Thermal photons and dileptons
Theory

Hendrik van Hees

Goethe University Frankfurt

August 20, 2014

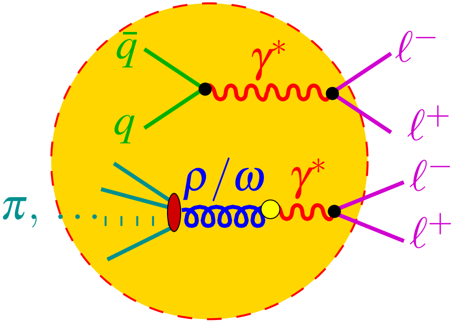
Outline

1. Electromagnetic probes in heavy-ion collisions
   - Em. current correlation function and electromagnetic probes
   - Sources of dilepton emission in heavy-ion collisions
   - Sources of thermal photons in heavy-ion collisions
2. Application to heavy-ion collisions
   - Models for bulk-medium evolution
   - Dielectrons (SIS/HADES) with S. Endres, M. Bleicher, R. Rapp
   - Dimuons (SPS/NA60) with S. Endres, M. Bleicher, R. Rapp
   - Direct Photons at RHIC and LHC with M. He, R. Rapp
3. Conclusions and Outlook

Em. current correlator
$\ell^+\ell^-$ and γ rates

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



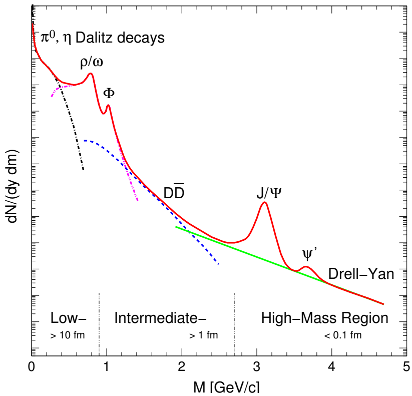


Fig. by A. Drees

Em. current correlation function and electromagnetic Probes

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

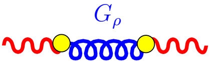
  [L. McLerran, T. Toimela 85, H. A. Weldon 90, C. Gale, J.I. Kapusta 91]

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

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

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

- 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:

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

Sources of dilepton emission in heavy-ion collisions

1. initial hard processes: Drell Yan
2. "core" ⇔ emission from thermal source [McLerran, Toimela 1985]

$$\frac{1}{q_T}\frac{\mathrm{d}N^{(\text{thermal})}}{\mathrm{d}M\mathrm{d}q_T} = \int \mathrm{d}^4 x \int \mathrm{d}y \int M \mathrm{d}\varphi \frac{\mathrm{d}N^{(\text{thermal})}}{\mathrm{d}^4 x \mathrm{d}^4 q}$$

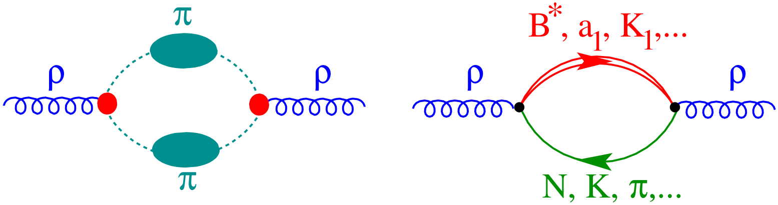
3. "corona" ⇔ emission from "primordial" mesons (jet-quenching)
4. after thermal freeze-out ⇔ emission from "freeze-out" mesons

   [Cooper, Frye 1975]

$$N^{(\text{fo})} = \int \frac{\mathrm{d}^3 q}{q_0} \int q_\mu \mathrm{d}\sigma^\mu f_B(u_\mu q^\mu / T) \frac{\Gamma_{\text{meson}\to\ell^+\ell^-}}{\Gamma_{\text{meson}}}$$

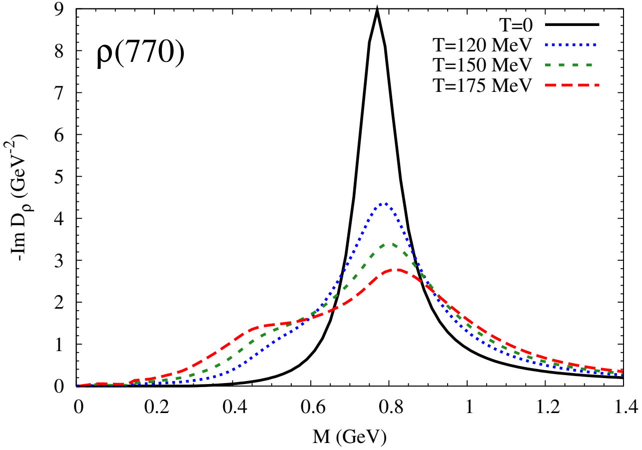
Hadronic many-body theory

- 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)

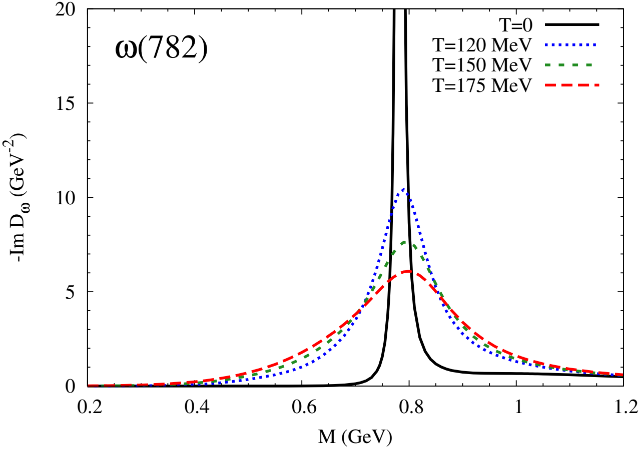
In-medium spectral functions and baryon effects



[R. Rapp, J. Wambach 99]

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

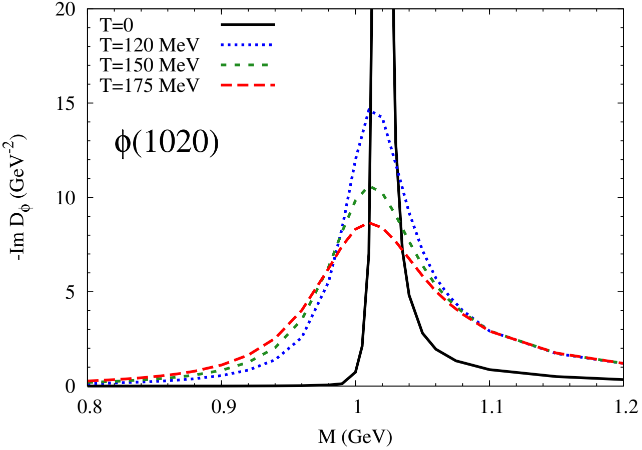
In-medium spectral functions and baryon effects



[R. Rapp, J. Wambach 99]

