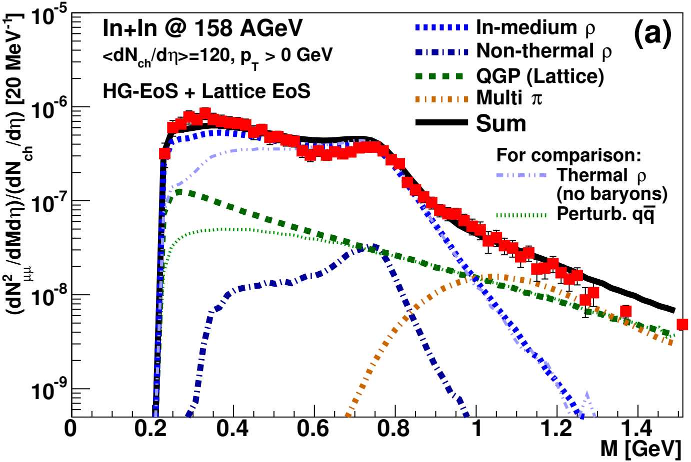
- caveat: pp/np acceptance filter with single-e cut, $p_t < 100$ MeV
- correct filter urgently needed!
- excellent agreement with preliminary HADES data
  (data points not shown here on request of the HADES collaboration)

Dimuons (SPS/NA60)

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

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

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



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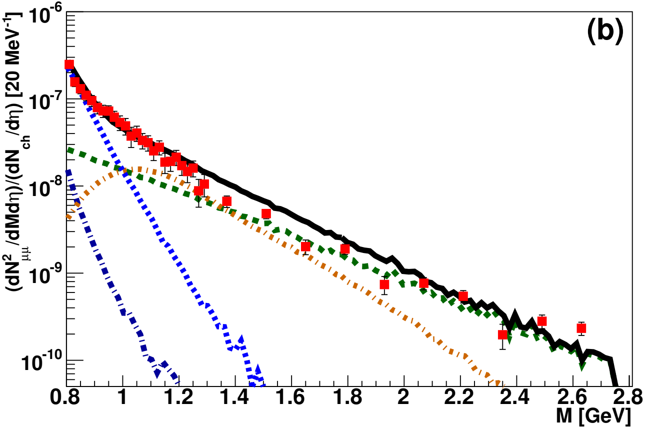
- min-bias data $(\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120)$
- higher IMR: provides averaged true temperature
  (no blueshifts in the invariant-mass spectra!)



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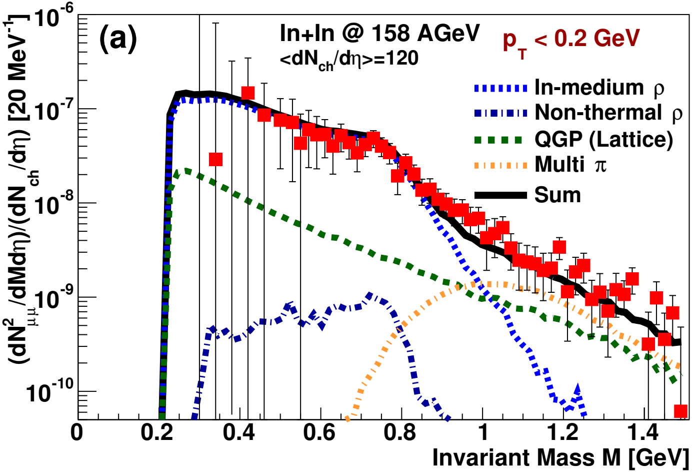
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $p_T < 0.2\,\mathrm{GeV}$



