# Thermal Photons at RHIC and LHC

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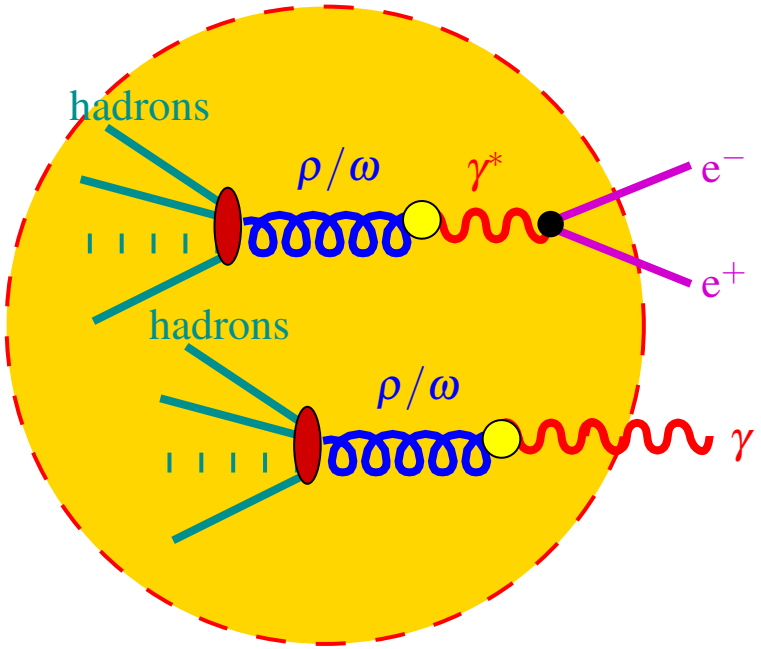
# Outline

# Why Electromagnetic Probes?

- $\gamma, \ell^{\pm}$: only electromagnetic interactions
- $\Rightarrow$ negligible final-state interactions
- shines during whole matter evolution
- probes from hot/dense inner region



# Photon and dilepton rates from a thermal medium

- photon and $\ell^+\ell^-$ rates from same em. current-correlation function
- medium modification of vector-meson spectral functions

$$\Pi^{<}_{\mu\nu}(q) = \int \mathrm{d}^4x \exp(\mathrm{i}q\cdot x)\left\langle J_\mu(0)J_\nu(x)\right\rangle_T = -2n_B(q_0)\,\mathrm{Im}\,\Pi^{(\mathrm{ret})}_{\mu\nu}(q)$$

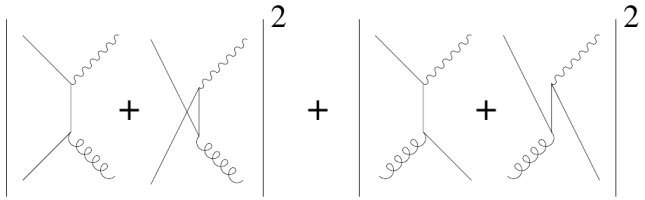
$$q_0\frac{\mathrm{d}N_\gamma}{\mathrm{d}^4x\mathrm{d}^3\vec{q}} = -\frac{\alpha_{\mathrm{em}}}{2\pi^2}g^{\mu\nu}\,\mathrm{Im}\,\Pi^{(\mathrm{ret})}_{\mu\nu}(q,u)\Big|_{q_0=|\vec{q}|} f_B(p\cdot u)$$

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

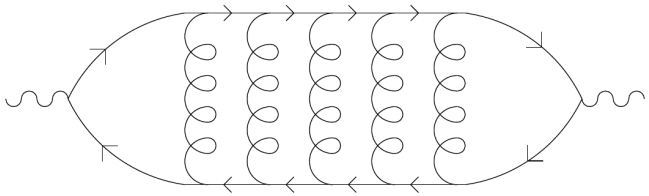
- it's not Planck radiation but carries information about source: partonic/hadronic em. current correlator!
- photon-$q_T$ spectra: blue shift from flow, $u$, of source
- radial flow $\Rightarrow$ effective slopes, $T_{\mathrm{eff}}$ larger than $T$
- anisotropic flow $\Rightarrow$ $v_2$ of photons