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

In-medium spectral functions and baryon effects

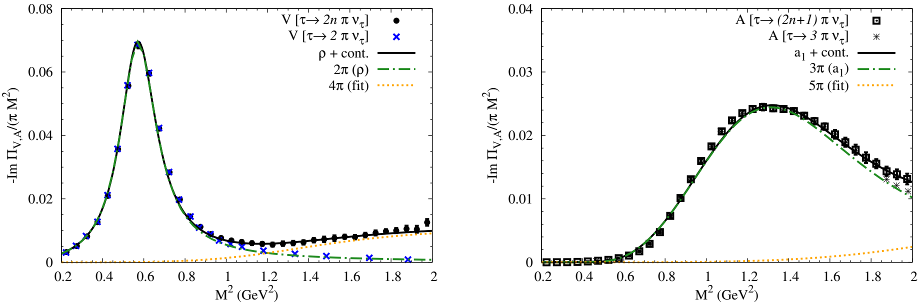


[R. Rapp, J. Wambach 99]

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

Intermediate masses: hadronic "4π contributions"

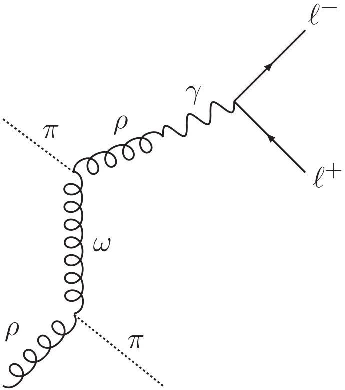
- e.m. current-current correlator $\Leftrightarrow$ $\tau \to 2n\pi$



- "4π contributions": $\pi + \omega, a_1 \to \mu^+ + \mu^-$
- leading-order virial expansion for "four-pion piece"
- additional strength through "chiral mixing"

Radiation from thermal sources: Meson t-channel exchange

- motivation: q_T spectra too soft compared to NA60 data
- thermal contributions not included in models so far

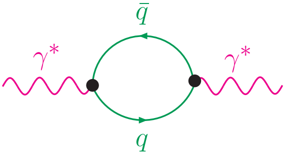


- also for π, a_1

Dileptons from thermal QGP

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

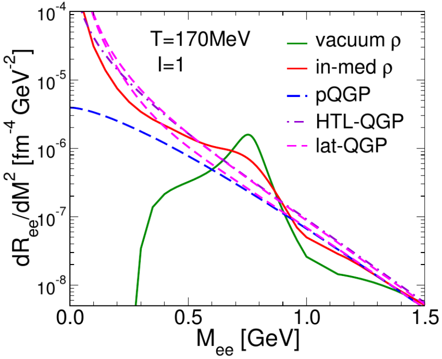
$$-\mathrm{i}\Pi_{\mathrm{em,QGP}} =$$



- or electromagnetic current correlator from the lattice [H.-T. Ding, A. Francis et al (Bielefeld) 2011] (extrapolated to finite q)
- "quark-hadron duality" around T_c

Dilepton rates: Hadron gas ↔ QGP

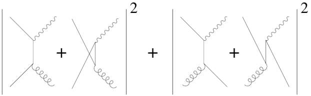
- in-medium hadron gas matches with QGP
- similar results also for γ rates
- "quark-hadron duality"?



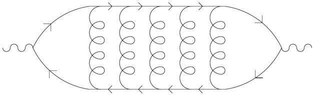
[R. Rapp, arXiv: 1304.2309 [hep-ph]]

Sources of thermal photons in heavy-ion collisions

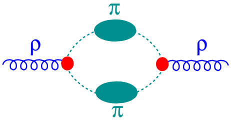
- QGP: rates from [Arnold, Moore, Yaffe, JHEP **12**, 009 (2001)]
  - $q\bar{q} \to \gamma g$, $qg \to \gamma q$

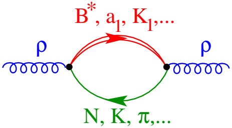


  - resummation of soft-gluon bremsstrahlung contributions
  - Landau-Pomeranchuk-Migdal effect



- hadronic matter from [Turbide, Rapp, Gale, PRC **69**, 014903 (2004); Rapp, Wambach EPJ A **6**, 415 (1999)]
  - pion-cloud dressing + vector meson-baryon/meson interactions



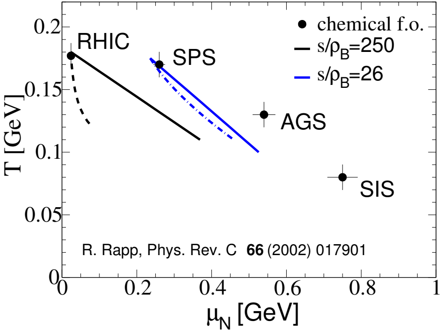


  - $\pi\rho a_1$, ω-t-channel exchange

Medium evolution

Thermal fireball

- cylindrical fireball model: $V_{\text{FB}} = \pi(z_0 + v_{z0}t + \frac{a_z}{2}t^2)\left(\frac{a_\perp}{2}t^2 + r_0\right)^2$
- thermodynamics:
  - isentropic expansion; S_{tot} fixed by N_{ch}; $T_c = T_{\text{chem}} = 175$ MeV
  - $T > T_c$: QGP; lattice equation of state
  - continuous cross-over (no 1st-order mixed state!)
  - $T < T_c$: hadron-resonance gas
- $\Rightarrow T(t), \mu_{\text{baryon,meson}}(t)$
- chemical freezeout:
  - $\mu_N^{\text{chem}} = 232$ MeV
  - hadron ratios fixed $\Rightarrow \mu_N, \mu_\pi, \mu_K, \mu_\eta$ at fixed $s/\rho_B = 27$
- thermal freezeout: $(T_{\text{fo}}, \mu_\pi^{\text{fo}}) \simeq (120, 80)$ MeV



Coarse-grained transport (UrQMD)

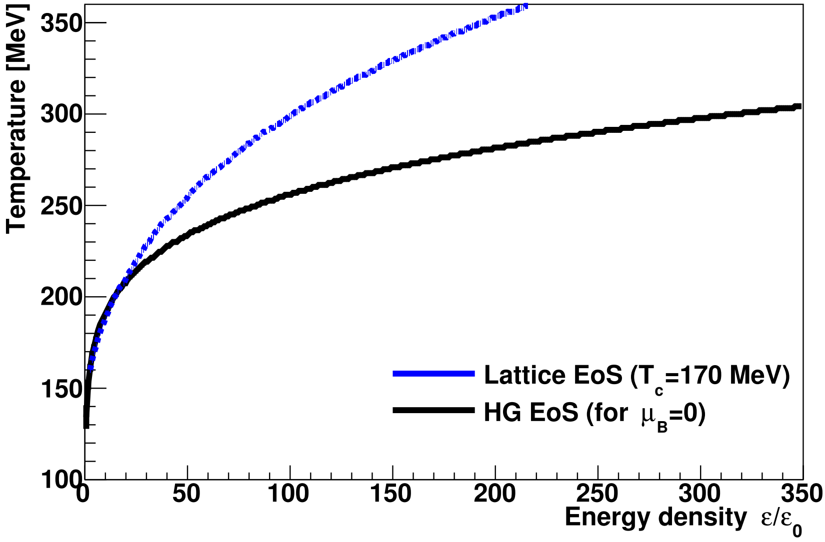
- Use ensemble of UrQMD runs with an equation of state
- map evolution of medium to locally thermalized fluid cells
- fit temperature, chemical potentials, flow-velocity field
  from anisotropic energy-momentum tensor [W. Florkowski et al, NPA **904-905**, 803c (2013)]

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

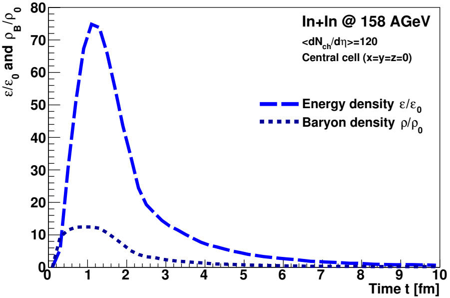
- thermal rates from partonic/hadronic QFT become applicable
- here: extrapolated lattice QGP and Rapp-Wambach hadronic many-body theory
- caveat: consistency between EoS, matter content of QFT model/UrQMD!

