

Electromagnetic Probes

Messengers from the hot and dense state

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- 2 QCD and ultra-hot and -dense matter
 - QCD and accidental symmetries
 - The QCD-phase diagram
- 3 Electromagnetic probes in heavy-ion collisions
 - motivation for electromagnetic probes
 - what do we measure? Electromagnetic radiation from hot/dense matter
 - the (essential) hadronic sources of em. probes
 - hadronic many-body theory
 - coarse-graining in UrQMD
- 4 Dileptons at SIS energies (HADES)
- 5 Dileptons at SPS and RHIC
- 6 Direct photons at RHIC and LHC: “the flow puzzle”

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 ($E_{\text{kin}} = 1.25\text{-}3.5 \text{ GeV}$)

Dielectrons from HADES

- CERN SPS: AA collisions with $E_{\text{kin}} = 158 \text{ GeV}$ per nucleon on a fixed target (center-mass energy: $\sqrt{s_{NN}} = 17.3 \text{ GeV}$)

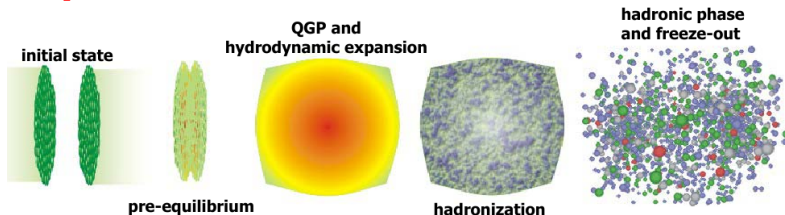
dileptons (particularly $\mu^+\mu^-$ in In-In collisions from NA60)

- BNL RHIC: Au Au collisions with center-mass energy of $\sqrt{s_{NN}} = 200 \text{ GeV}$; “beam-energy scan” $\sqrt{s_{NN}} = 7.7\text{-}39 \text{ GeV}$

dileptons from STAR and PHENIX; direct photons from PHENIX

- CERN LHC: Pb-Pb collisions at $\sqrt{s} = 2.76 \text{ TeV}$ per nucleon

direct photons from ALICE



QCD and (“accidental”) symmetries

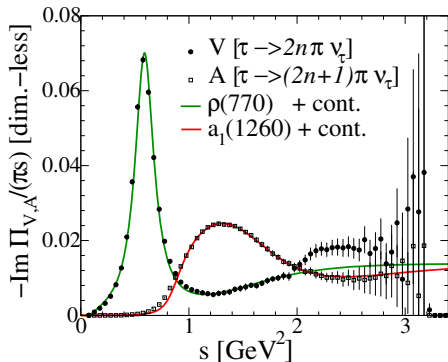
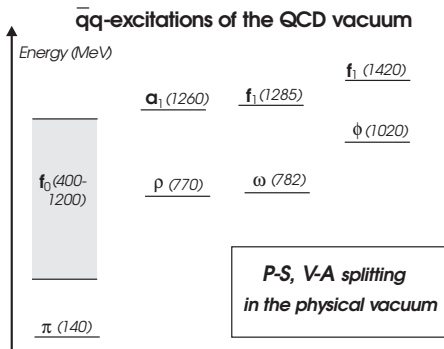
- fundamental theory of strong interactions: QCD

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

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

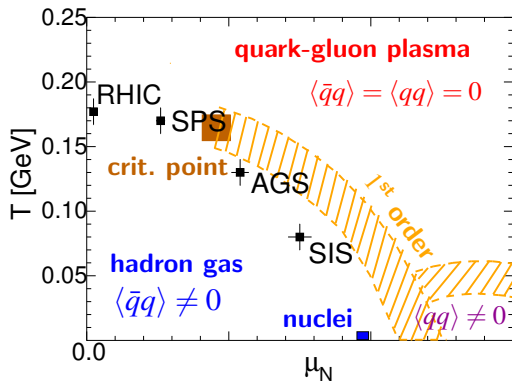
Phenomenology and Chiral symmetry

- in **vacuum**: Spontaneous breaking of **chiral symmetry**
- \Rightarrow mass splitting of chiral partners



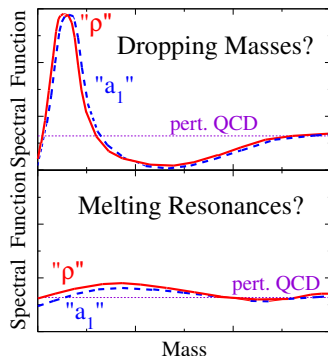
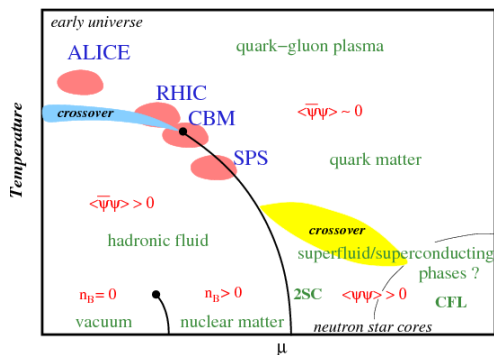
The QCD-phase diagram

- **hot and dense matter**: quarks and gluons close together
- highly energetic collisions \Rightarrow “**deconfinement**”
- quarks and gluons relevant degrees of freedom \Rightarrow **quark-gluon plasma**
- still strongly interacting \Rightarrow fast thermalization!



