Elliptic Flow of Thermal Photons and Dileptons*

Ulrich Heinz

Department of Physics
The Ohio State University
191 West Woodruff Avenue
Columbus, OH 43210

Presented at

Hard Probes 2006

Asilomar, June 9-16, 2006

Based on work done with R. Chatterjee, E. Frodermann, C. Gale, and D.K. Srivastava [PRL 96 (2006) 202302, and to be published]

*Work supported by the U.S. Department of Energy (DOE)

This will be a hard measurement – why bother?

- Hadron elliptic flow (v_2) measurements have led to the new paradigm that the QGP at RHIC is an (almost) ideal fluid
- Hadrons decouple late, but flow anisotropy is created early when pressure anisotropies are largest $\Longrightarrow$ dynamical models required to connect them
- Monotonic dependence of v_2 on microscopic scattering rate $\Longrightarrow$ v_2 places tight constraints on such models.
  Only one successful model so far: Ideal fluid QGP + viscous HG
- It would be nice, however, to test not only the outcome, but also the detailed early spacetime dynamics predicted by this model
  $\Longrightarrow$ thermal photons and dileptons
- Photons decouple immediately $\Longrightarrow$
  emitted from all collision stages ($\Rightarrow$ time integral over collision history), but emission rate biased towards high temperatures ($\Rightarrow$ emphasis on early times)
  $\Longrightarrow$ window on early expansion stage
- Here: Pioneering study of thermal photon v_2 ($\Rightarrow$ early evolution of flow anisotropy), using ideal fluid dynamical model from initial thermalization to final kinetic freeze-out

Hydrodynamics

P. Kolb et al. PRC 62 (2000) 054909

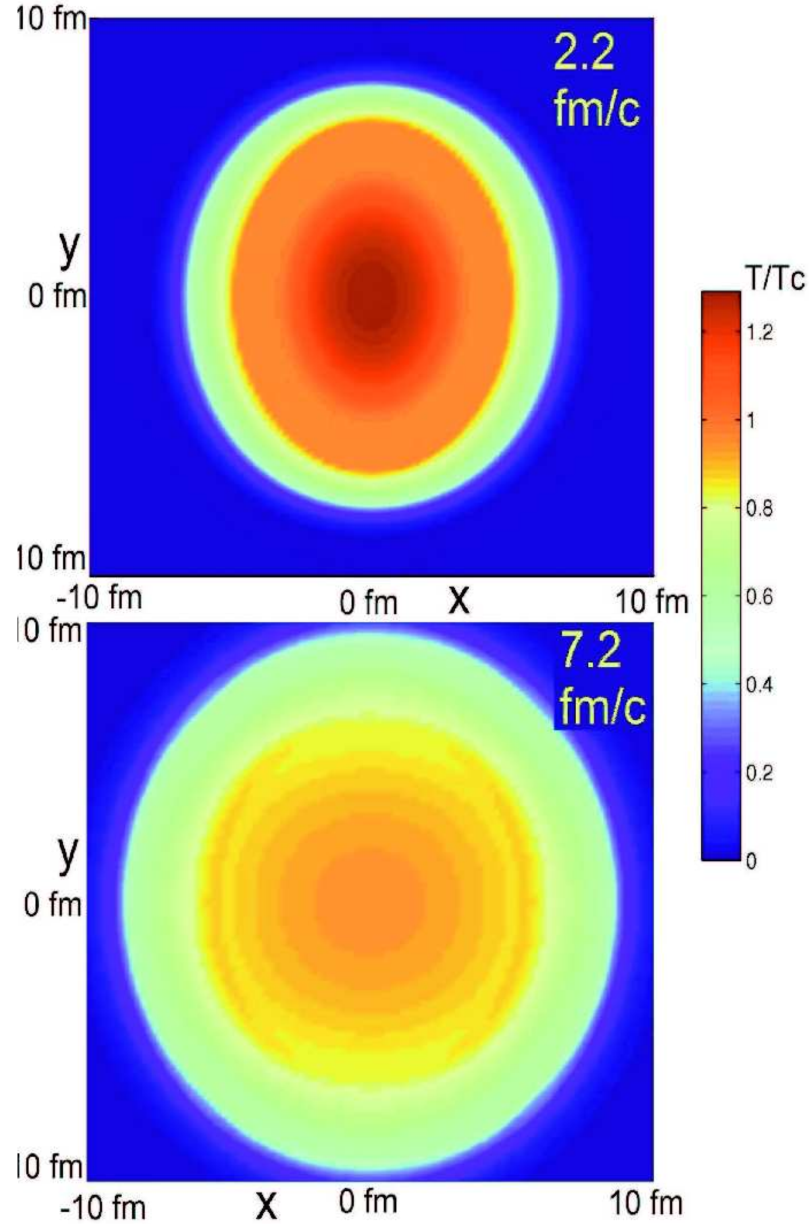
$$\dot{n}_B = -n_B\,(\partial\cdot u)$$
$$\dot{\varepsilon} = -(\varepsilon + p)\,(\partial\cdot u)$$
$$\dot{u}^\mu = \frac{\nabla^\mu p}{\varepsilon + p}$$

- ideal fluid dynamics
- flow driven by pressure gradients $\nabla^\mu p$

Photon spectrum $\sim \int [\ldots] e^{-\frac{k\cdot u(x)}{T(x)}}\, d^4x$

$$\frac{k^\mu u_\mu(x)}{T(x)} = \frac{\gamma_\perp(x)}{T(x)}\Big(E_\gamma \cosh\eta - \boldsymbol{k}_\perp \cdot \boldsymbol{v}_\perp(x)\Big)$$
$$= \frac{\gamma_\perp(x)}{T(x)} E_\gamma \Big(\cosh\eta - v_\perp(x)\cos\theta_{vk}\Big)$$

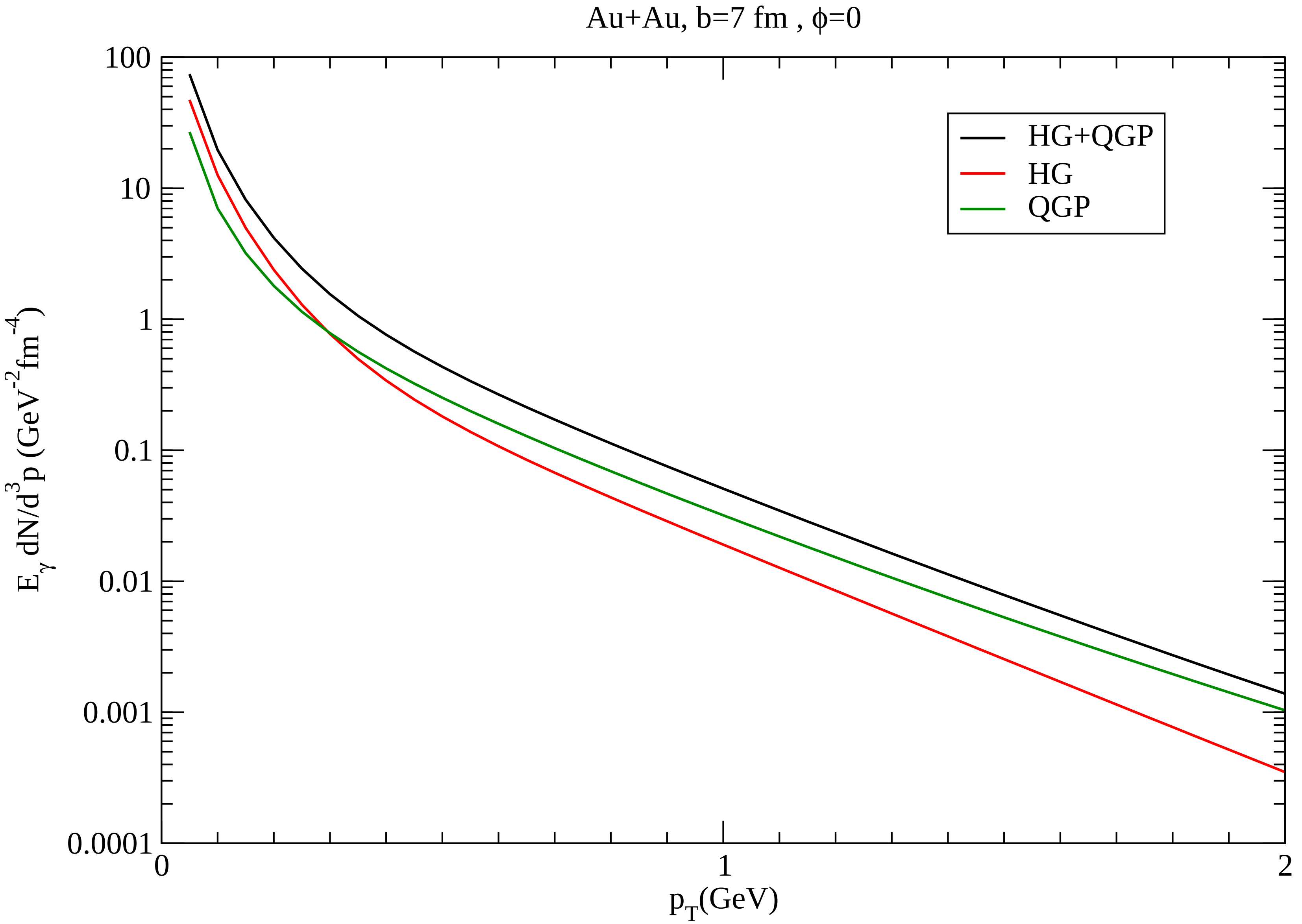
v_2 affected by anisotropies of $\boldsymbol{v}_\perp(\boldsymbol{x}_\perp)$ and $T(\boldsymbol{x}_\perp)$