# Sources of thermal photons in heavy-ion collisions

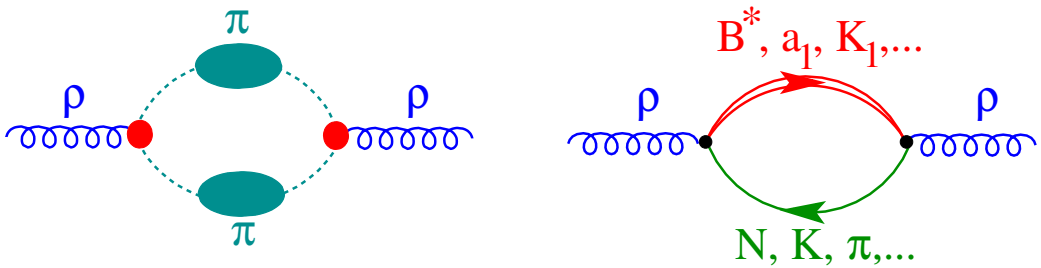
- QGP: rates from [Arnold, Moore, Yaffe, JHEP 12, 009 (2001)]
  - $q\bar{q} \to \gamma g, qg \to \gamma q$



  - 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



# Fireball parameterization

- thermal elliptic fireball
- 1st-order equation of state
- isentropic expansion $\Rightarrow T, \mu_B, \mu_\pi, \mu_K$
- elliptic cylinder; boundary in transverse plane ellipse
- long and short axes move as relativistic particle under constant acceleration:

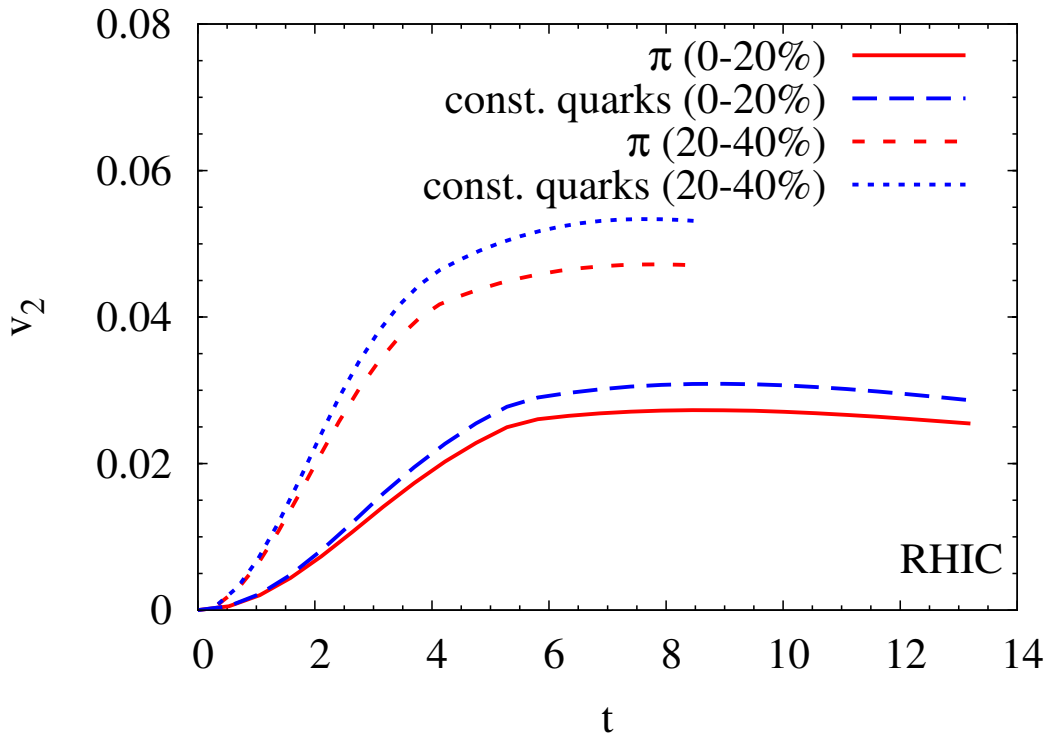
$$v_a(t) = \frac{a_a t}{\sqrt{1+(a_a t)^2}}, \quad v_b(t) = \frac{a_b t}{\sqrt{1+(a_b t)^2}},$$

$$a(t) = a_0 + \frac{\sqrt{1+(a_a t)^2}-1}{a_a}, \quad b(t) = b_0 + \frac{\sqrt{1+(a_b t)^2}-1}{a_b}.$$