The QCD-phase diagram

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



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

Electromagnetic probes in heavy-ion collisions

- γ, l^\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**

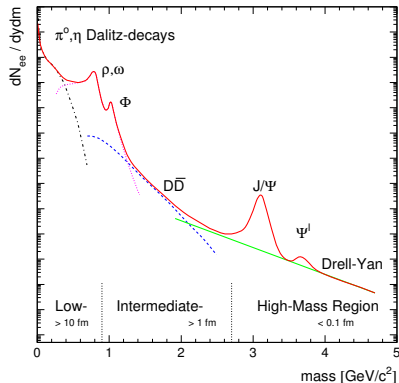
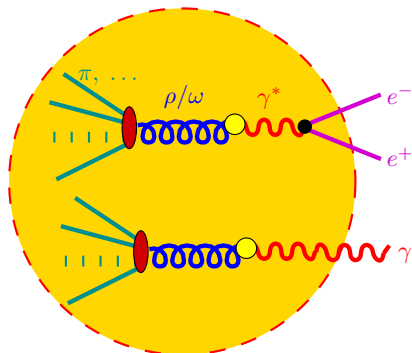


Fig. by A. Drees

Electromagnetic probes from thermal source

- **photon** and **dilepton** thermal emission rates given by **same** electromagnetic-current-correlation function ($J_\mu = \sum_f Q_f \bar{\psi}_f \gamma_\mu \psi_f$)
- **McLerran-Toimela formula** [L. D. McLerran, T. Toimela PRD 31, 545 (1985); C. Gale, J. I. Kapusta, NPB 357, 65 (1991)]

$$\Pi_{\mu\nu}^<(q) = \int d^4x \exp(iq \cdot x) \langle J_\mu(0) J_\nu(x) \rangle_T = -2 f_B(q \cdot u) \text{Im} \Pi_{\mu\nu}^{(\text{ret})}(q)$$

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

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

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

$$\Sigma_{\mu\nu}^\gamma = \text{---} \overset{G_\rho}{\text{---}} \text{---}$$

- l^+l^-M spectra \Rightarrow **in-med. spectral functions of vector mesons (ρ, ω, ϕ)!**

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

- General: **McLerran-Toimela formula**

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

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


$$\Pi_{\text{em},i}^{\mu\nu} = i \int d^4x \exp(iq \cdot x) \Theta(x^0) \langle [j_{\text{em},i}^{\mu}(x), j_{\text{em},i}^{\nu}(0)] \rangle$$

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

$$-i\Pi_{\text{em},\text{QGP}} = \text{diagram}$$

Radiation from thermal sources: ρ decays

- model assumption: **vector-meson dominance**



$$\Sigma_{\mu\nu}^{\gamma} = \text{diagram showing } \rho \text{ meson decaying into two photons}$$

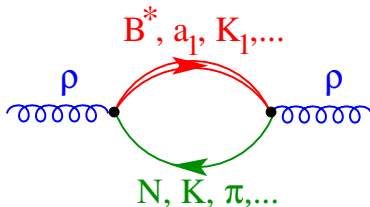
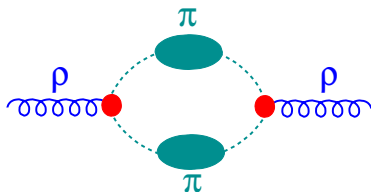
$$\frac{dN_{\rho \rightarrow l+l-}^{(\text{MT})}}{d^4x d^4q} = \frac{M}{q^0} \Gamma_{\rho \rightarrow l+l-}(M) \frac{dN_{\rho}}{d^3\vec{x} d^4q}$$

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

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

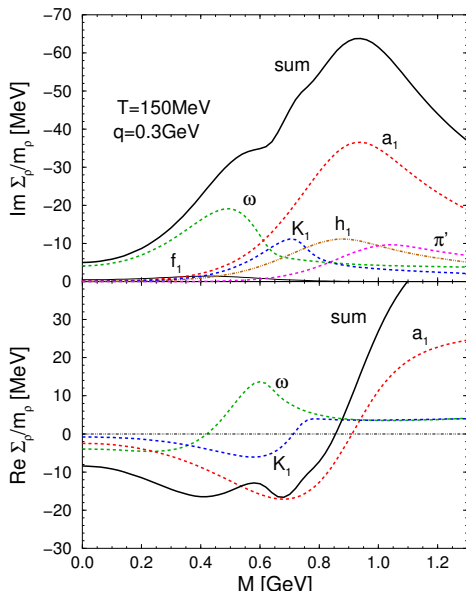
Hadronic many-body theory

- 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 \Rightarrow **mass shift and broadening** of particle in the medium

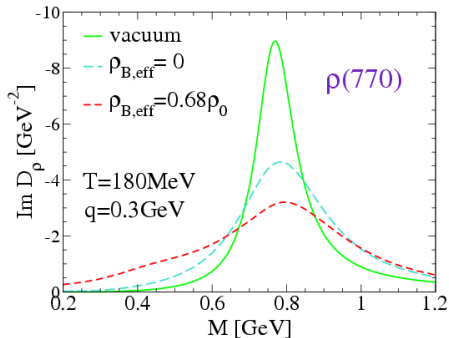


- **Baryon (resonances)** important, even at low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

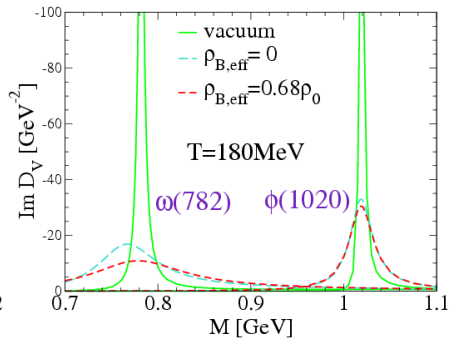
Meson contributions



In-medium spectral functions and baryon effects



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



- **baryon effects** important

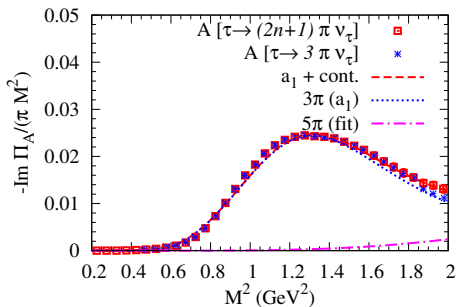
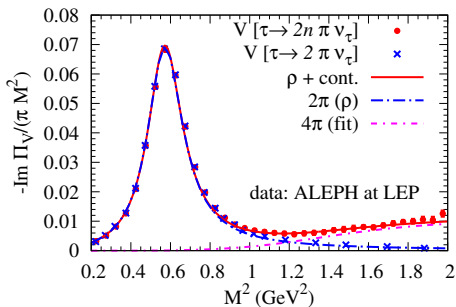
- large contribution to broadening of the peak
- responsible for most of the strength at small M