Hydrodynamics, photon spectra and elliptic flow

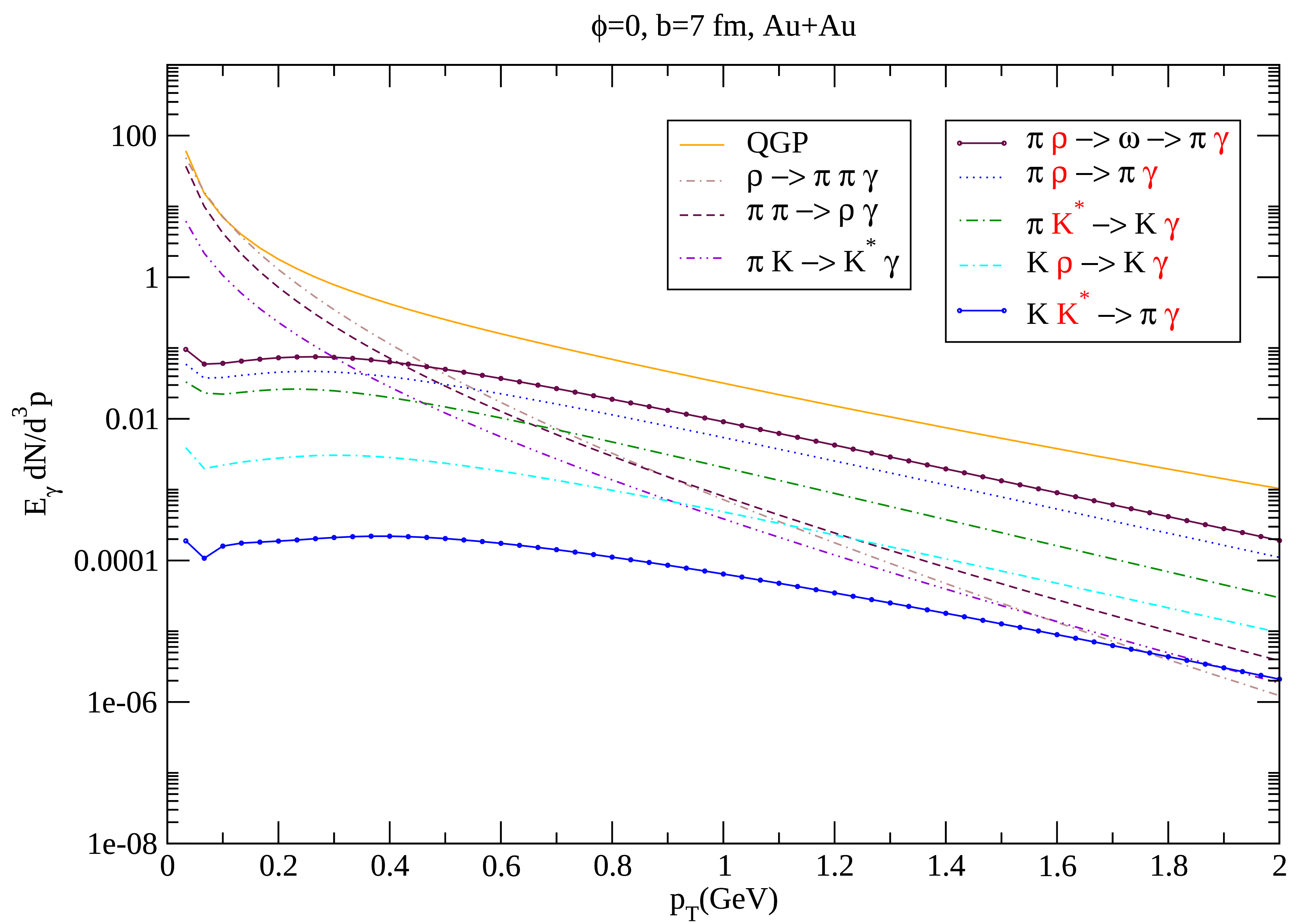
- Use AZHYDRO [(2+1)-dimensional ideal hydro with longitudinal boost invariance (P. Kolb et al., 2000-2003)] with EOS Q
- Reduce initial time $\tau_0 = 0.6\,\frac{\text{fm}}{c} \to 0.2\,\frac{\text{fm}}{c}$
(increase initial peak entropy density $s_0 = 117\,\text{fm}^{-3} \to 351\,\text{fm}^{-3}$)
to capture/simulate pre-equilibrium photons
- Take published photon emission rate $R(\frac{k}{T})$ in local rest frame (QGP rate: Arnold, Yaffe, Moore, JHEP 0112 (2001); HG rate: Turbide, Rapp, Gale, PRC 69 (2004)) and boost it to lab frame, $\frac{k}{T} \longrightarrow \frac{p \cdot u(x)}{T(x)}$, using hydrodynamic $u_\mu(x)$ and $T(x)$
- Integrate over entire space-time volume enclosed by hadronic freeze-out surface to compute photon spectrum $E_\gamma \frac{dN_\gamma}{d^3p} = \frac{dN_\gamma}{dy\, p_T dp_T\, d\phi}$
- Compute photon elliptic flow $$v_2(p_T, b) = \frac{\int d\phi\, \cos(2\phi)\, E_\gamma \frac{dN_\gamma}{d^3p}}{\int d\phi\, E_\gamma \frac{dN_\gamma}{d^3p}}$$
- HG rates from Turbide et al. don't include hadron chemical potentials $\Longrightarrow$ use HG EOS with chemical equilibrium all the way to kinetic freeze-out $\Longrightarrow$ needs to be fixed later

Single-photon spectra

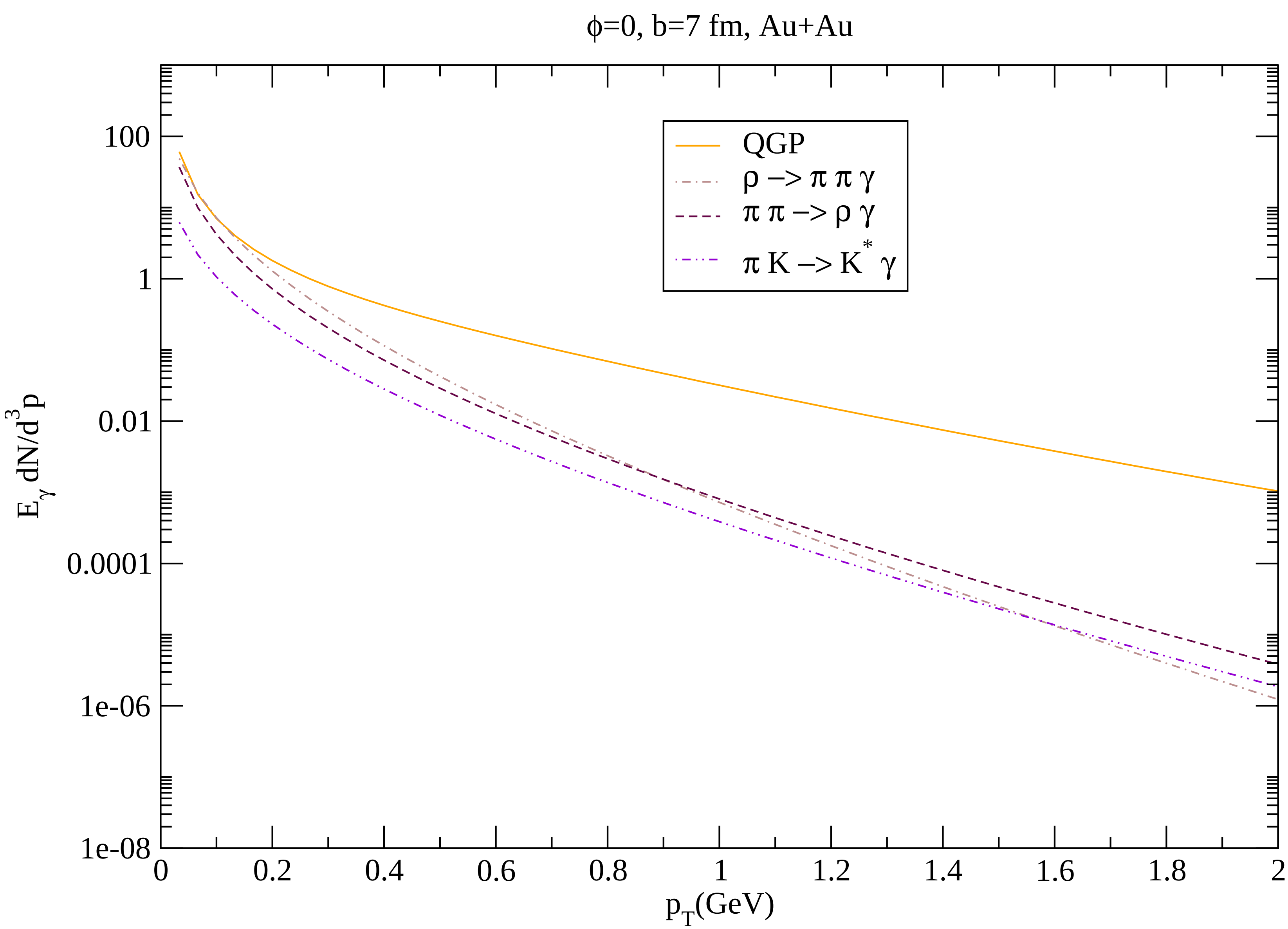


- QGP dominates over HG for $p_T > 0.5\,\text{GeV}$
- Inverse slope for $1 < p_T < 2\,\text{GeV}/c \Rightarrow$ lower limit for initial QGP temperature!