- for flow-field: confocal elliptic coordinates
- $\vec{x}_\perp = r_0(\sinh u \cos v, y = \cosh u \sin v)$
- $\vec{v}_\perp = r/r_{\rm max}(v_b \cos v, v_a \sin v)$
- early freeze-out of multi-strange hadrons (at $T_c \simeq 180$ MeV)
- different $(a_a, a_b)$ for $t < t_{\rm mix}$ and $t >_{\rm mix}$

# Fireball parameterization

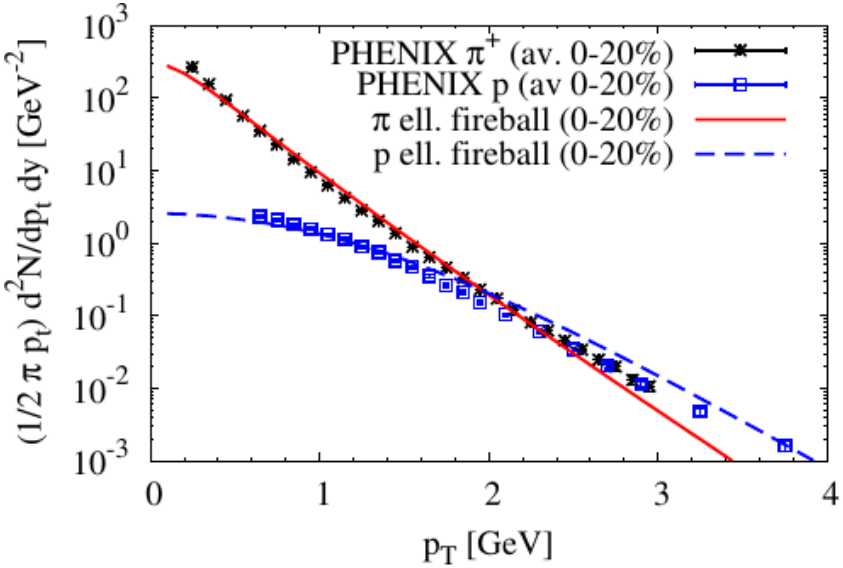
- parameters fit to initial condition + measured $p_T$ spectra and $v_2$ of multi-strange and other hadrons, respectively
- can be achieved with (ideal) hydro [He, Fries, Rapp, PRC **85**, 044911 (2012)]