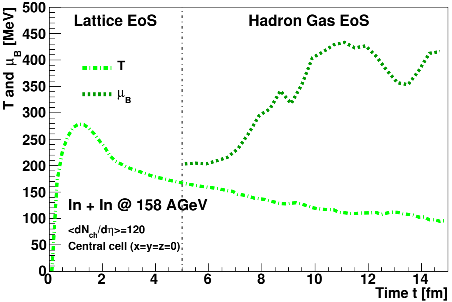
Coarse-grained transport (UrQMD)

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

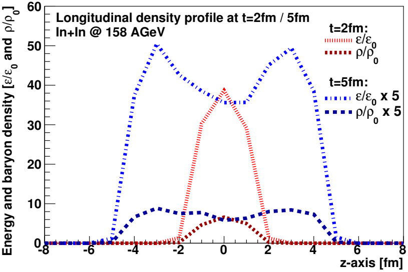


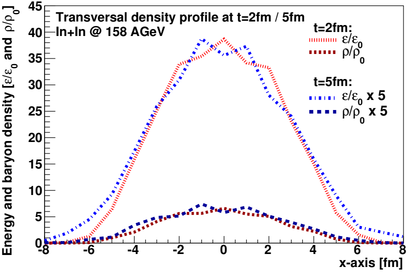
- energy/baryon density $\Rightarrow T, \mu_B$ (for In+In @ SPS; NA60)
- central "fluid" cell!





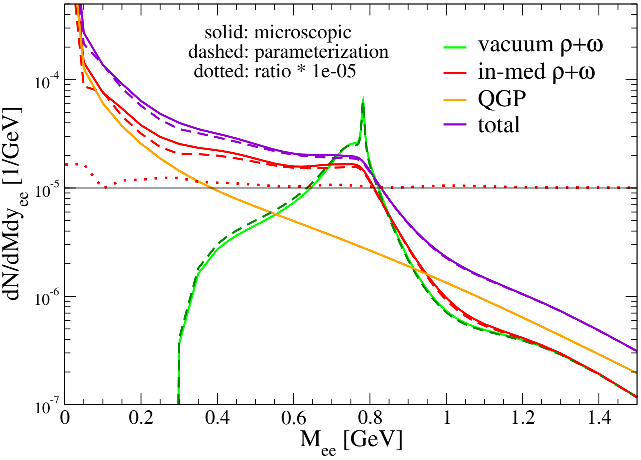
- temperature/density profiles (for In+In@SPS; NA60)





Parametrized Rapp-Wambach rates

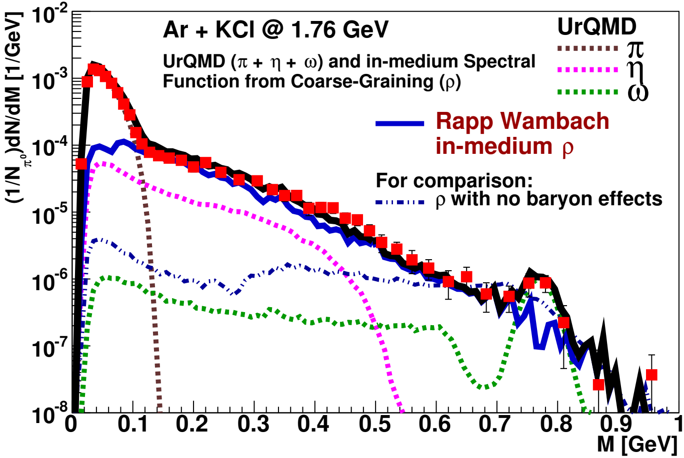
- need rates as function of T, μ_{B}, μ_π, μ_{K}
- parametrization of the microscopic rates necessary
- comparison for 20 AGeV Au Au collisions (min bias) [R. Rapp private commun.]
- pion-cloud effects not fully implemented ⇒ some deviations in LMR



Dielectrons (SIS/HADES)

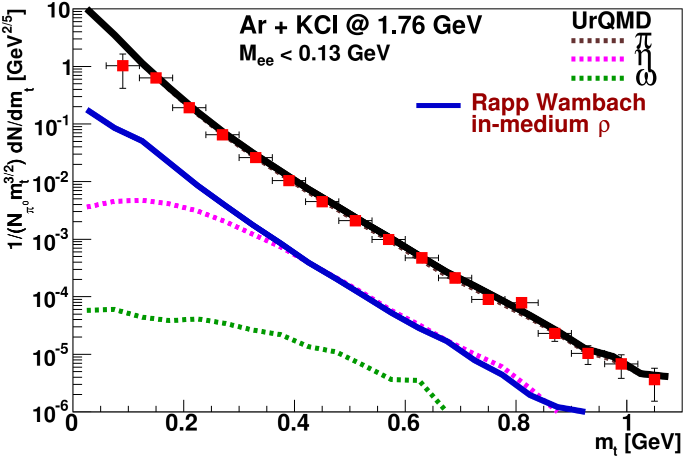
e^+e^- M spectrum (SIS/HADES)

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



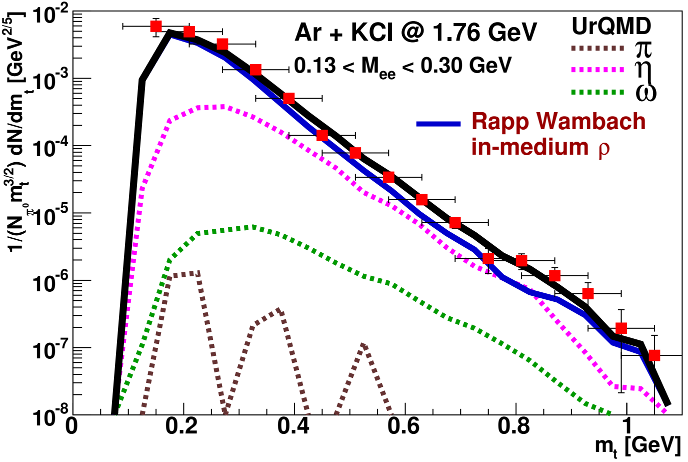
e^+e^- m_T spectra (SIS/HADES)

- dielectron spectra from $\mathrm{Ar} + \mathrm{K\,Cl}(1.76 A\mathrm{GeV}) \rightarrow e^+e^-$ (SIS/HADES)