Two classes of hadronic photon emission processes:

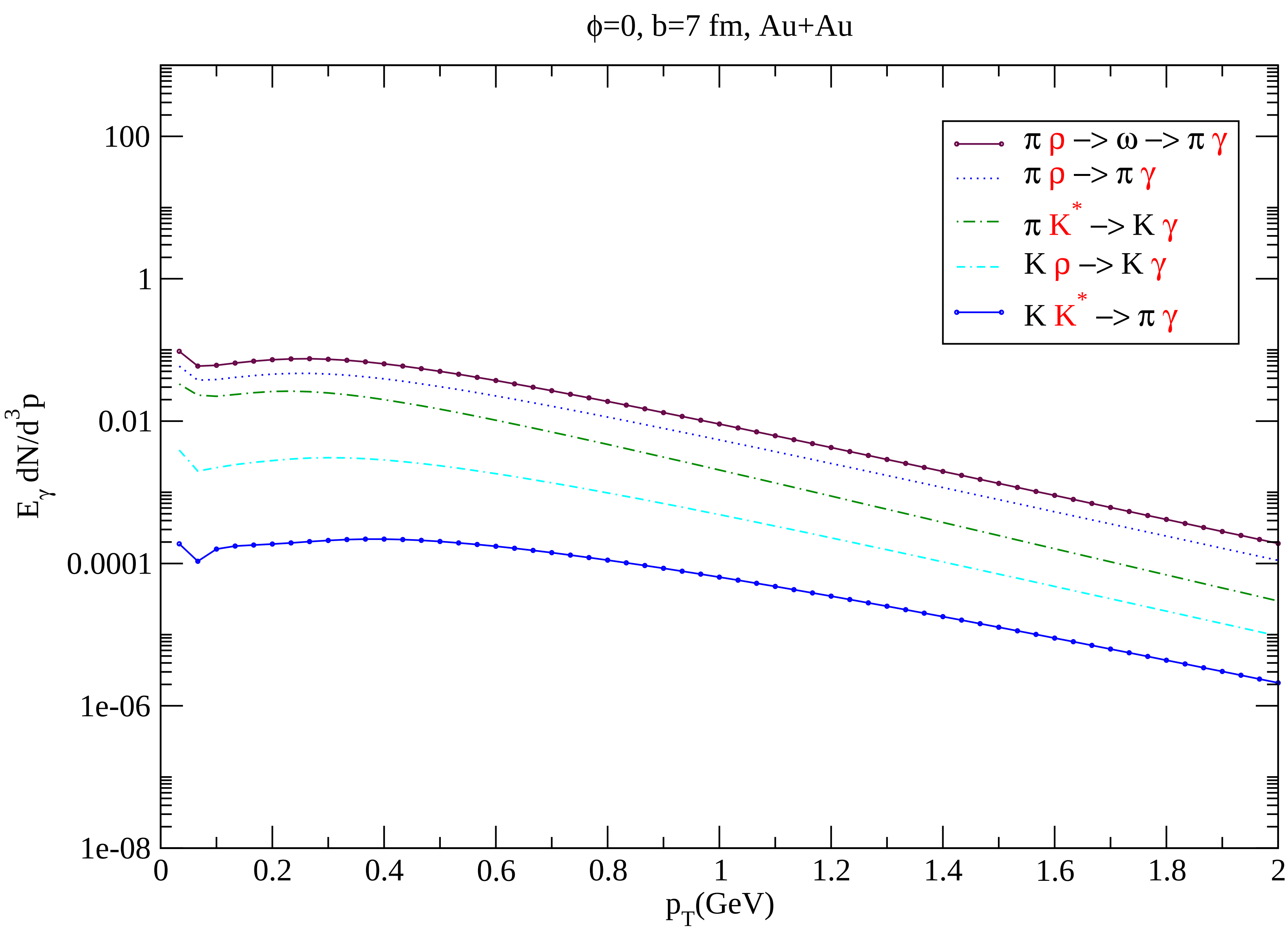


Hadronic photons I: pion scattering



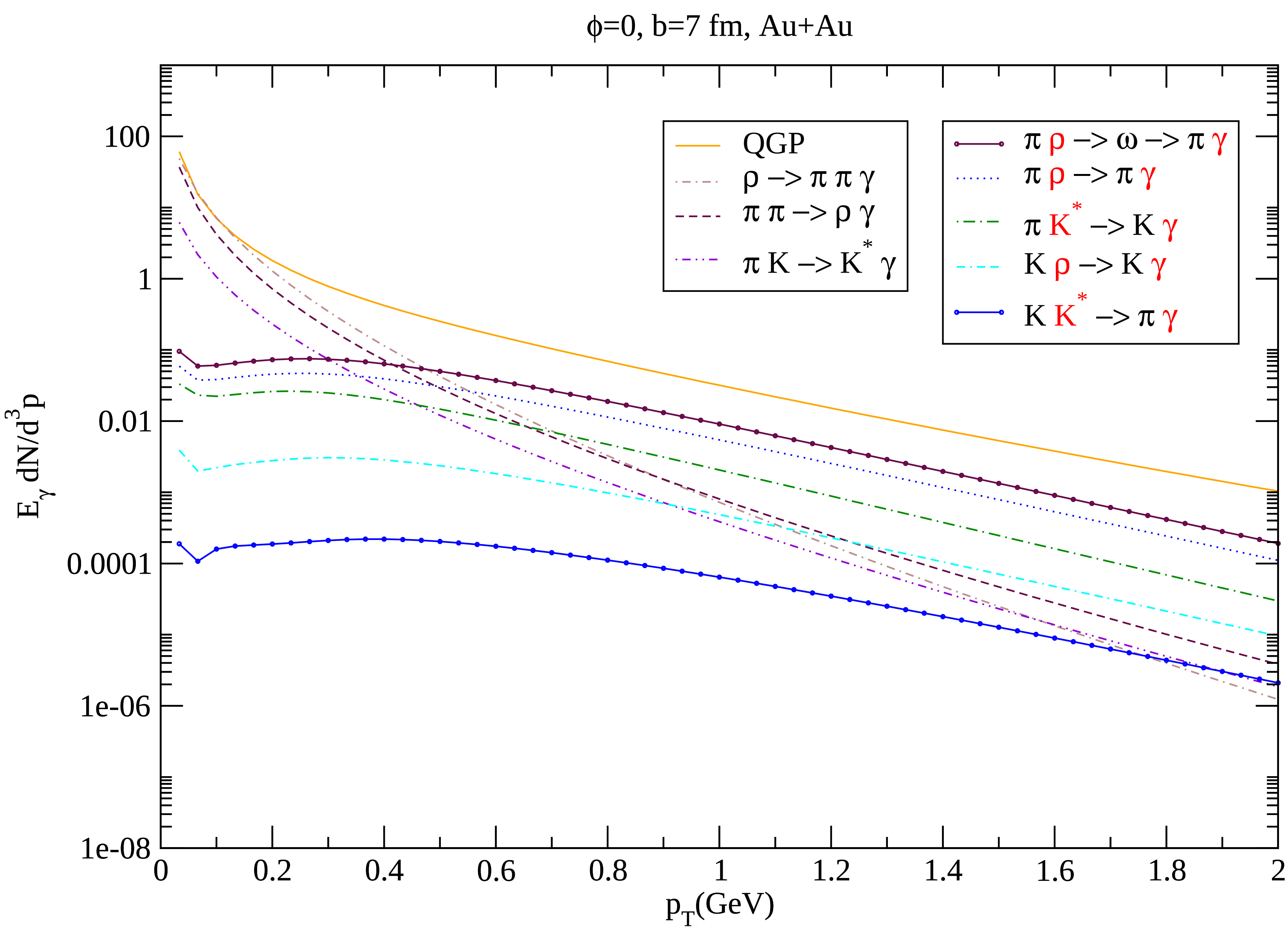
- dominates at low p_T, falls rapidly at high p_T