Radiation from thermal sources: multi- π processes

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

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

- avoid double counting: leave out two-pion piece and $a_1 \rightarrow \rho + \pi$ (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** \Rightarrow local thermal equilibrium
 \Rightarrow use equilibrium rates
 - use transport-hydro hybrid model: treat early stage with transport, then **coarse grain** \Rightarrow switch to hydro
 \Rightarrow switch back to transport (**Cooper-Frye “particlization”**)
- here: **UrQMD transport** for entire bulk evolution
 - \Rightarrow use **coarse graining** in space-time cells \Rightarrow extract T, μ_B, μ_π, \dots
 - \Rightarrow 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)]

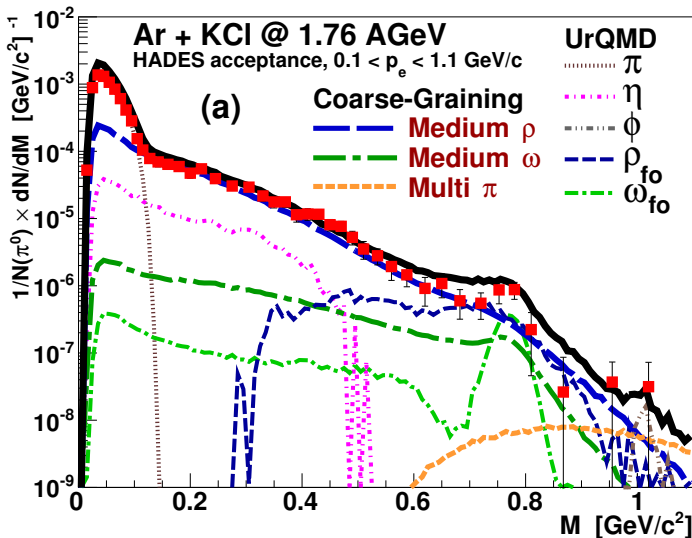
$$T^{\mu\nu} = (\epsilon + P_{\perp})u^{\mu}u^{\nu} - P_{\perp}g^{\mu\nu} - (P_{\parallel} - P_{\perp})V^{\mu}V^{\nu}$$

- 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)

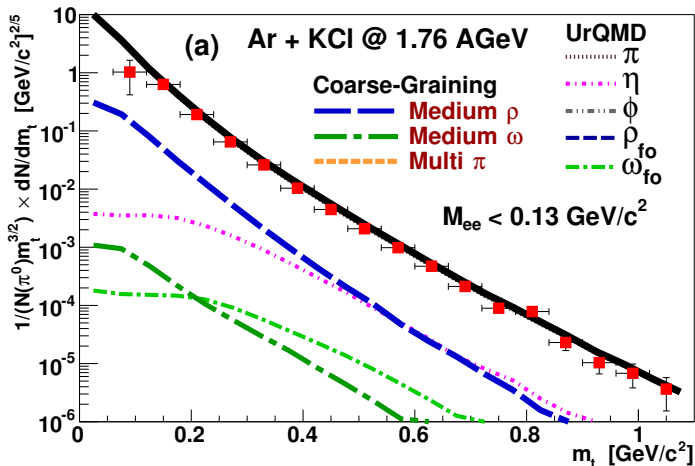
CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

- 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]]



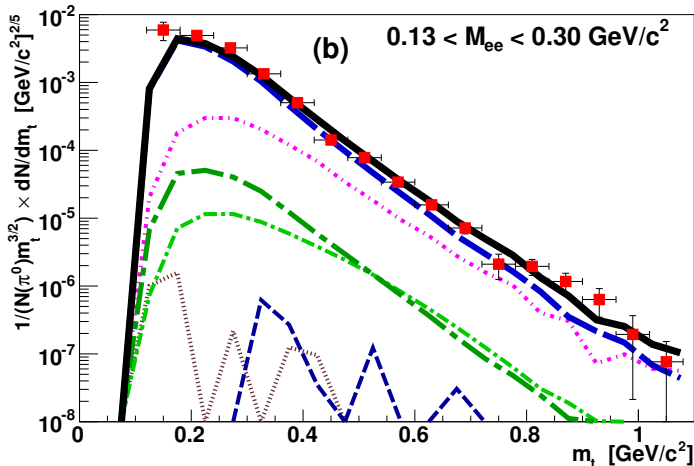
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- m_t spectra [S. Endres, HvH, J. Weil, M. Bleicher, arXiv: 1505.06131 [nucl-th]]
- $M_{ee} < 0.13$ GeV



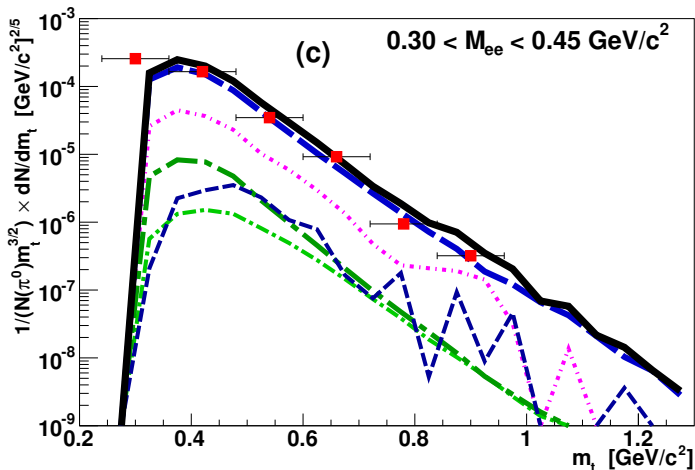
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- m_t spectra [S. Endres, HvH, J. Weil, M. Bleicher, arXiv: 1505.06131 [nucl-th]]
- $0.13 \text{ GeV} < M_{ee} < 0.3 \text{ GeV}$



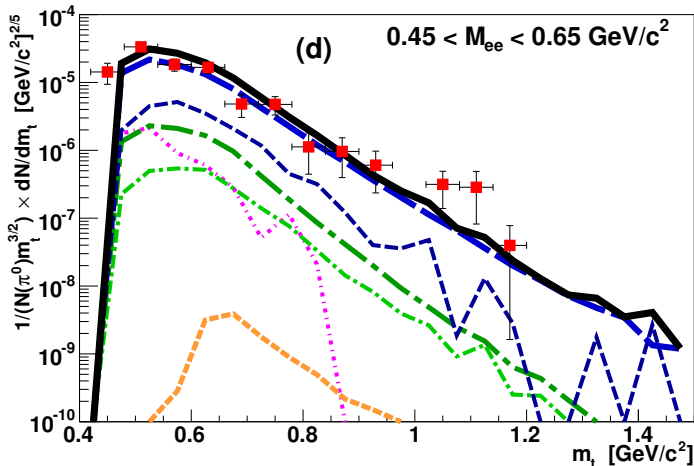
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- m_t spectra [S. Endres, HvH, J. Weil, M. Bleicher, arXiv: 1505.06131 [nucl-th]]
- $0.3 \text{ GeV} < M_{ee} < 0.45 \text{ GeV}$