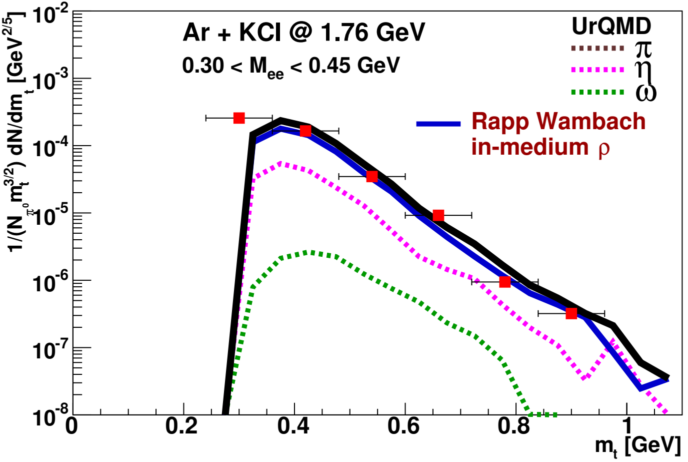
e^+e^- m_T spectra (SIS/HADES)

- dielectron spectra from $\mathrm{Ar} + \mathrm{K\,Cl}(1.76 A\mathrm{GeV}) \rightarrow \mathrm{e}^+\mathrm{e}^-$ (SIS/HADES)



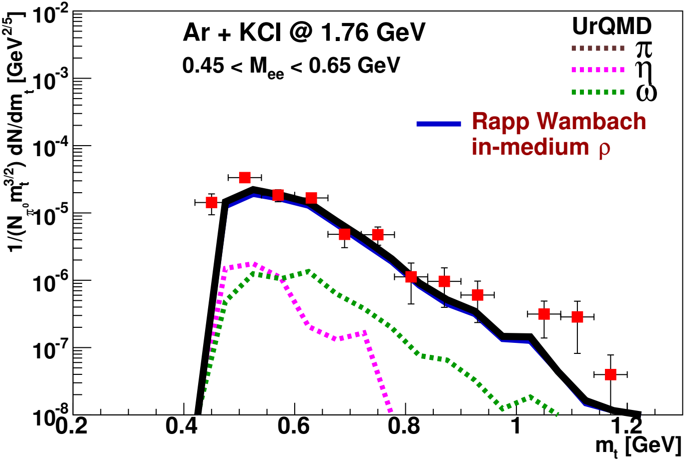
e^+e^- m_T spectra (SIS/HADES)

- dielectron spectra from $\mathrm{Ar}+\mathrm{K\,Cl}(1.76A\mathrm{GeV}) \rightarrow \mathrm{e}^+\mathrm{e}^-$ (SIS/HADES)



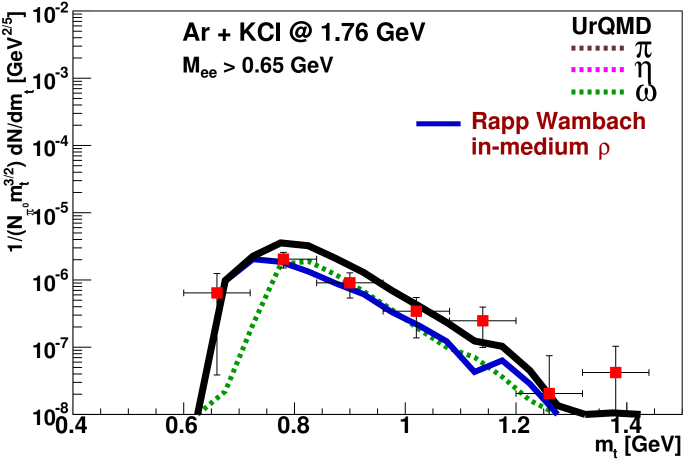
e^+e^- m_T spectra (SIS/HADES)

- dielectron spectra from $\mathrm{Ar} + \mathrm{K\,Cl}(1.76 A\mathrm{GeV}) \rightarrow \mathrm{e^+e^-}$ (SIS/HADES)



e^+e^- m_T spectra (SIS/HADES)

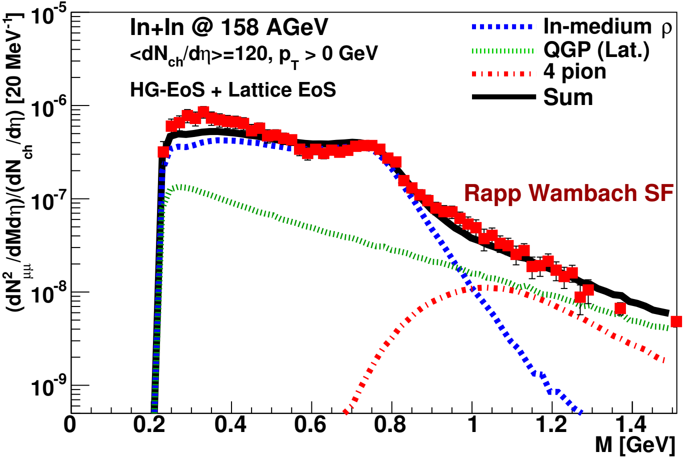
- dielectron spectra from $\mathrm{Ar} + \mathrm{K\,Cl}(1.76 A\mathrm{GeV}) \rightarrow e^+e^-$ (SIS/HADES)



Dimuons (SPS/NA60)

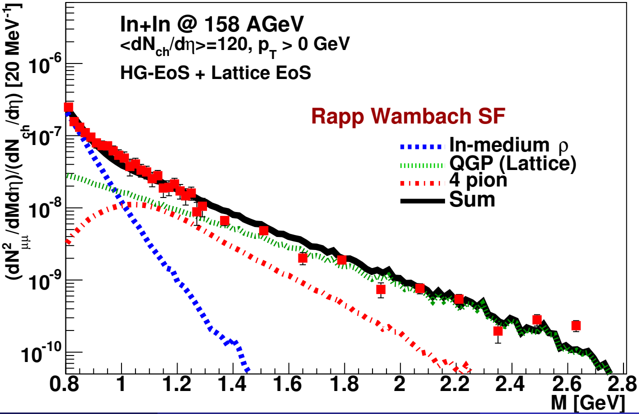
$\mu^+\mu^-$ M spectra (SPS/NA60)

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



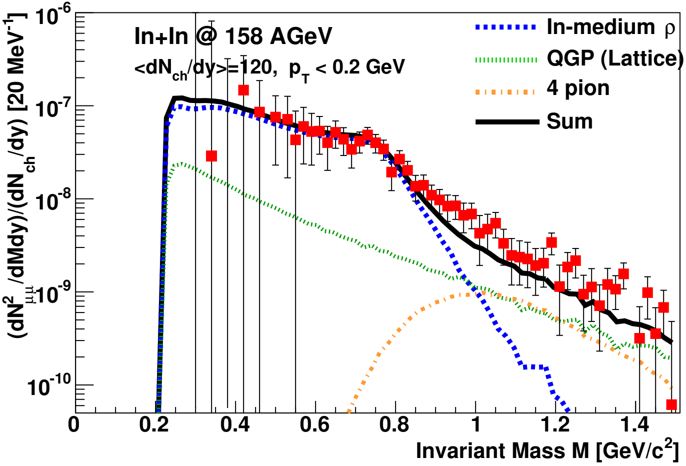
$\mu^+\mu^-$ M spectra (SPS/NA60)