Hadronic photons II: vector meson → photon conversion



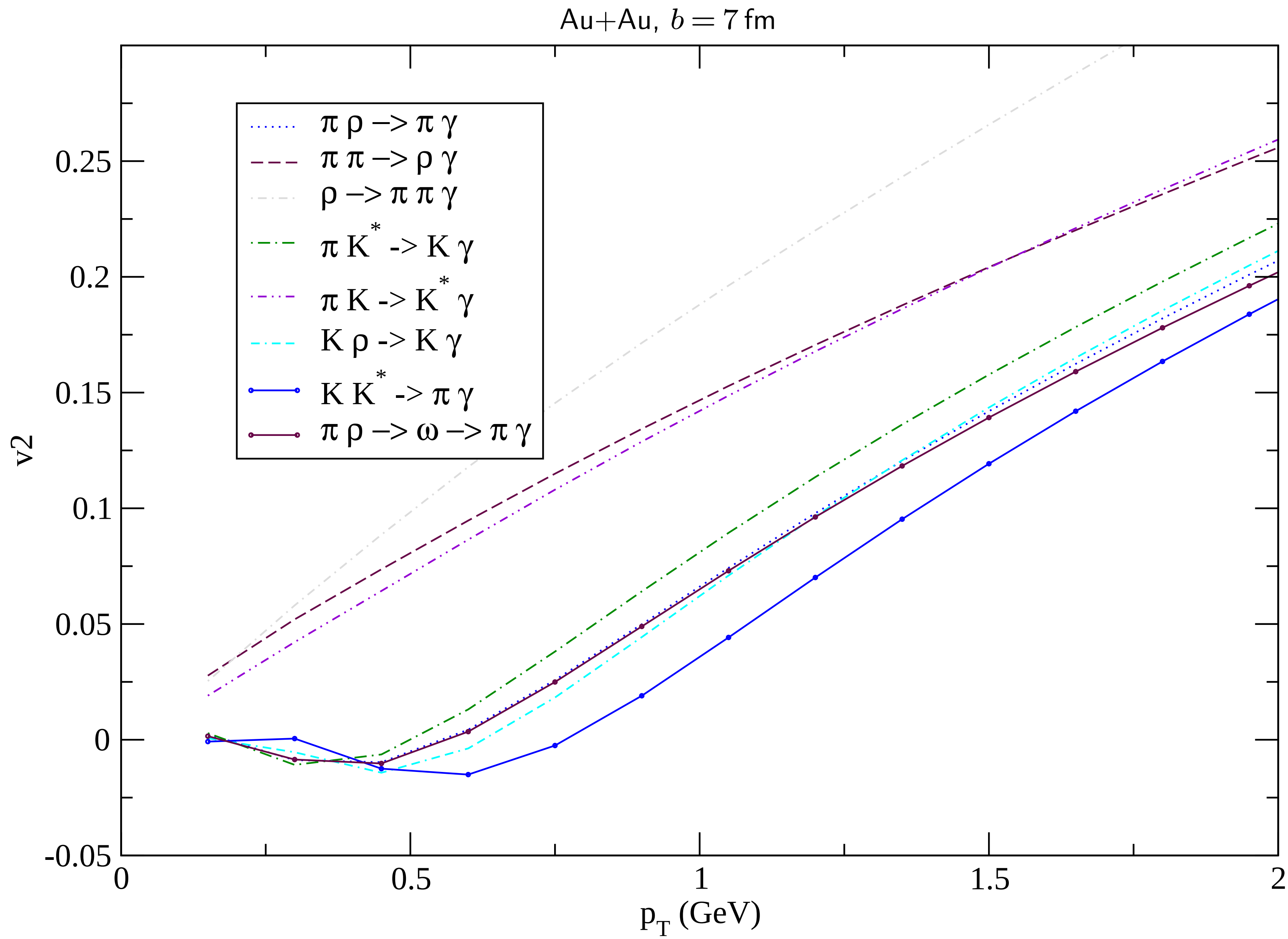
- shoulder and flatter slope reflects radial flow effects on heavy vector mesons

Hadronic photons: relative contributions



- collision-induced VM $\longrightarrow \gamma$ conversion dominates over π scattering for $p_T > 0.4\,\text{GeV}/c$

Elliptic flow contributions from hadron gas phase



(Heavy) vector mesons carry less elliptic flow than (light) pions!

Thermal photon elliptic flow

R. Chatterjee, E. Frodermann, UH, D.K. Srivastava, PRL 96 (2006) 202302

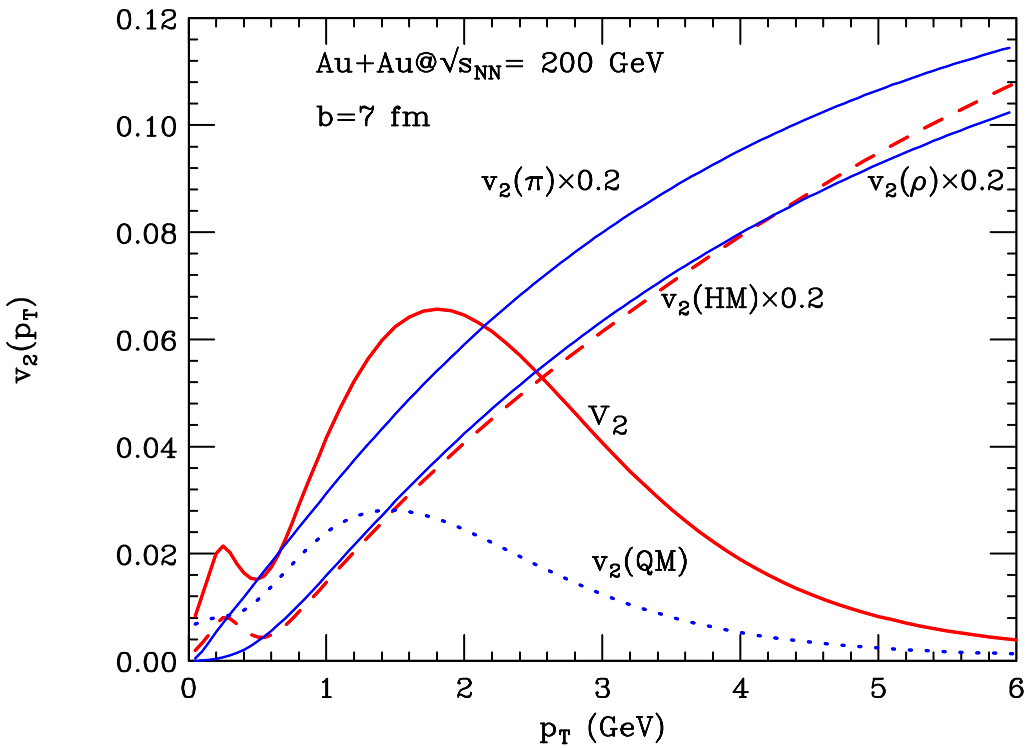
- Hadronic photons track . . .
  - π's for $p_T < 400\,\mathrm{MeV}/c$
  - ρ's for $p_T > 400\,\mathrm{MeV}/c$

  $\Rightarrow$ structure in v_2 at $p_T \sim 400\,\mathrm{MeV}$

- QGP photons track quark flow

  $\Rightarrow$ small at high p_T (early times)

- Total photon v_2 dominated by QGP for $p_T \gtrsim 1-2\,\mathrm{GeV}/c$ $\Rightarrow$ v_2 decreases at high p_T



Note: For $p_T > 1\,\mathrm{GeV}$, hydrodynamic prediction = upper limit for v_2!

- viscosity and prompt photon contribution will further reduce v_2 at large p_T
- structure around $p_T \sim 400\,\mathrm{MeV}/c$ should be reliable

Virtual photons: thermal dileptons

R. Chatterjee, C. Gale, UH, D.K. Srivastava, in preparation

Dilepton mass $M \equiv M_{\ell\bar{\ell}} = M_{\gamma^*}$ as additional variable:

$$v_2(M, p_T, b) = \frac{\int d\phi\, \cos(2\phi)\, \frac{dN_{\ell\bar{\ell}}}{dM^2\, dY\, p_T dp_T\, d\phi}}{\int d\phi\, \frac{dN_{\ell\bar{\ell}}}{dM^2\, dY\, p_T dp_T\, d\phi}}$$