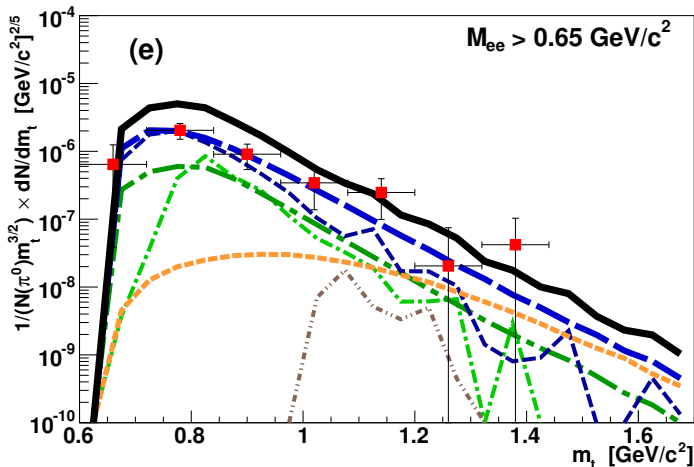
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- m_t spectra [S. Endres, HvH, J. Weil, M. Bleicher, arXiv: 1505.06131 [nucl-th]]
- $0.45 \text{ GeV} M_{ee} < 0.65 \text{ GeV}$



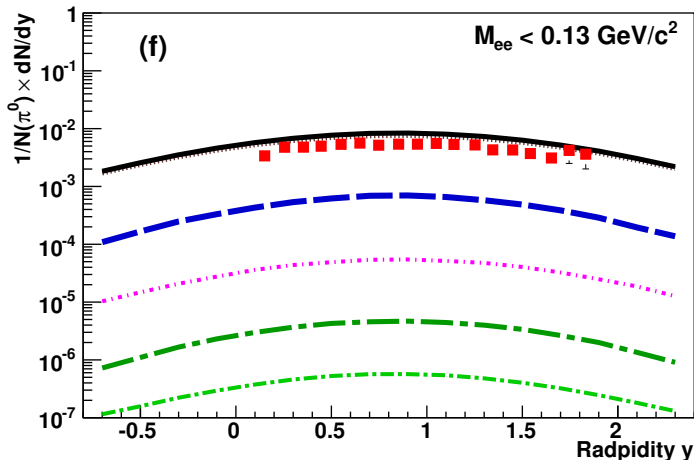
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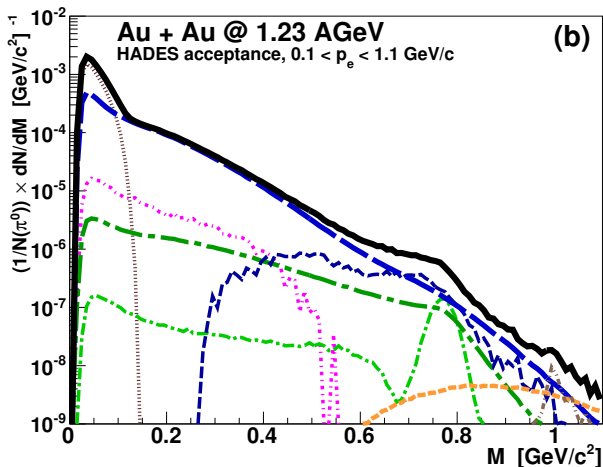
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- m_t spectra [S. Endres, HvH, J. Weil, M. Bleicher, arXiv: 1505.06131 [nucl-th]]
- $M_{ee} > 0.65$ GeV



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





- 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)

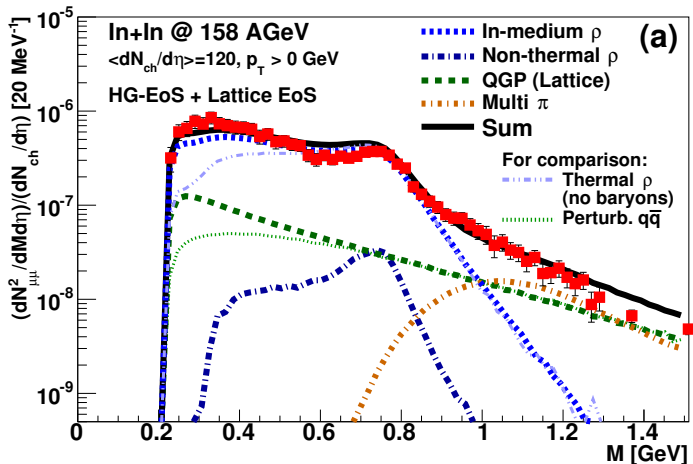
Dimuons (SPS/NA60)

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

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+\mu^-$ (NA60)

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

- min-bias data ($dN_{\text{ch}}/dy = 120$)
- note the importance of **baryon effects!**

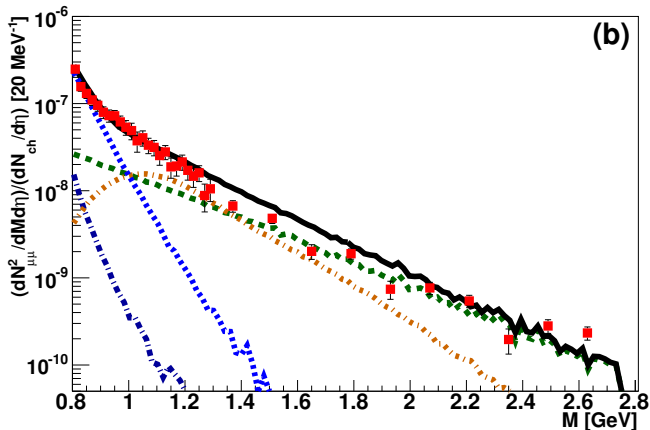


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- min-bias data ($dN_{\text{ch}}/dy = 120$)
- higher IMR: provides **averaged true temperature**
(no blueshifts in the **invariant-mass spectra!**)