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



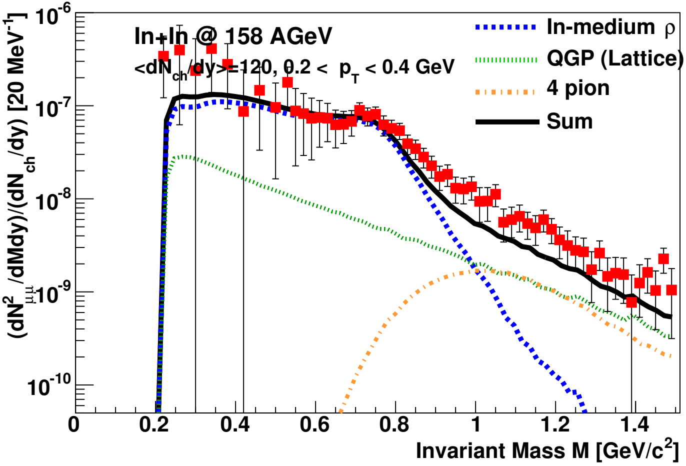
$\mu^+\mu^-$ M spectra (SPS/NA60)

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



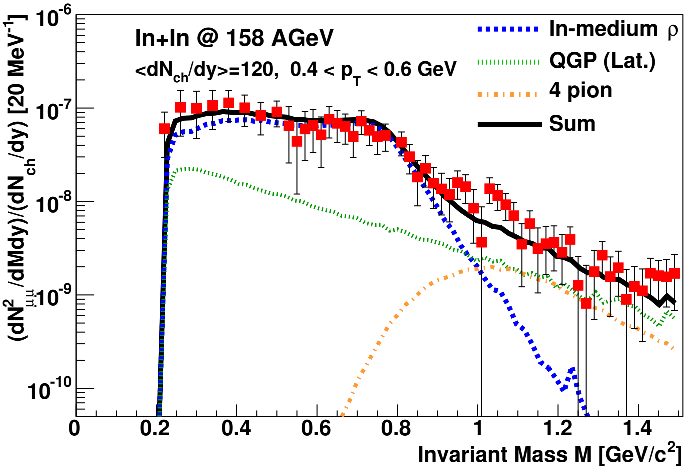
$\mu^+\mu^-$ M spectra (SPS/NA60)

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

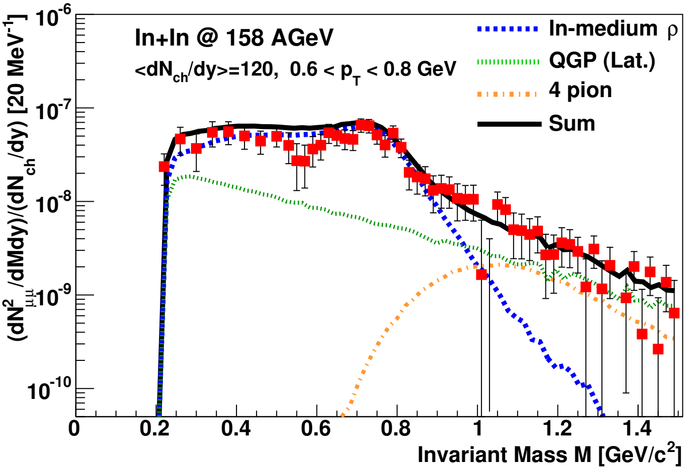


$\mu^+\mu^-$ M spectra (SPS/NA60)

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

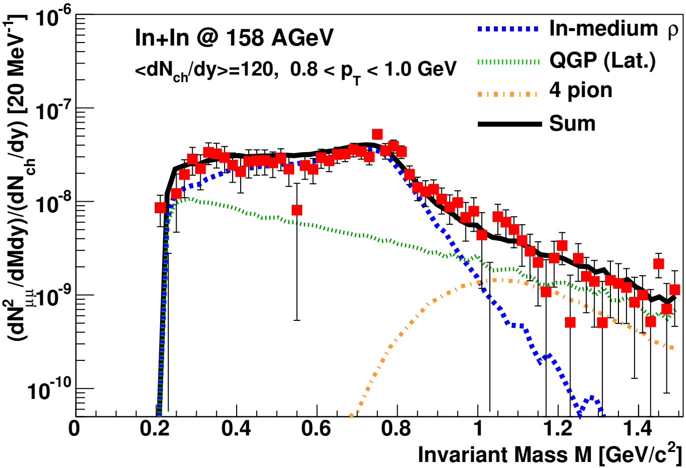


- dimuon spectra from $\mathrm{In}+\mathrm{In}(158A\mathrm{GeV}) \to \mu^+\mu^-$ (NA60)
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{dy}=120$)



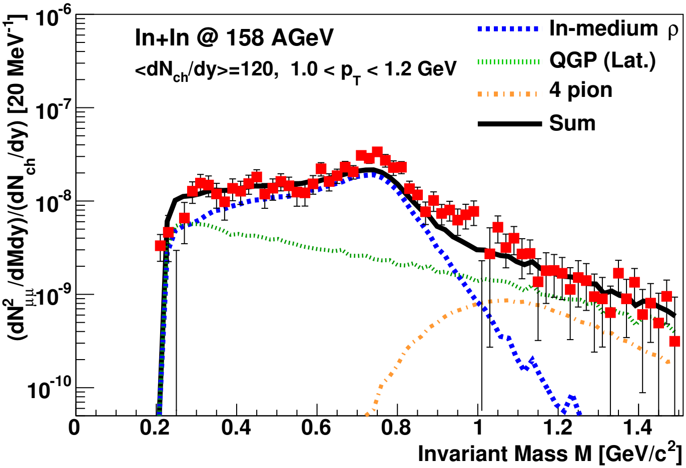
$\mu^+\mu^-$ M spectra (SPS/NA60)

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



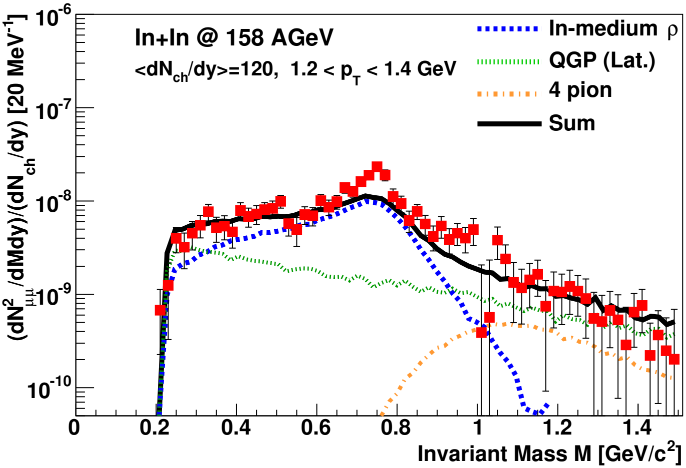
$\mu^+\mu^-$ M spectra (SPS/NA60)

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



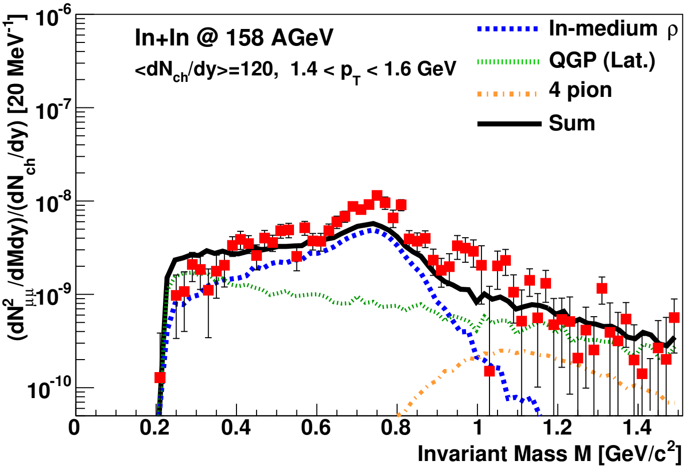
$\mu^+\mu^-$ M spectra (SPS/NA60)