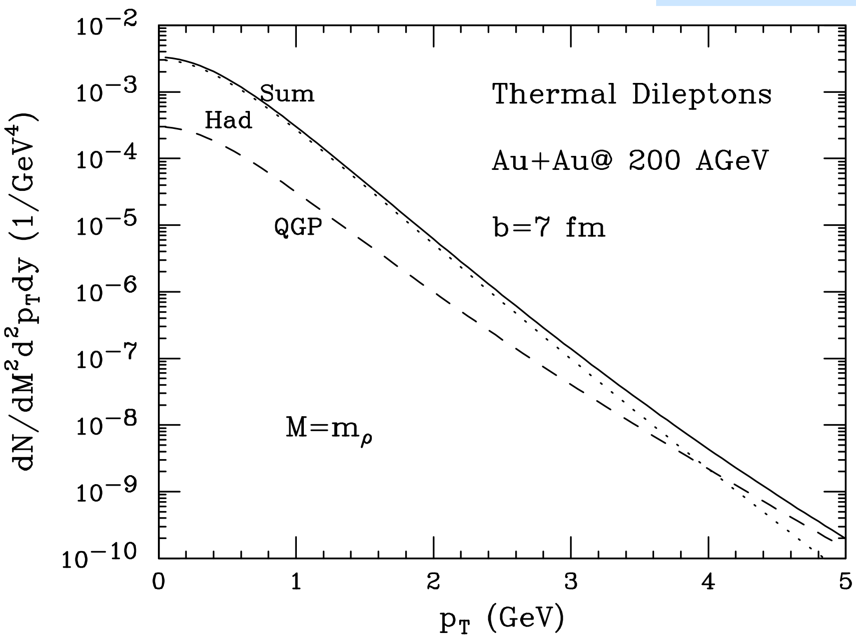
Virtual photons: thermal dileptons with $M = m_\rho$

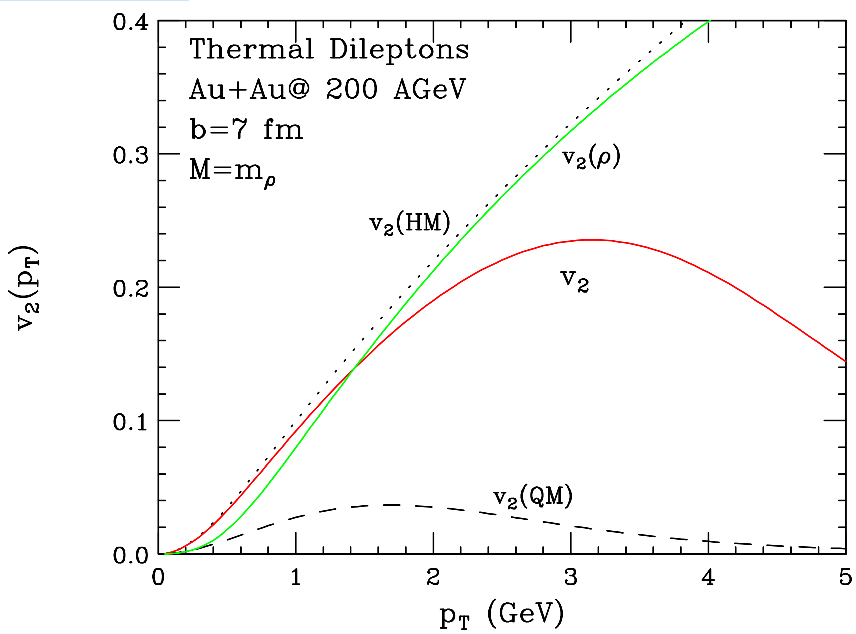
R. Chatterjee, C. Gale, UH, D.K. Srivastava, in preparation

Dilepton mass $M \equiv M_{\ell\bar{\ell}} = M_{\gamma^*}$ as additional variable:

$$v_2(M, p_T, b) = \frac{\int d\phi \, \cos(2\phi) \, \frac{dN_{\ell\bar{\ell}}}{dM^2\, dY\, p_T dp_T\, d\phi}}{\int d\phi \, \frac{dN_{\ell\bar{\ell}}}{dM^2\, dY\, p_T dp_T\, d\phi}}$$

Dilepton p_T-spectrum: **$M = m_\rho$:** Dilepton elliptic flow:



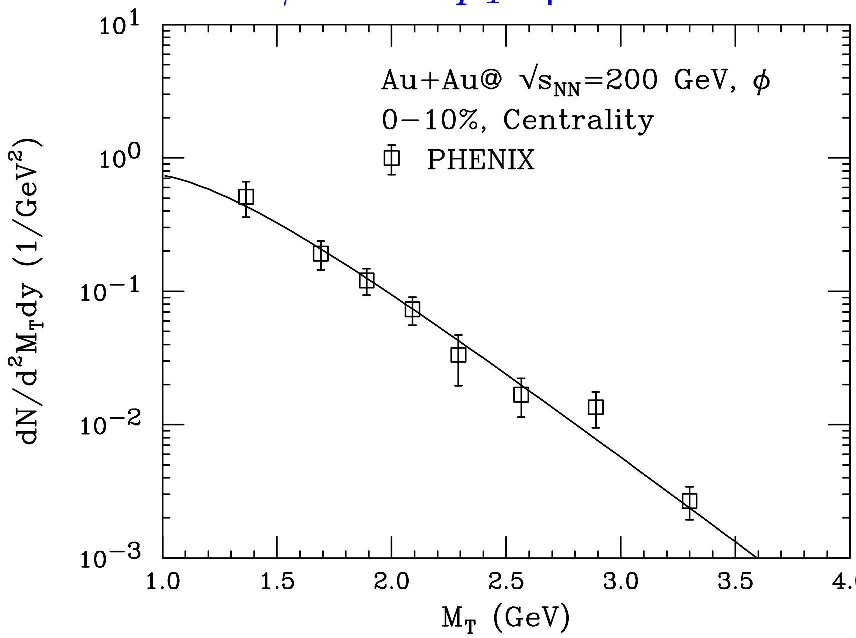


- HG rate dominates over QGP rate up to $p_T \sim 4\,\text{GeV}/c$
- total dilepton v_2 follows hadronic dilepton v_2 up to $p_T \sim 1.5{-}2\,\text{GeV}/c$

ϕ mesons from K^+K^- decays

$$M = m_\phi:$$

ϕ meson p_T-spectrum

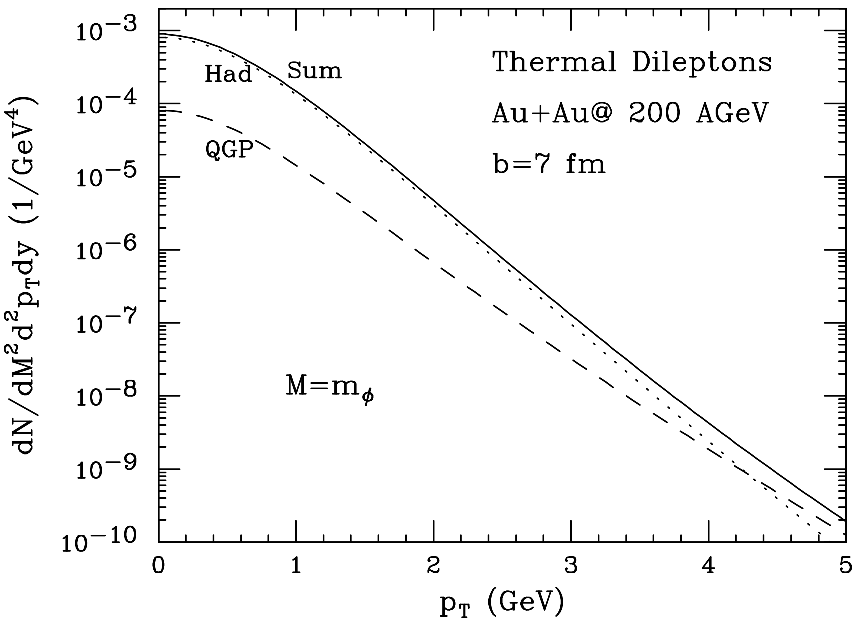


- measured ϕ mesons from K^+K^- decays are well described by hydro model

Thermal dileptons with $M\!=\!m_\phi$

$M = m_\phi$:

Dilepton p_T-spectrum

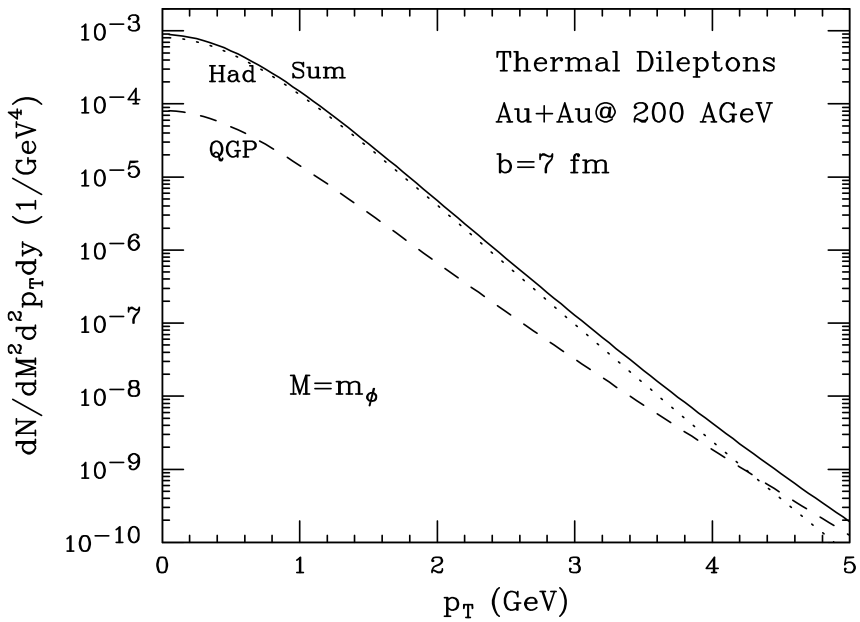


- measured ϕ mesons from K^+K^- decays are well described by hydro model
- HG dilepton rate dominates over QGP dilepton rate up to $p_T \sim 4\,\mathrm{GeV}/c$