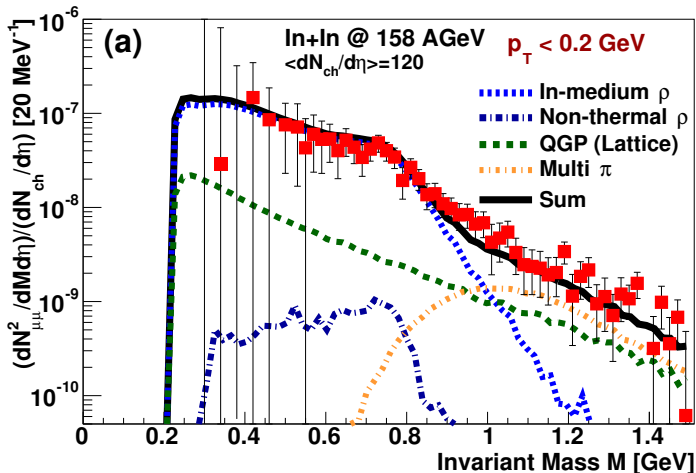


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- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $p_T < 0.2$ GeV

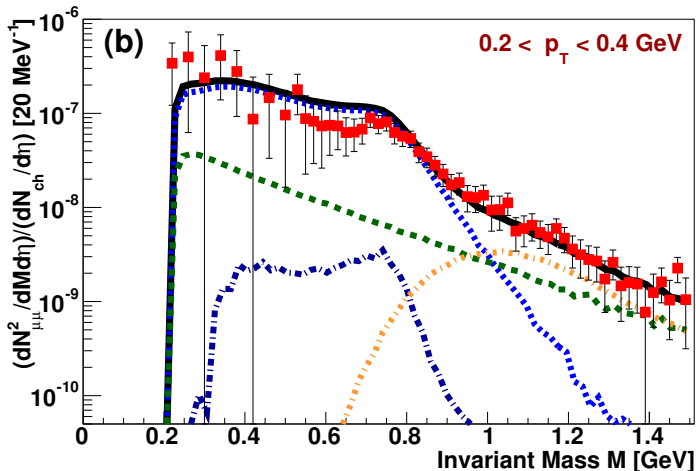


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- $0.2 \text{ GeV} < p_T < 0.4 \text{ GeV}$

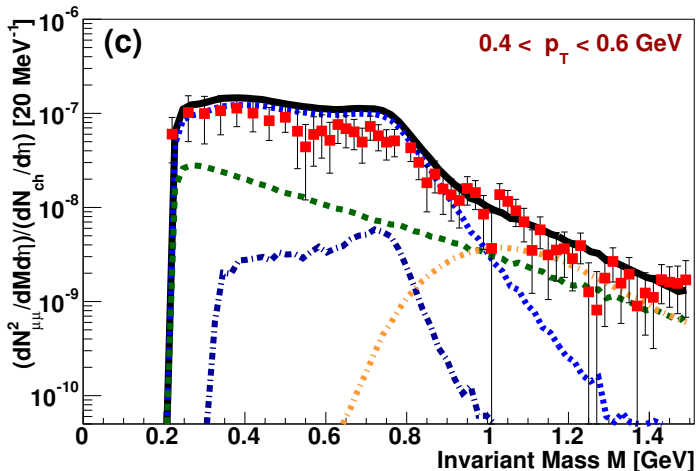


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- $0.4 \text{ GeV} < p_T < 0.6 \text{ GeV}$

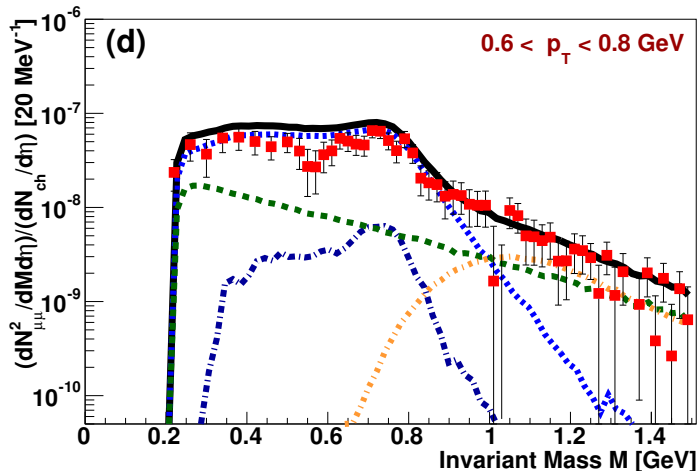


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- $0.6 \text{ GeV} < p_T < 0.8 \text{ GeV}$

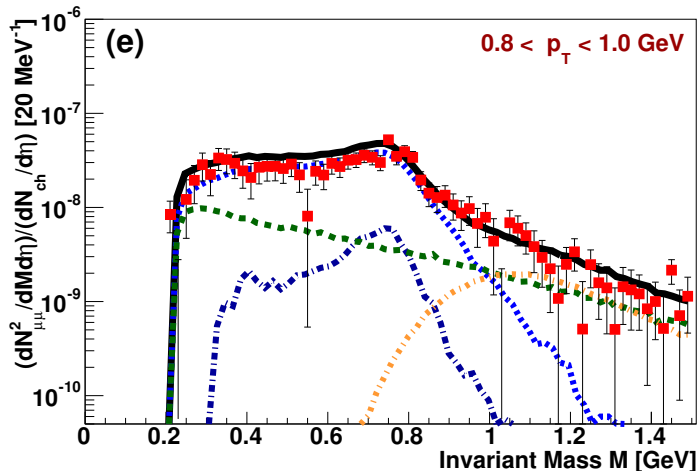


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- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $0.8 \text{ GeV} < p_T < 1.0 \text{ GeV}$