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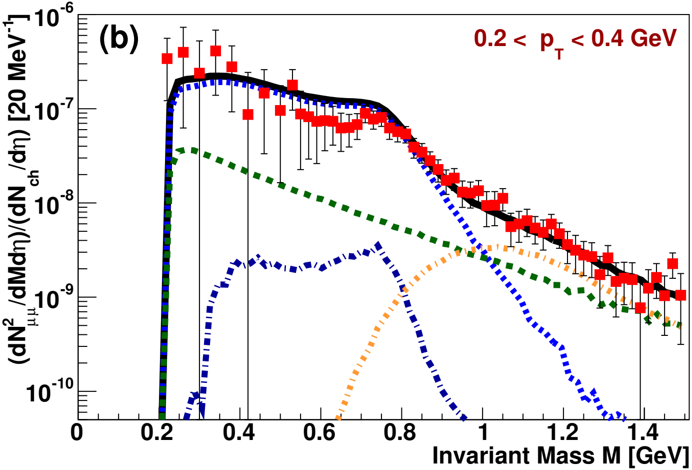
- $0.2\,\text{GeV} < p_T < 0.4\,\text{GeV}$



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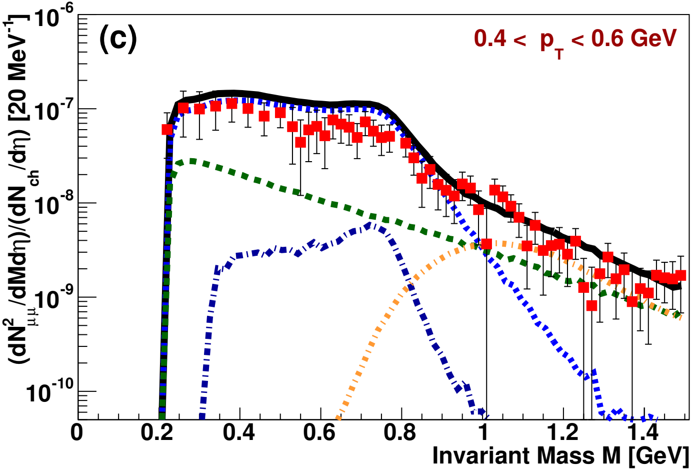
- $0.4\,\mathrm{GeV} < p_T < 0.6\,\mathrm{GeV}$



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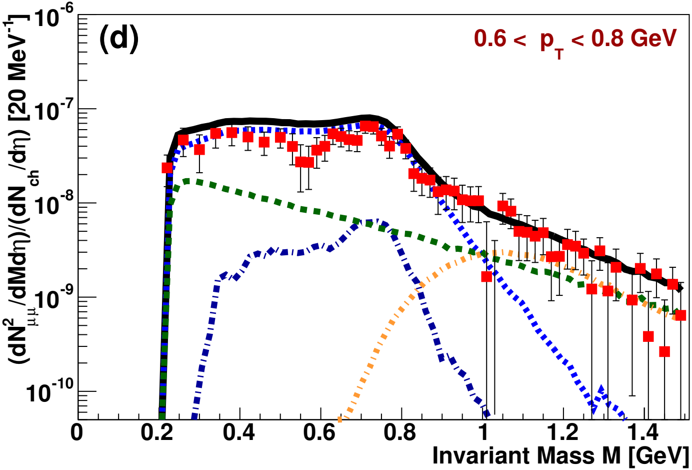
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $0.6\,\mathrm{GeV} < p_T < 0.8\,\mathrm{GeV}$



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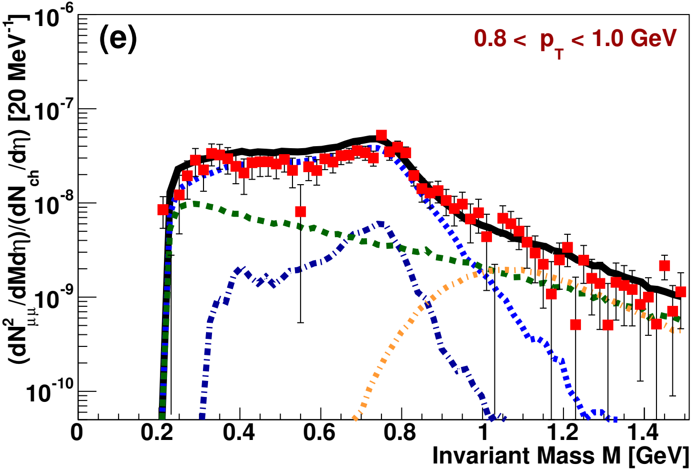
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $0.8\,\mathrm{GeV} < p_T < 1.0\,\mathrm{GeV}$