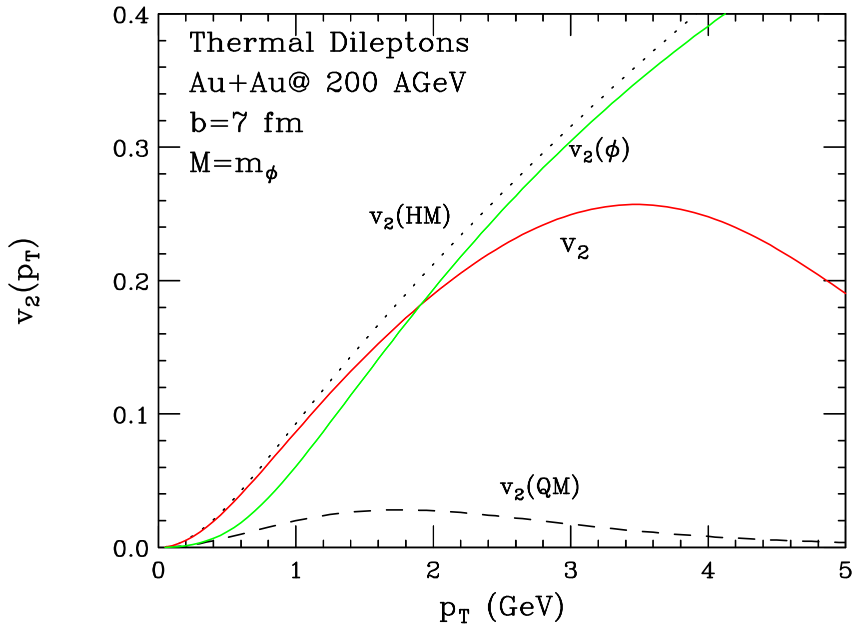
Thermal dileptons with $M = m_\phi$

$M = m_\phi$:

Dilepton p_T-spectrum:



Dilepton elliptic flow:

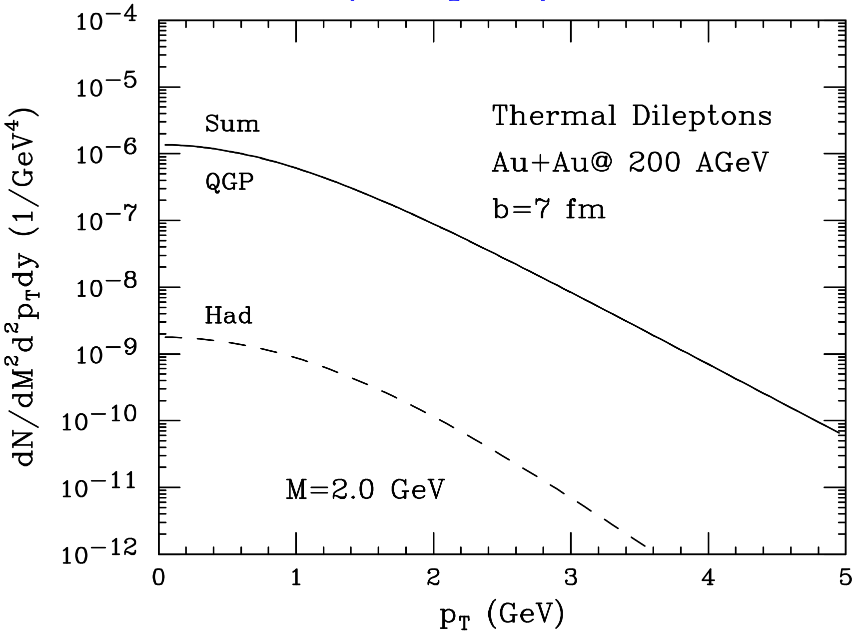


- measured ϕ mesons from K^+K^- decays are well described by hydro model
- HG dilepton rate dominates over QGP dilepton rate up to $p_T \sim 4\,\mathrm{GeV}/c$
- total dilepton v_2 follows hadronic dilepton v_2 up to $p_T \sim 1.5{-}2\,\mathrm{GeV}/c$

Intermediate mass dileptons with $M\!=\!2$ GeV

$M = 2$ GeV:

Dilepton p_T-spectrum

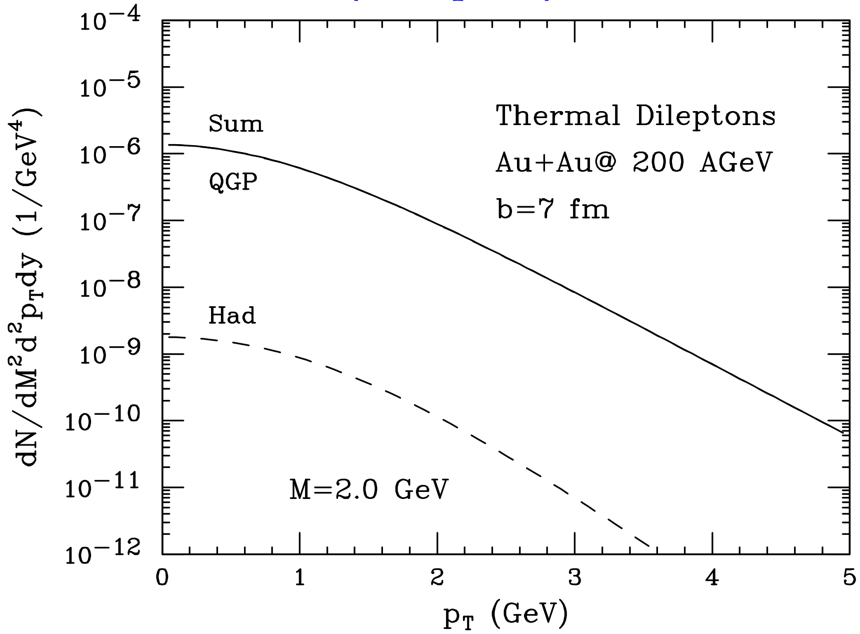


- QGP dilepton rate dominates over HG dilepton rate at all p_T

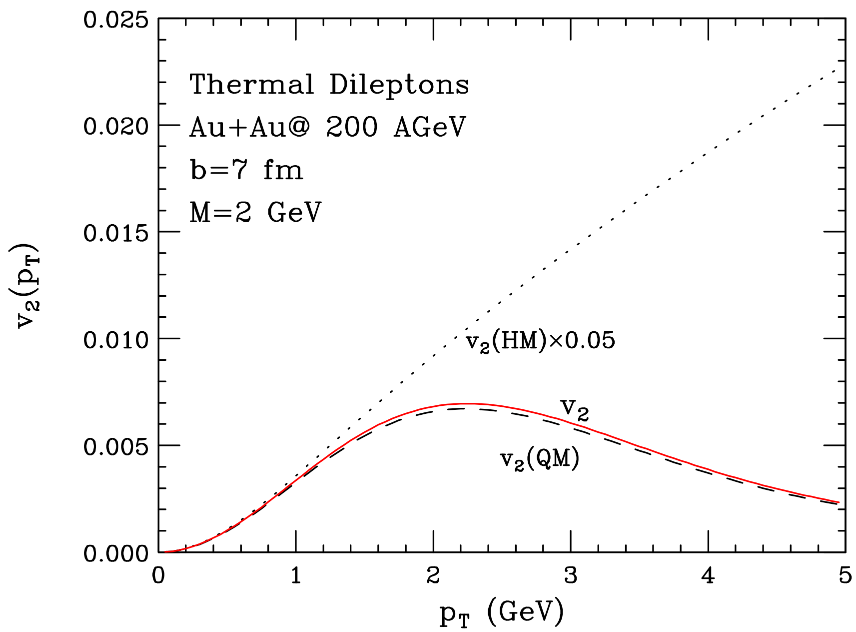
Intermediate mass dileptons with $M = 2$ GeV

$M = 2\,\mathrm{GeV}$:

Dilepton p_T-spectrum



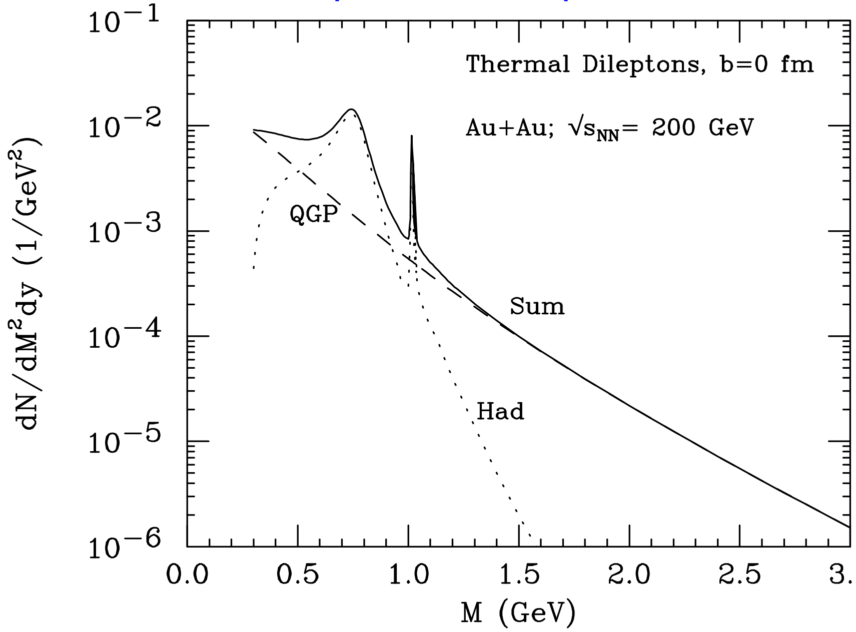
Dilepton elliptic flow



- QGP dilepton rate dominates over HG dilepton rate at all p_T
- total dilepton v_2 is small and follows elliptic flow of QGP dileptons over entire p_T range

Mass dependence of p_T-integrated dileptons

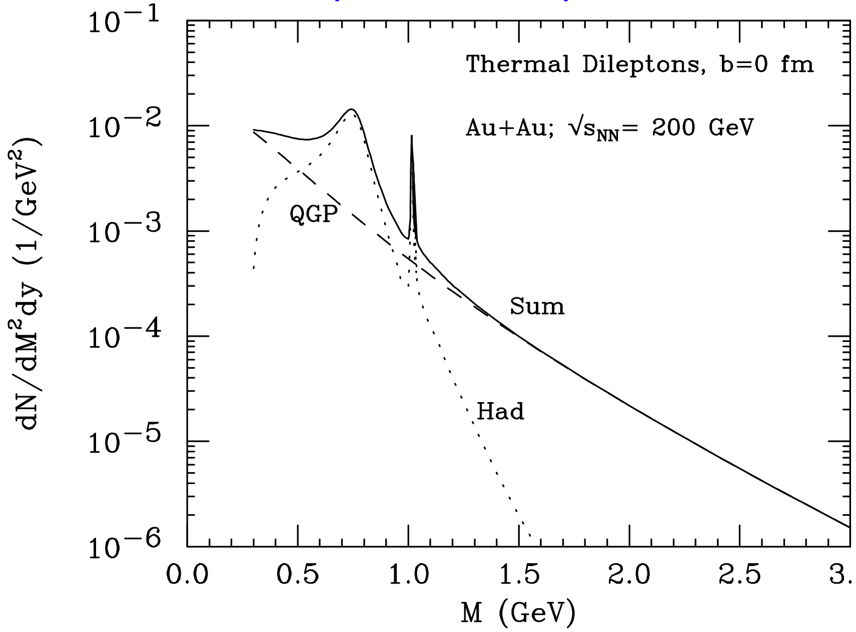
Dilepton mass spectrum



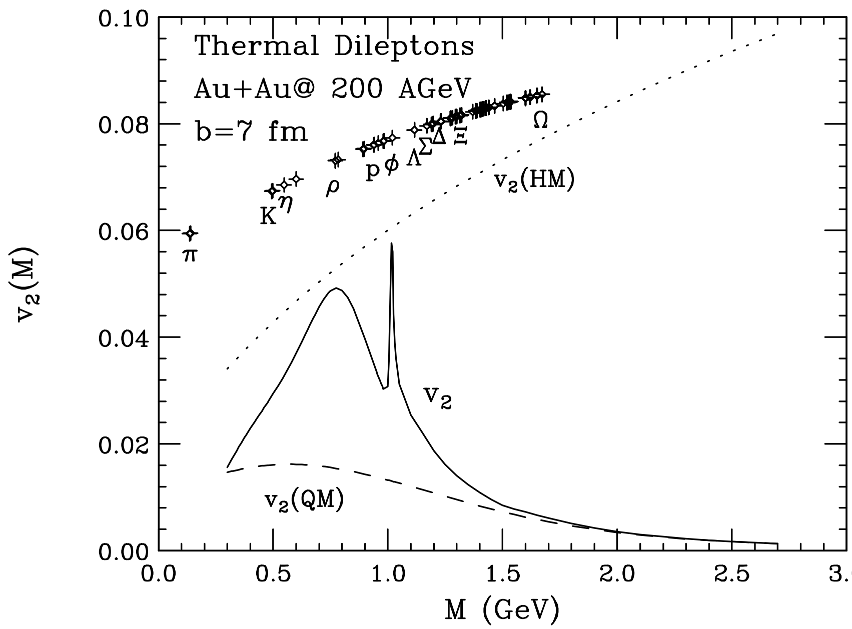
- strong variation of relative QGP/HG contributions as function of dilepton mass M

Mass dependence of p_T-integrated dileptons

Dilepton mass spectrum



Dilepton elliptic flow

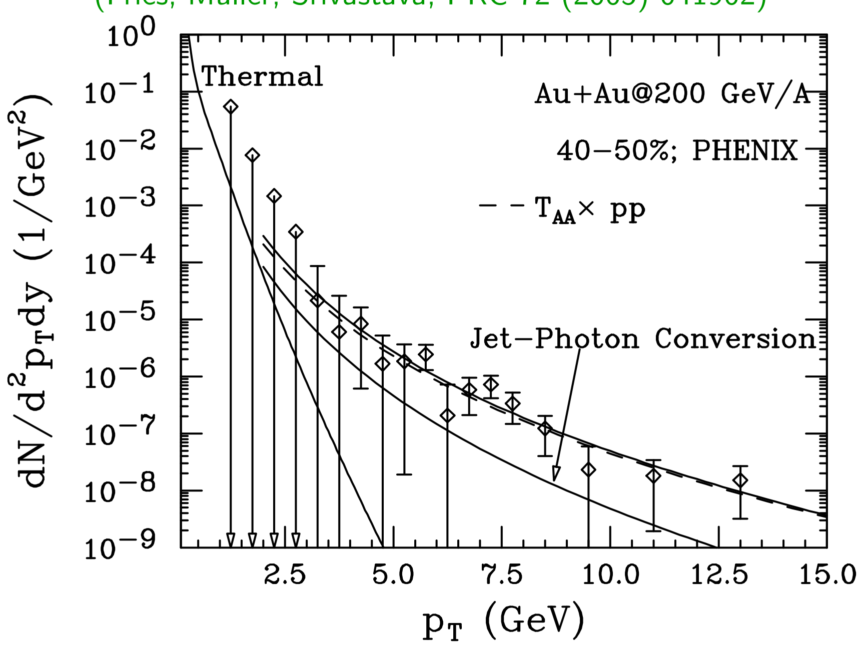


- strong variation of relative QGP/HG contributions as function of dilepton mass M
- near ρ, ϕ resonances, dilepton v_2 approaches hadronic v_2
- for dilepton mass > 1.5 GeV, QGP contribution dominates and dilepton v_2 tracks quark elliptic flow

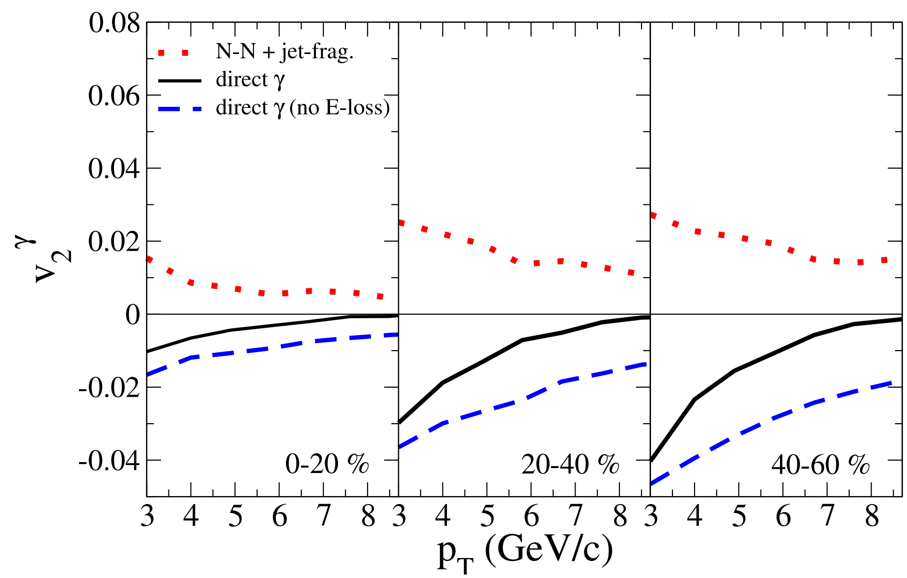
The next steps:

- implement chemical freeze-out at $T_c = 170\,\text{MeV}$ via non-equilibrium chemical potentials in HG EOS and hadronic γ emission rates
- compute photons from post-freeze-out resonance decays in order to construct "hydro model cocktail" for background subtraction
- include prompt and pre-equilibrium photons from $\tau < \tau_0$
  – e.g. jet conversion photons, predicted to cause negative photon v_2 at high p_T

photon spectrum with jet ⟶ photon conversion
(Fries, Müller, Srivastava, PRC 72 (2005) 041902)



photon v_2 for direct and jet conversion photons
(Turbide, Gale, Fries, PRL 96 (2006) 032303)