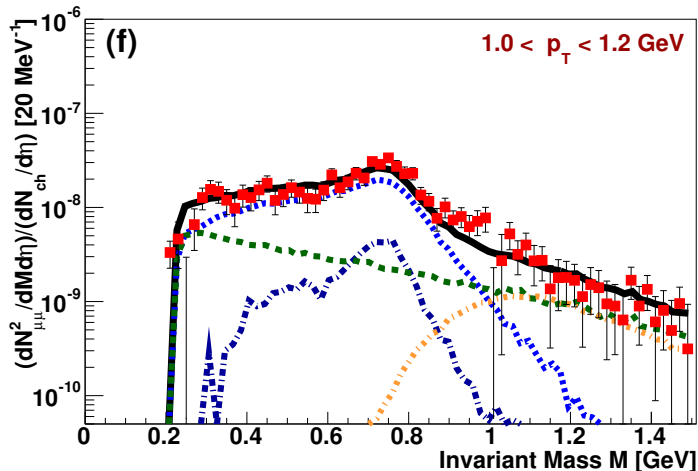


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- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $1.0 \text{ GeV} < p_T < 1.2 \text{ GeV}$

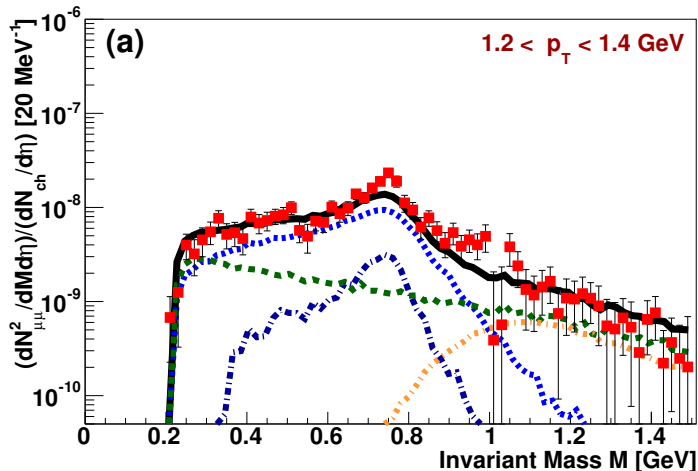


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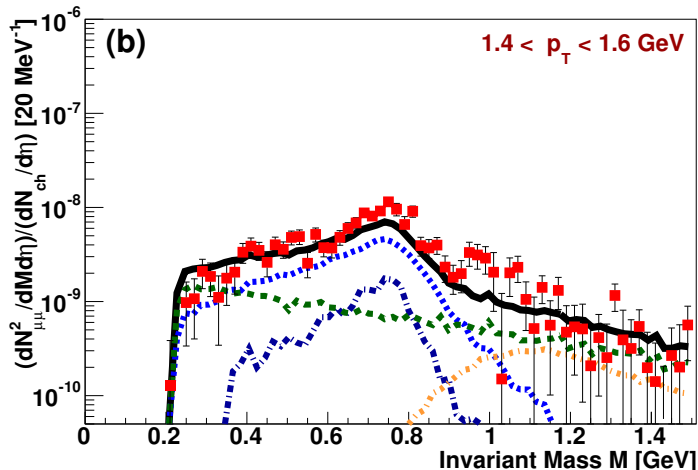


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- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $1.4 \text{ GeV} < p_T < 1.6 \text{ GeV}$

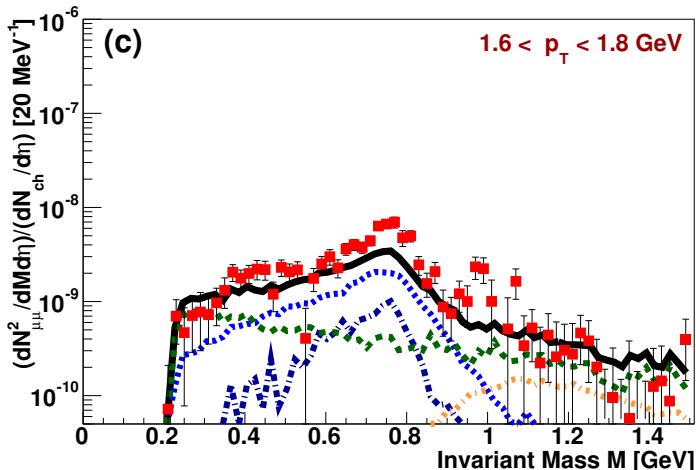


CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+\mu^-$ (NA60)

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

- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $1.6 \text{ GeV} < p_T < 1.8 \text{ GeV}$

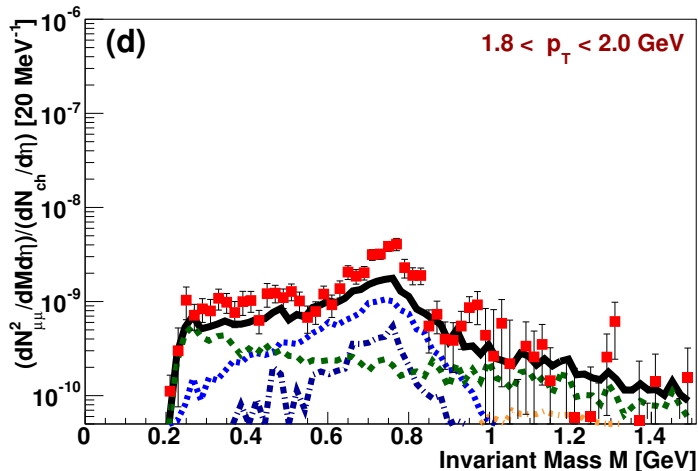


CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+\mu^-$ (NA60)

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

- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $1.8 \text{ GeV} < p_T < 2.0 \text{ GeV}$

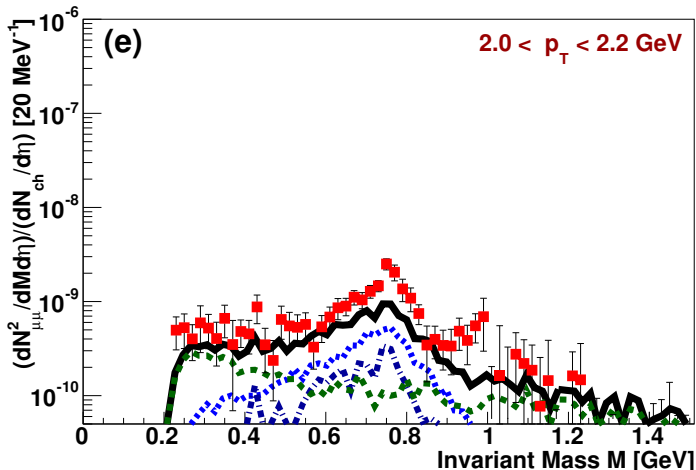


CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+\mu^-$ (NA60)