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



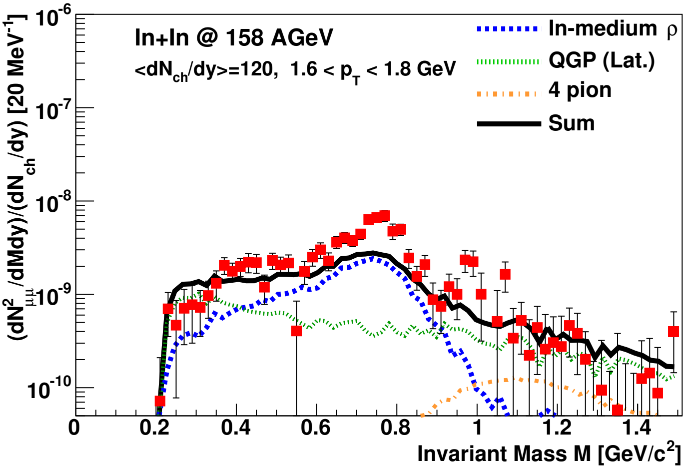
$\mu^+\mu^-$ M spectra (SPS/NA60)

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



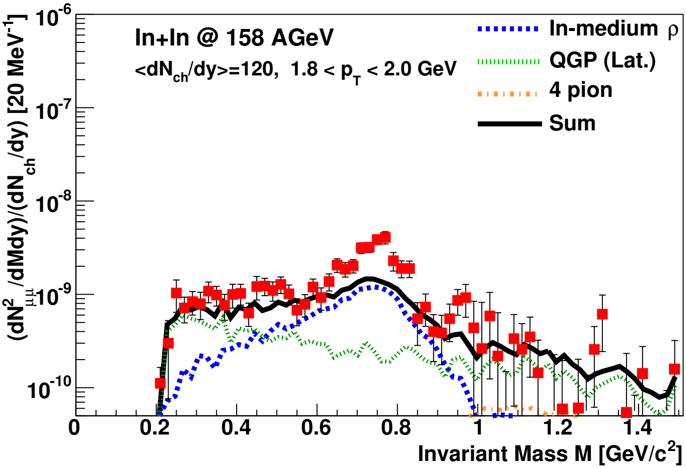
$\mu^+\mu^-$ M spectra (SPS/NA60)

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



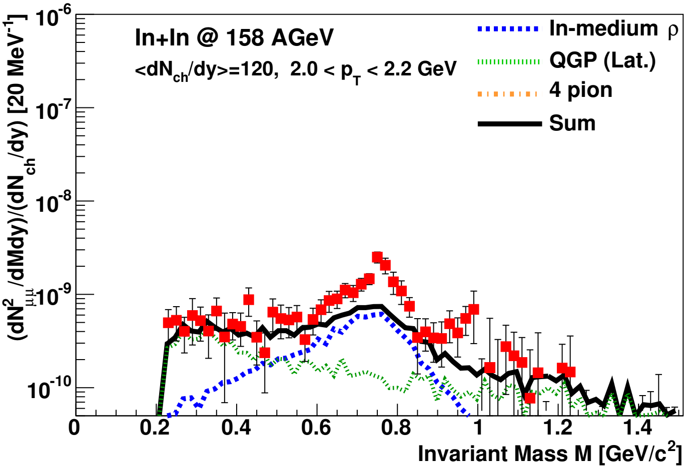
$\mu^+\mu^-$ M spectra (SPS/NA60)

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



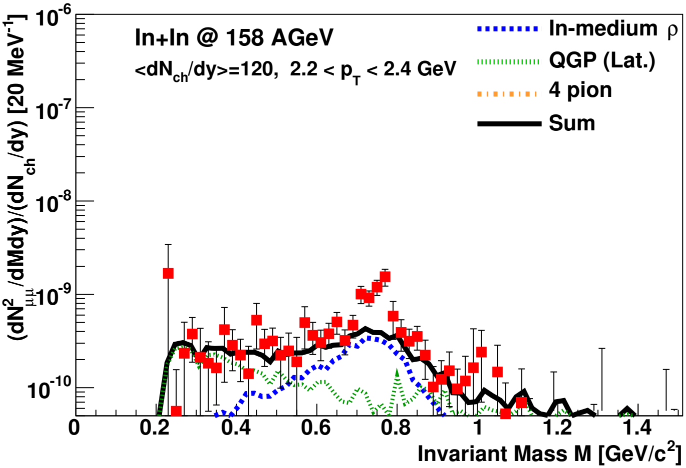
$\mu^+\mu^-$ M spectra (SPS/NA60)

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



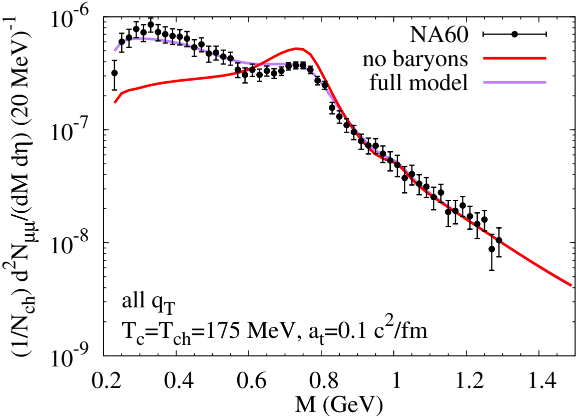
$\mu^+\mu^-$ M spectra (SPS/NA60)

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



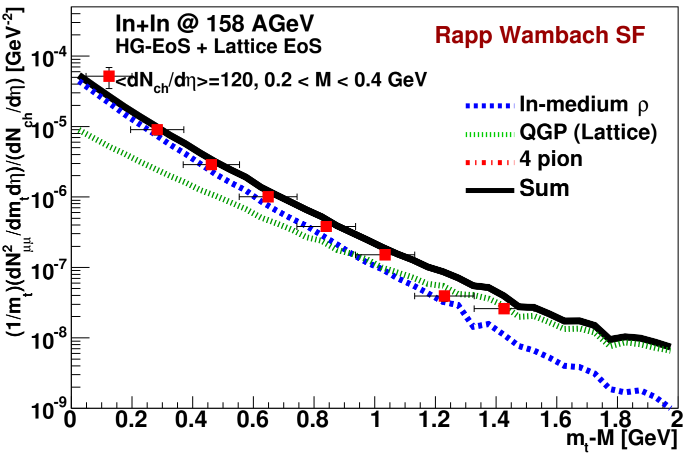
$\mu^+\mu^-$ M spectra (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60)
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- influence of baryon interactions in spectral function
- from previous calculation with thermal-fireball parametrization (compatible with course-grained UrQMD)