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

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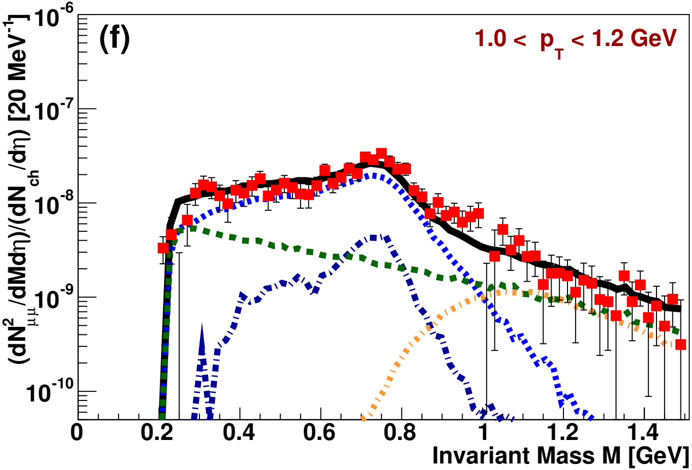
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- $1.0\,\mathrm{GeV} < p_T < 1.2\,\mathrm{GeV}$



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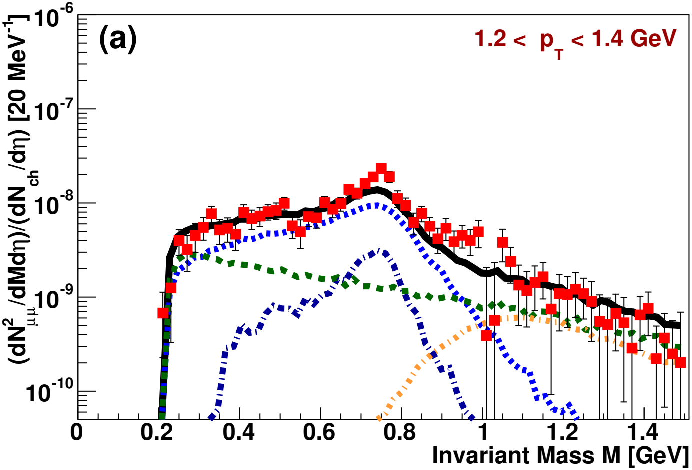

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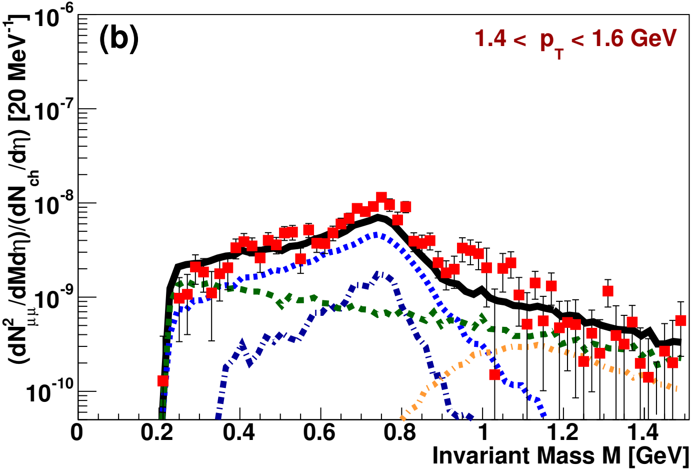

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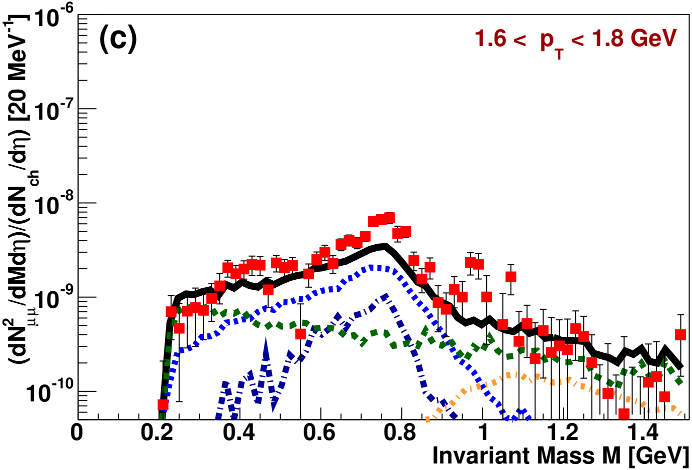