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

- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $2.0 \text{ GeV} < p_T < 2.2 \text{ GeV}$

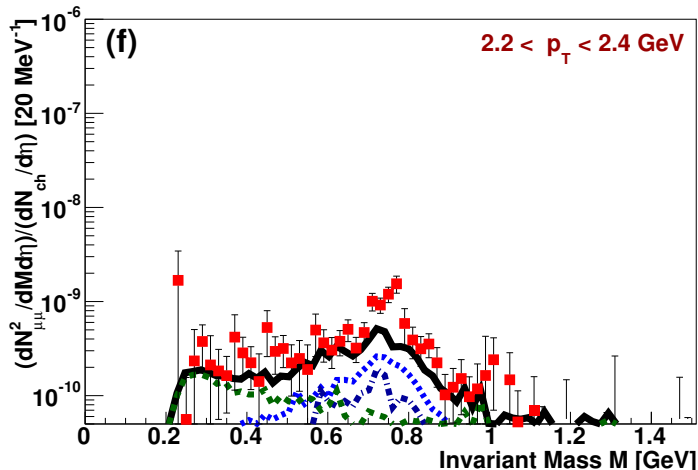


CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+\mu^-$ (NA60)

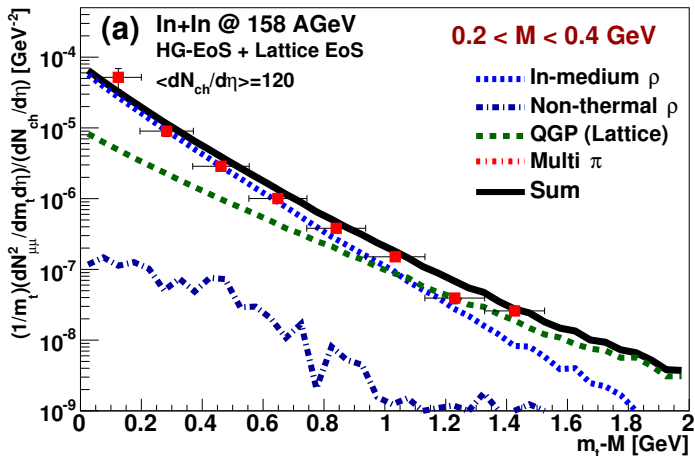
[S. Endres, HvH, J. Weil, M. Bleicher, PRC **91**, 054911 (2015)]

- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $2.2 \text{ GeV} < p_T < 2.4 \text{ GeV}$

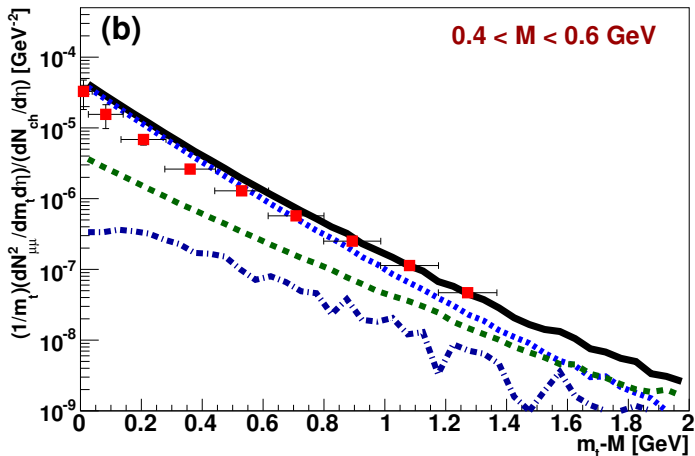


CGUrQMD: In+In (158 AGeV) (SPS/NA60)

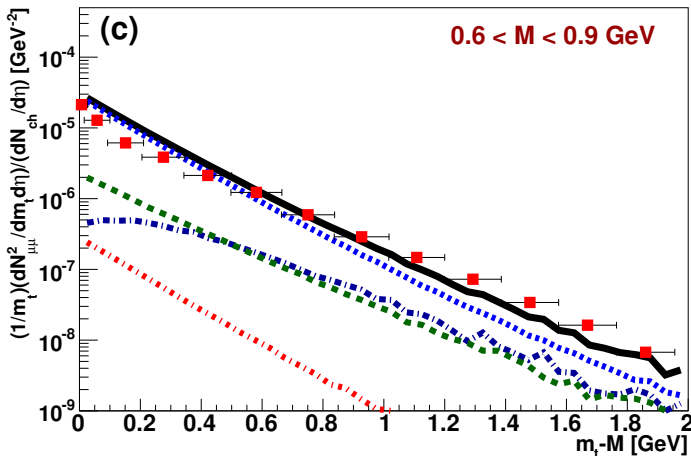
- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [S. Endres, HvH, J. Weil, M. Bleicher, PRC **91**, 054911 (2015)]
- min-bias data ($dN_{\text{ch}}/dy = 120$)



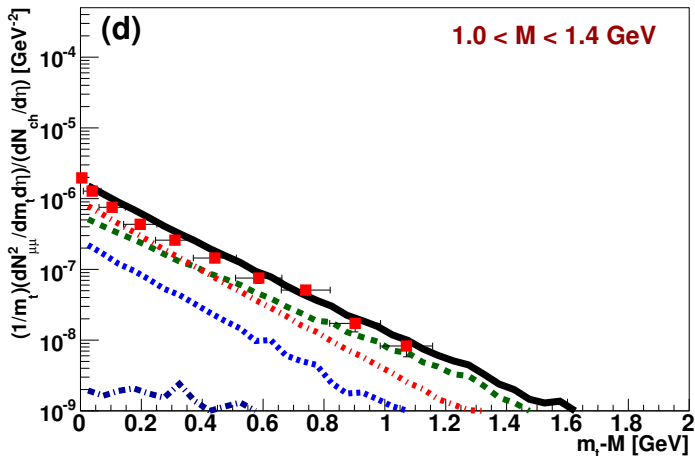
- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [S. Endres, Hvh, J. Weil, M. Bleicher, PRC **91**, 054911 (2015)]
- min-bias data ($dN_{\text{ch}}/dy = 120$)