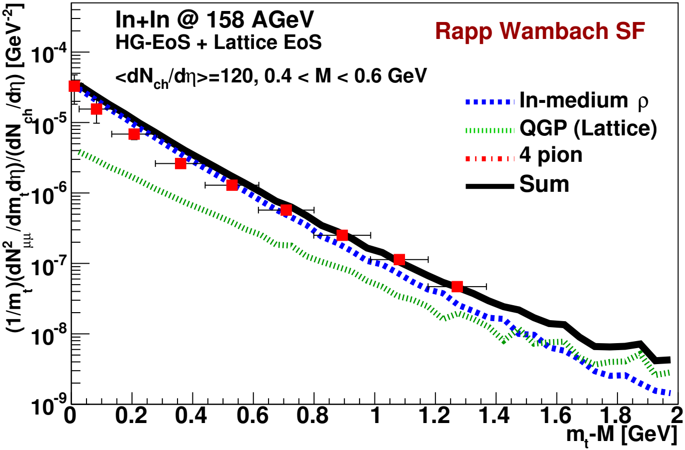


$\mu^+\mu^-$ m_T spectra (SPS/NA60)

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

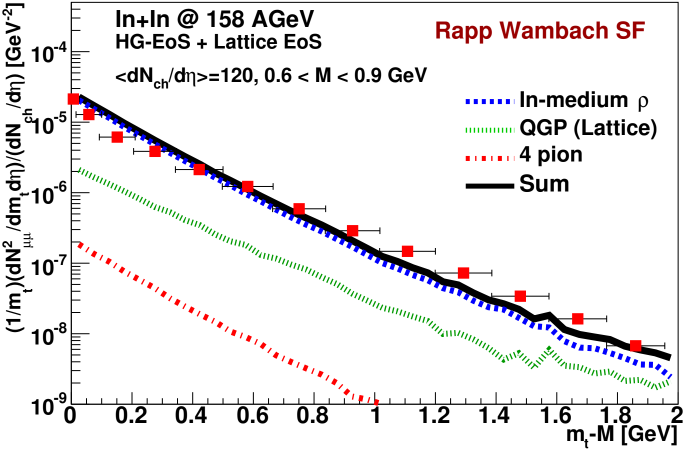


- dimuon spectra from $\mathrm{In}+\mathrm{In}(158A\mathrm{GeV}) \to \mu^+\mu^-$ (NA60)
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)



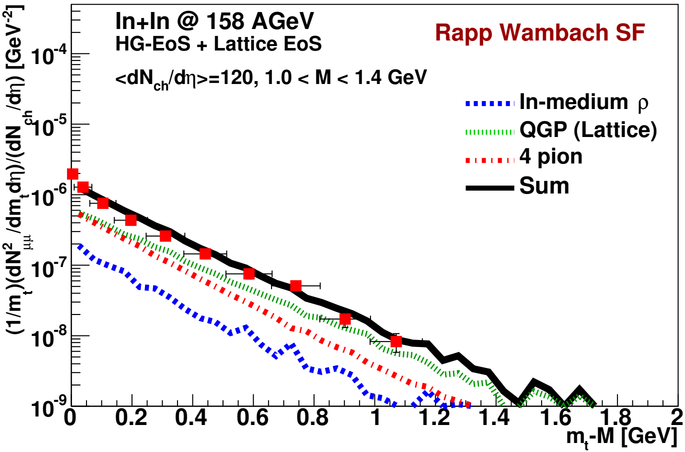
$\mu^+\mu^-$ m_T spectra (SPS/NA60)

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



$\mu^+\mu^-$ m_T spectra (SPS/NA60)

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

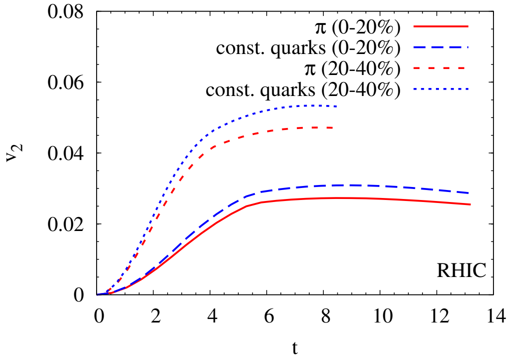


Direct Photons at RHIC and LHC

Direct Photons at RHIC and LHC: elliptic fireball/hydro

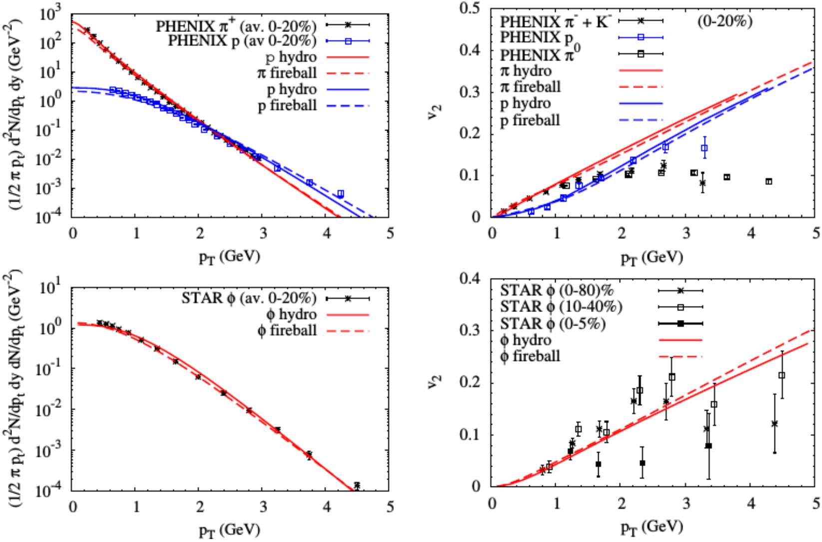
- fitted to measured p_T spectra and v_2; multi-strange hadrons: fo at T_c!
- can be achieved with (ideal) hydro

[He, Fries, Rapp, PRC **85**, 044911 (2012); HvH, He, Rapp arXiv: 1404.2846 [nucl-th]]



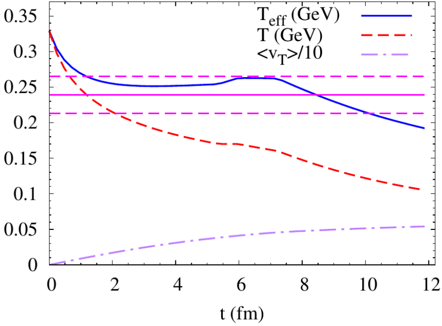
- important for "sufficient" photon v_2:
  - rapid buildup of v_2
  - (nearly) full v_2 at end of mixed phase
  - consistent with CQN scaling for multi-strange and other hadrons!