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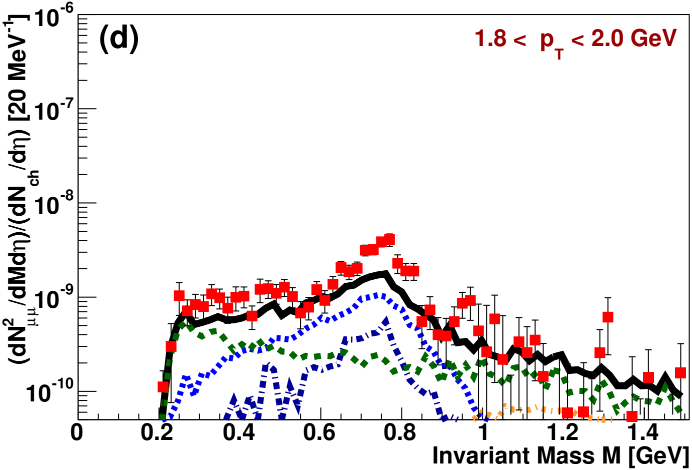
- min-bias data ($\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120$)
- $1.8\,\text{GeV} < p_T < 2.0\,\text{GeV}$



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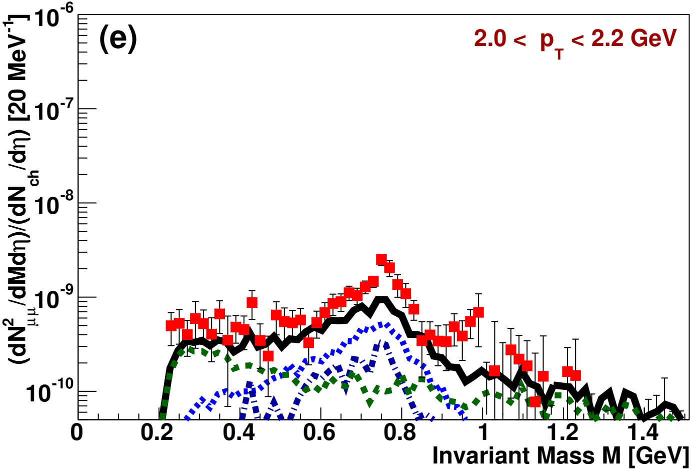
- min-bias data $(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120)$
- $2.0\,\mathrm{GeV} < p_T < 2.2\,\mathrm{GeV}$



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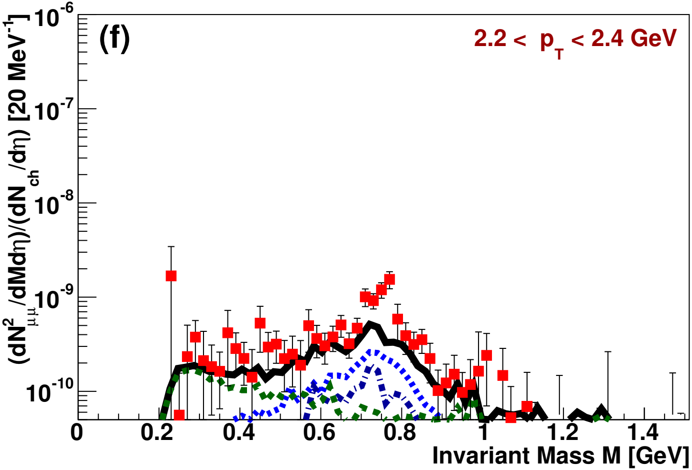