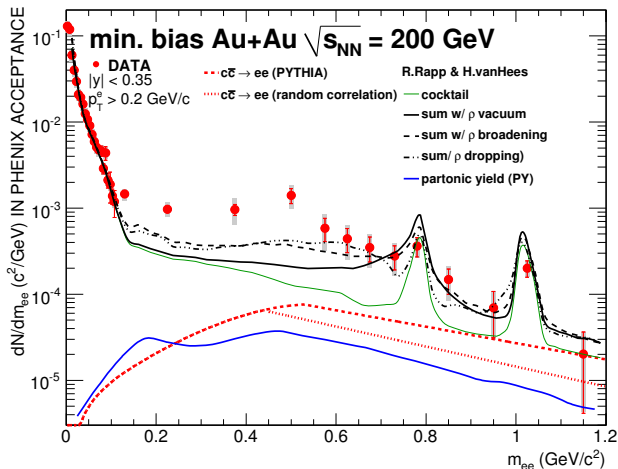


- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [S. Endres, HvH, J. Weil, M. Bleicher, PRC **91**, 054911 (2015)]
- min-bias data ($dN_{\text{ch}}/dy = 120$)



- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60) [S. Endres, Hvh, J. Weil, M. Bleicher, PRC **91**, 054911 (2015)]
- min-bias data ($dN_{\text{ch}}/dy = 120$)

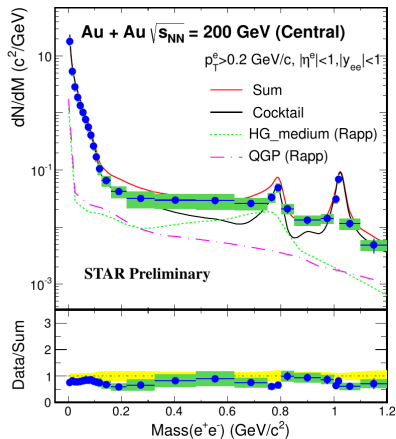
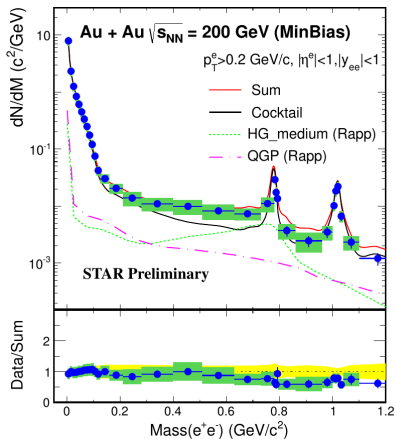




model: Rapp, HvH, data [A. Adare et al, PRC **81**, 034911 (2010)]

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

Dileptons@RHIC: STAR (QM 2012)



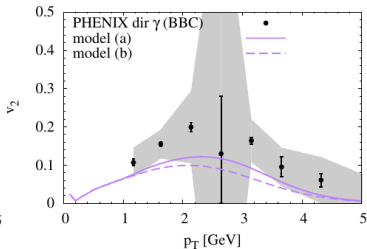
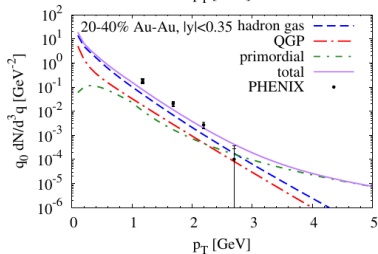
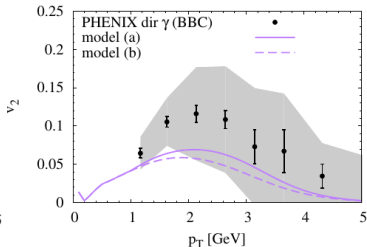
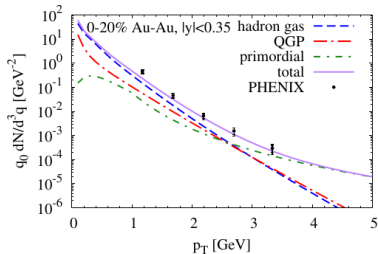
[R. Rapp, Adv. HEP **2013**, 148253 (2013)], data from [J. P. Zhao, JPG **38**, 124134 (2011)]

- 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

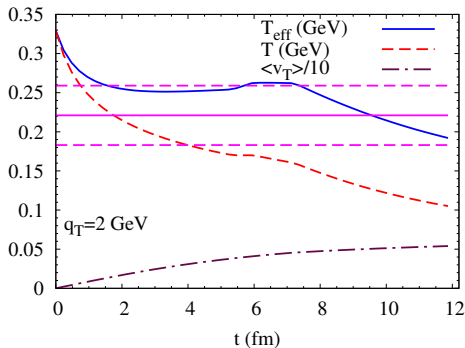


[HvH, C. Gale, R. Rapp, PRC **84**, 054906 (2011); HvH, M. He, R. Rapp, NPA **933**, 256 (2015)]

Effective slopes vs. temperatures

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

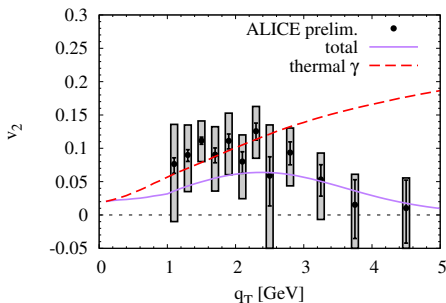
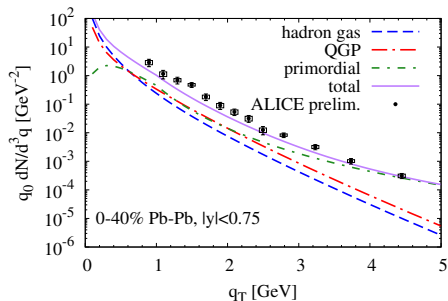
$$T_{\text{eff}} \simeq \sqrt{\frac{1 + \langle v_T \rangle}{1 - \langle v_T \rangle}} T$$



[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!) \Rightarrow
- \Rightarrow source has already developed radial flow and v_2
- large effective slopes **include blueshift from radial flow!**
- still additional (hadronic?) sources (bremsstrahlung?) missing!?

- em. probes, $\ell^+\ell^-$ and γ : **negligible 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**
⇒ 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>