RHIC:

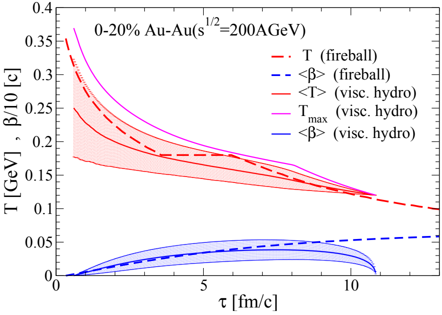


[HvH, Gale, Rapp, Phys. Rev. C **84**, 054906 (2011); HvH, He, Rapp arXiv: 1404.2846 [nucl-th]]

Temperature vs. effective Slope



[Rapp, HvH, He, arXiv: 1408.0612 [nucl-th]]



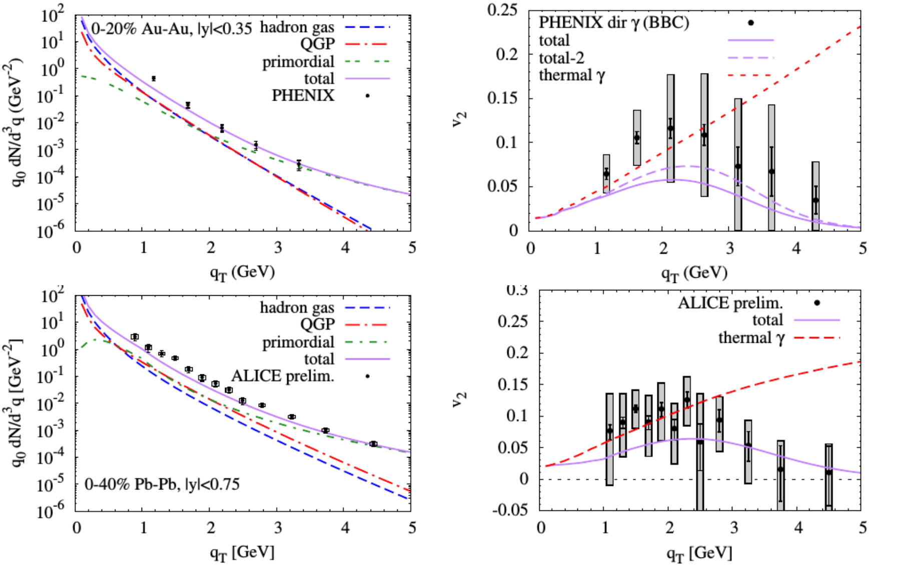
[C. Shen, U. W. Heinz, J.-F. Paquet, C. Gale]
[arXiv:1308.2440 [nucl-th]]

- blue-shift formula (Doppler effect) translates into

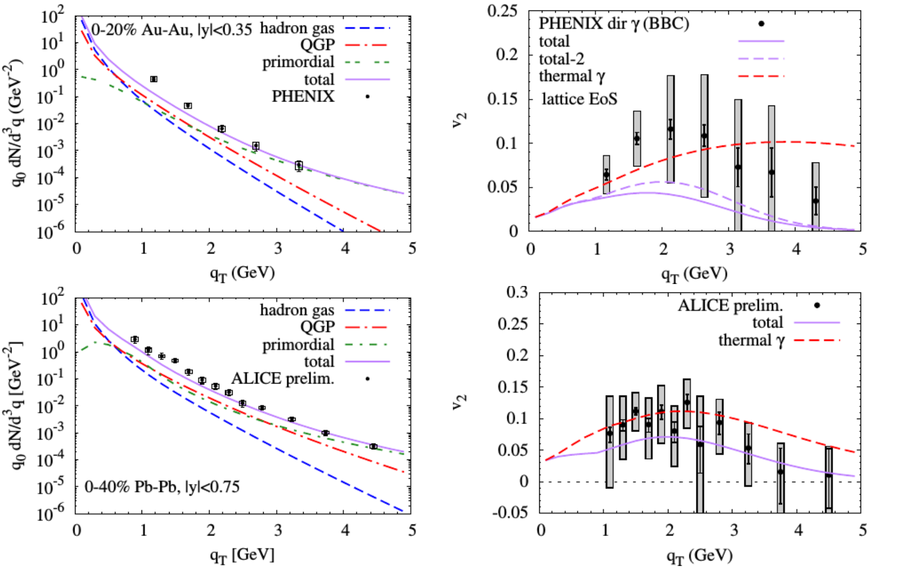
$$T_{\text{eff}} \simeq T\sqrt{\frac{1+\langle v_T\rangle}{1-\langle v_T\rangle}}, \quad v_T: \quad \text{transverse fluid flow}$$

- measured slope indicates emission from source around T_c

Direct photons: fireball

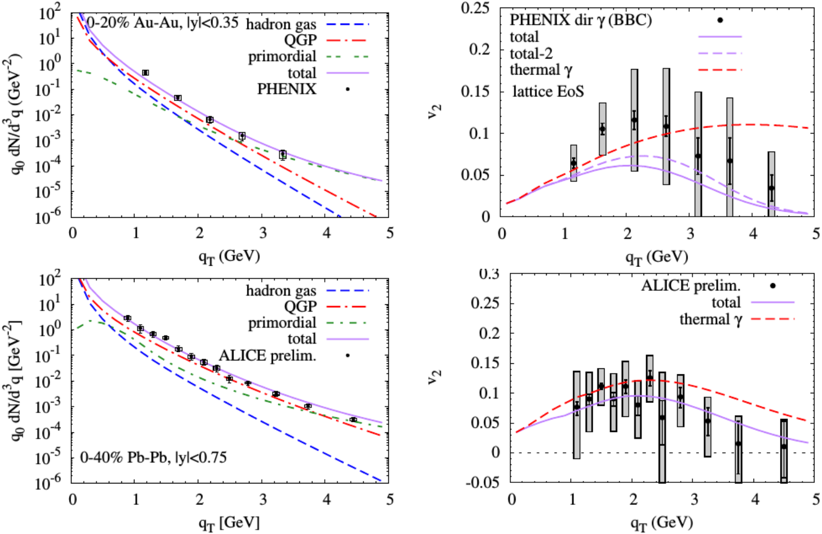


Direct photons: ideal hydro



Direct photons: enhanced rates

- assume enhancement of baseline rates by factor of 2
- augmented up to factor of 3 for 140 MeV $< T <$ 200 MeV



Conclusions and Outlook

- General ideas
  - em. probes $\Leftrightarrow$ in-medium em. current-correlation function
  - dual rates around T_c (compatible with χ symmetry restoration)
    $\Rightarrow$ see Paul Hohler's talk
  - medium modifications of ρ, ω, ϕ
  - importance of baryon-resonance interactions
- Application to dileptons in HICs
  - need realistic bulk-medium evolution
  - thermal fireball, (ideal) hydrodynamics
  - new: coarse-grained transport
  - applicable also at low collision energies
  - allows use of thermal-QFT models for em. current-correlation functions
  - successful description at HADES, SPS, and RHIC (STAR)
  - consistent description of M and m_T spectra!
  - Outlook: effective slope of M spectra in higher IMR
    ($1.5\,\text{GeV} < M < M_{J/\psi}$) provides $\langle T \rangle$
  - applied in beam-energy scan at RHIC and FAIR $\Rightarrow$
    signature of phase transition?
  - signature of cross-over vs. 1st order (or even critical endpoint)?

Conclusions and Outlook

- Application to photons in HICs
  - so far: bulk evolution with elliptic thermal fireball and hydro
  - direct-photon "v_2 puzzle"
  - dominated from fireball temperatures around T_c (remnant of latent heat)

  $\Rightarrow$ Early build-up of elliptic flow
  - compatible with early freeze-out of multi-strange hadrons
  - can be achieved with fireball parametrization or choice of appropriate hydro-initial conditions (initial flow)
  - still yield missing $\Rightarrow$ probable enhancement of rates due to non-perturbative enhanced cross sections around T_c?!?