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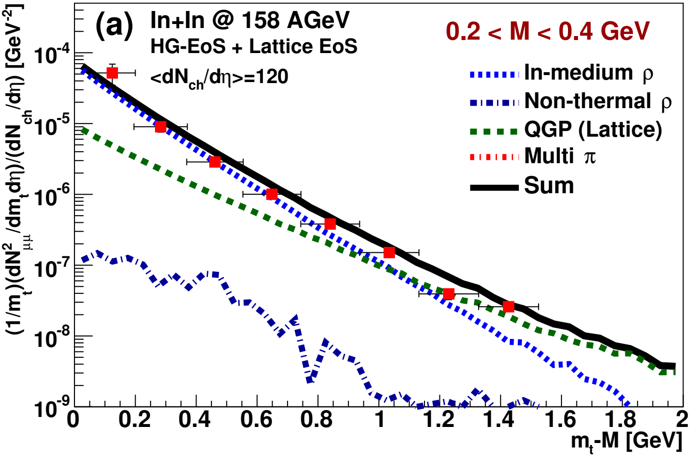

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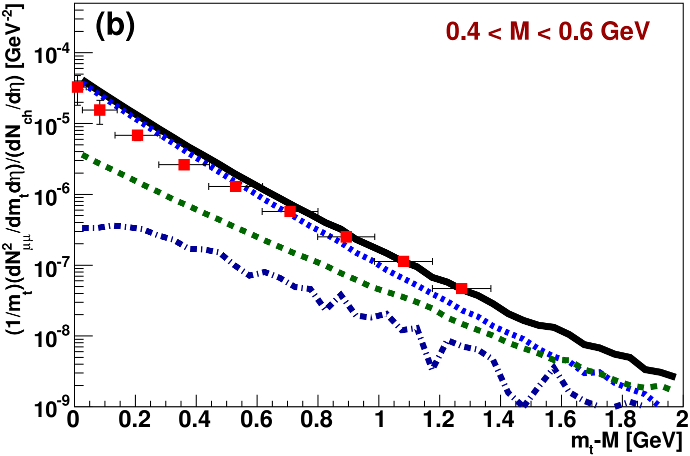

CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

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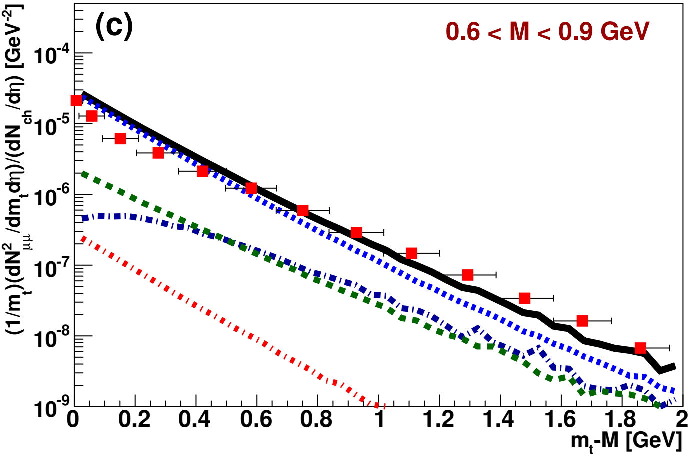

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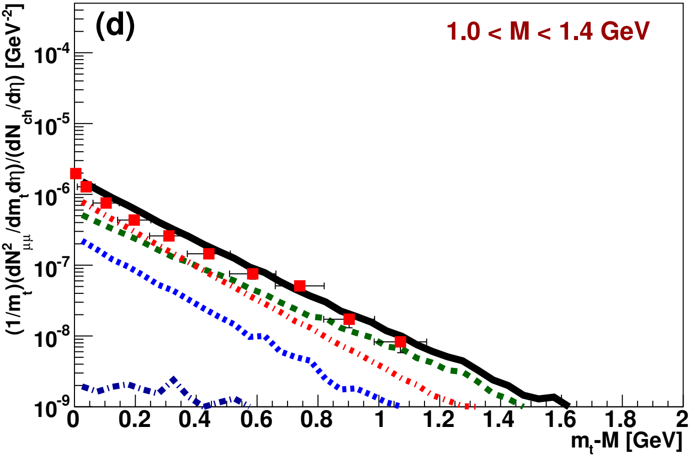
- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60)

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

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



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
- prevalence of baryon resonance interactions in vector-meson SFs at all collision energies!