Conclusions

- Different from hadrons, elliptic flow of thermal photons and dileptons tends to zero at large p_T and $M_{\ell\bar{\ell}}$

  $\Longrightarrow$ reflects QGP emission and weak transverse flow at early times

- $v_2^\gamma(p_T)$ and $v_2^{\ell\bar{\ell}}(M)$ exhibit rich structures which reflect interplay of different emission processes

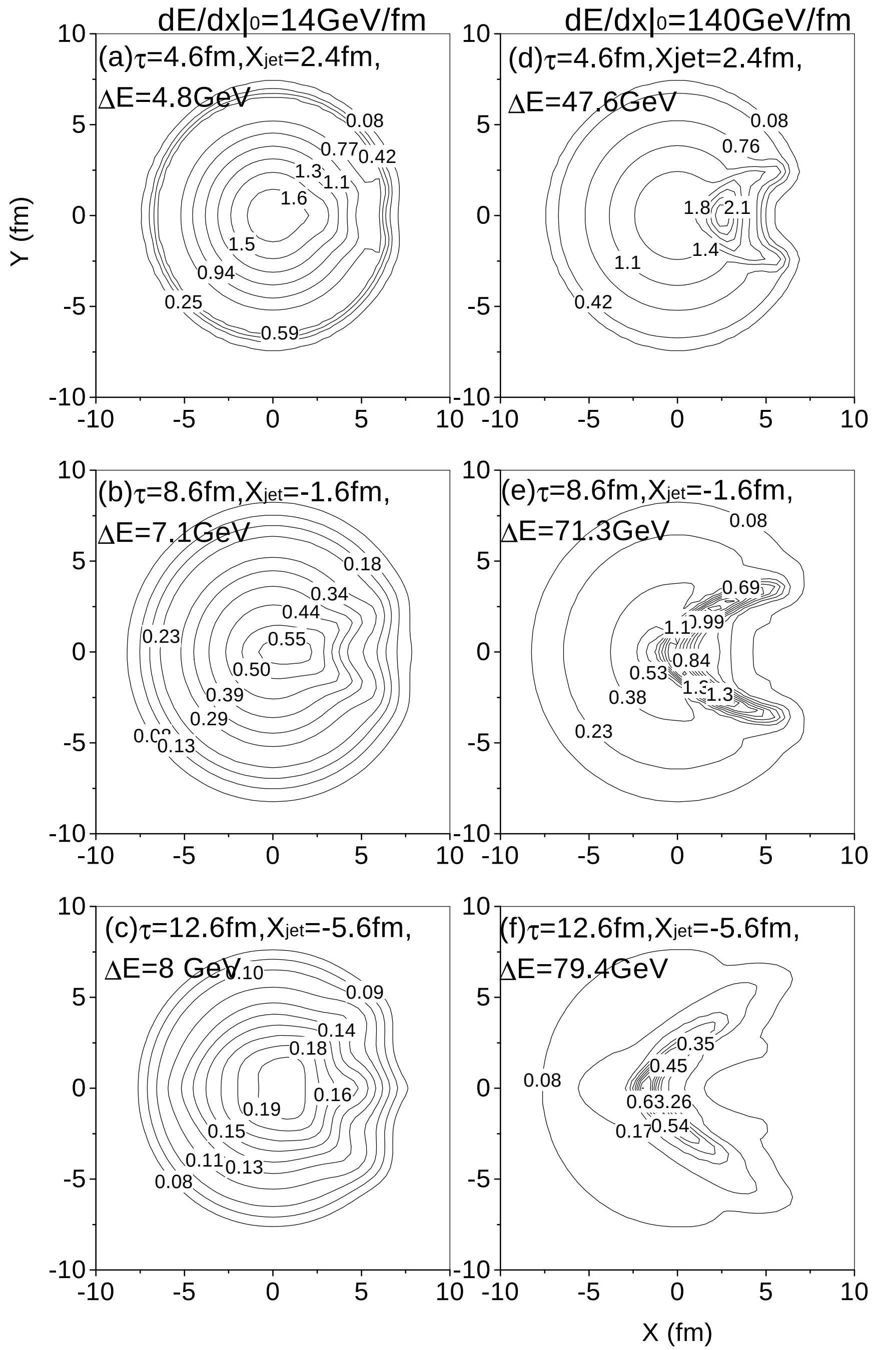
  $\Longrightarrow$ detailed and differential information on different expansion stages

- Elliptic flow of hadronic photons tracks v_2 of hadrons

  $\Longrightarrow$ possibility to subtract hadronic photon contribution to isolate v_2 of QGP photons (?)

And now for something completely different. . .

Hydrodynamic Mach cones from quenching jets. . .



Left: $\frac{dE}{dx}\Big|_0 = 14\,\text{GeV/fm}$

Right: $\frac{dE}{dx}\Big|_0 = 140\,\text{GeV/fm}$

- Energy density contours exhibit Mach cone feature, but Mach shock hardly visible for standard value of $dE/dx|_0$

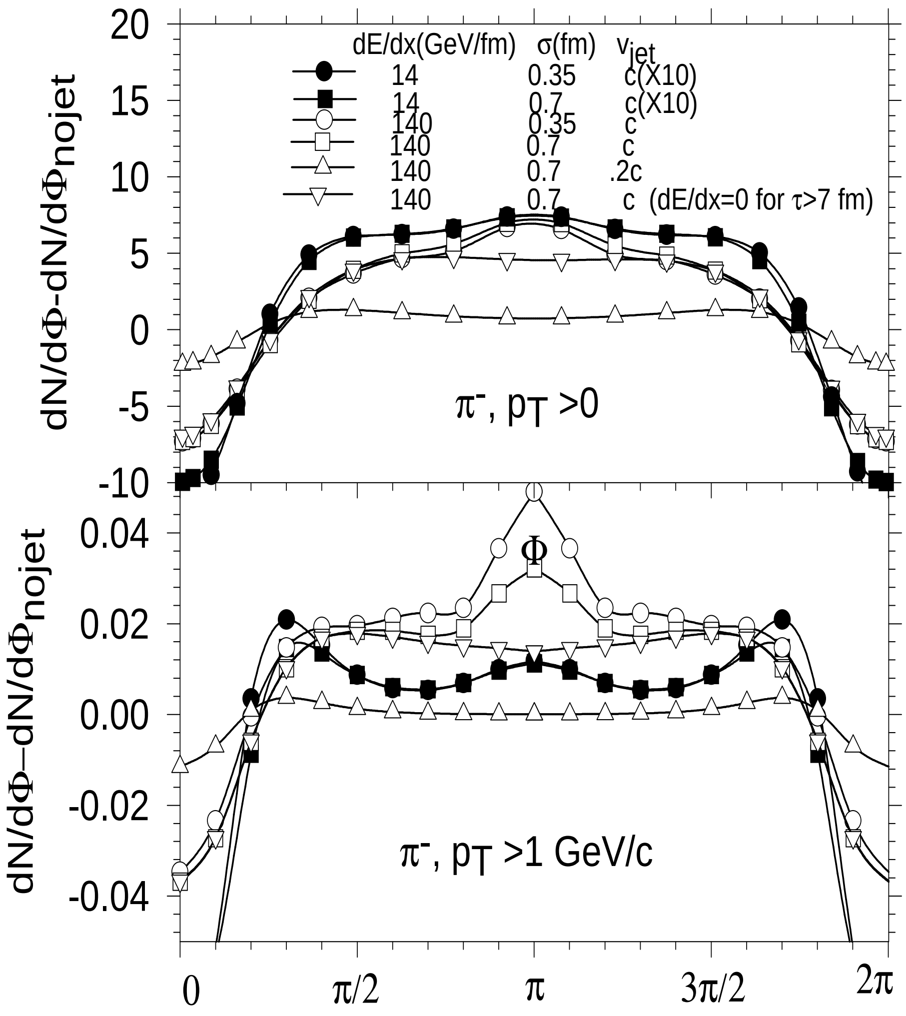
- $10\times$ larger energy loss produces clearly visible Mach shock

- Mach cone angle not sharply defined, due to inhomogeneous density profile and radial flow, but roughly in agreement with expectations

- Cone angle gets better defined for smaller σ

. . . but no Mach peaks in angular correlation function!

Pions, $T_{\mathrm{dec}} = 100\,\mathrm{MeV}$



- No peaks at the predicted Mach angle, no dip at $\phi = \pi$!
- Peak at $\phi = \pi$ reflects momentum imparted by fast parton on medium (absent if parton gets "lost")
- Broad shoulder in $dN/d\phi$ extends into right hemisphere; exists also for subsonic parton speed
- For $p_T > 1\,\mathrm{GeV}/c$, shoulder edges turn into small peaks (sharper for smaller σ)

$\Longrightarrow$ **Backsplash!**

Existence of Mach cones does not automatically imply Mach peaks in angular distribution

$\Longrightarrow$ **explicit computation of $dN/d\phi$ required!**