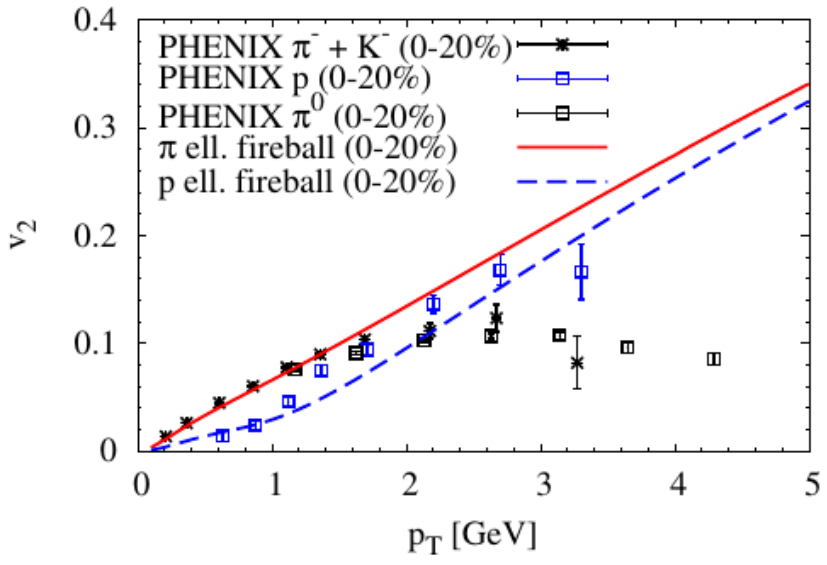


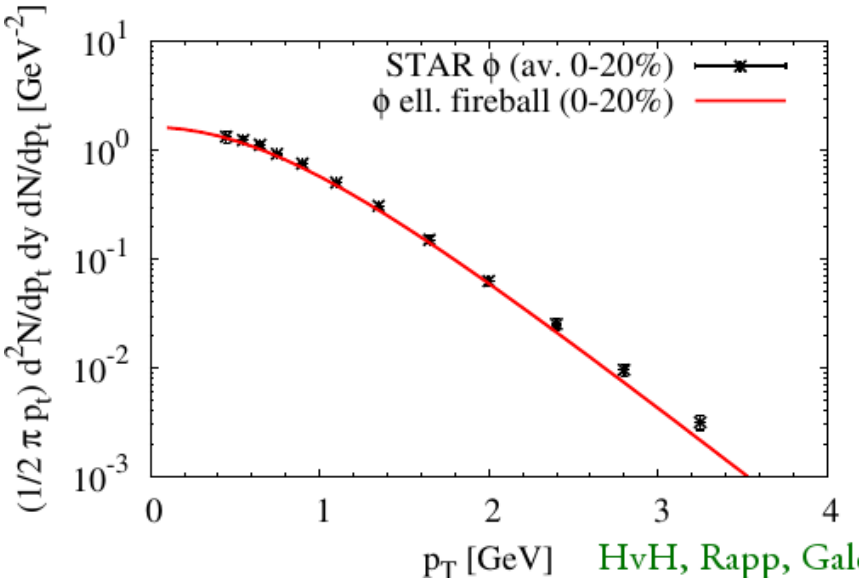

- important for "sufficient" photon $v_2$:
  - rapid buildup of $v_2$
  - (nearly) full $v_2$ at end of mixed phase
  - consistent with CQN scaling for multi-strange and other hadrons!

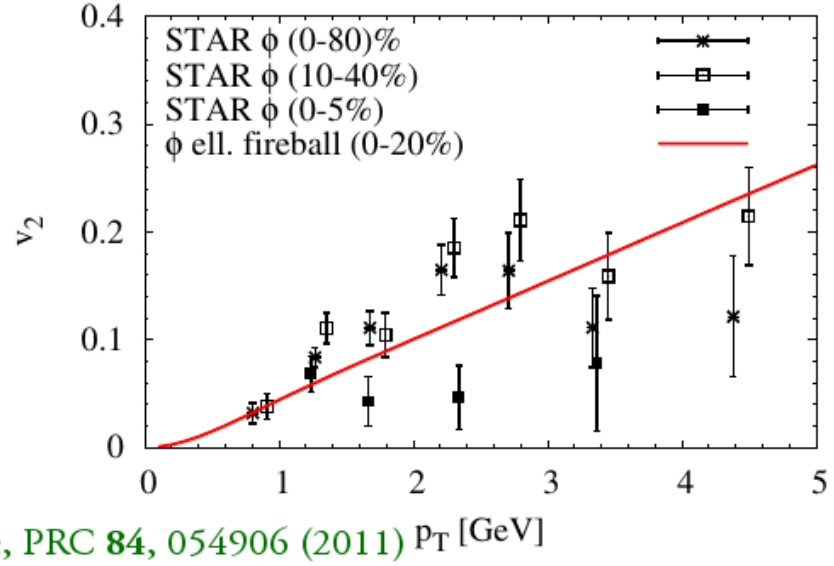
# Fireball parameterization

RHIC:



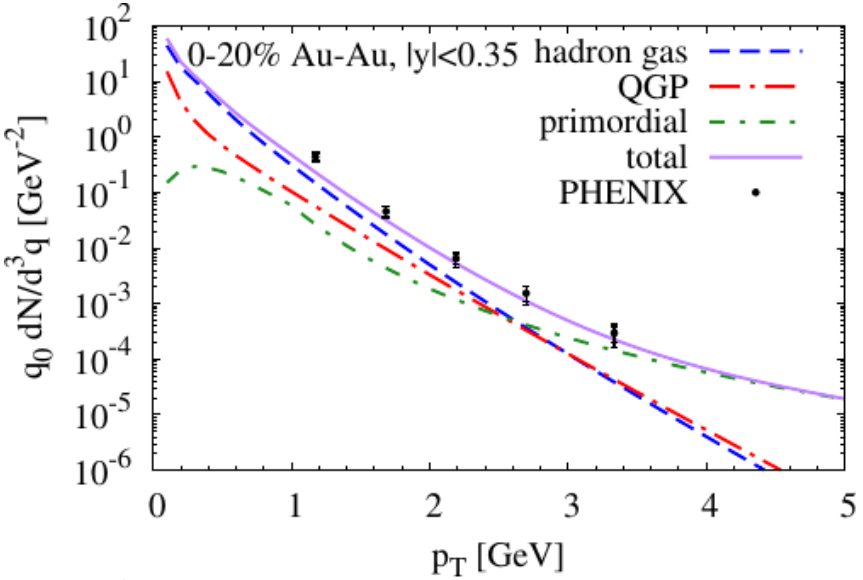



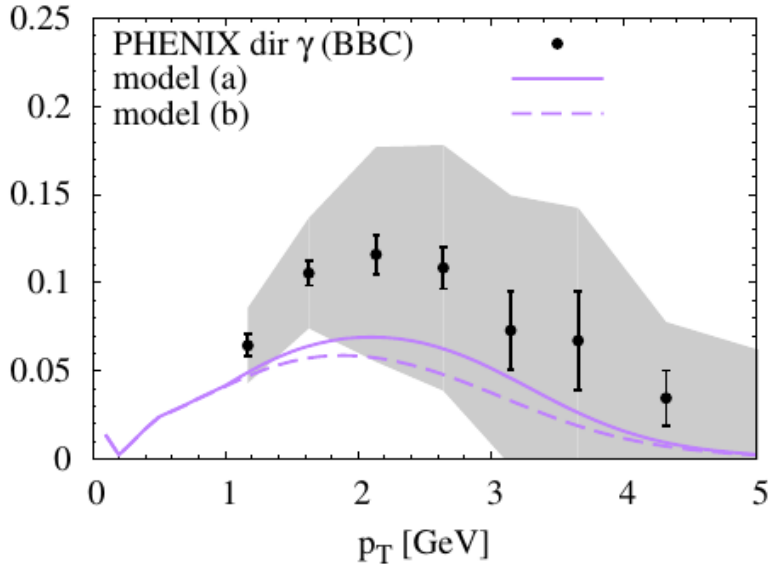



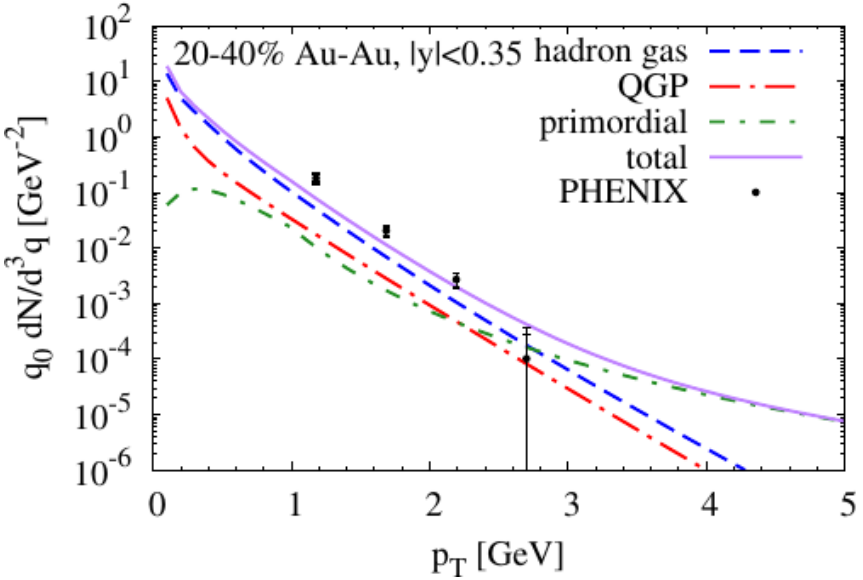

HvH, Rapp, Gale, PRC **84**, 054906 (2011)

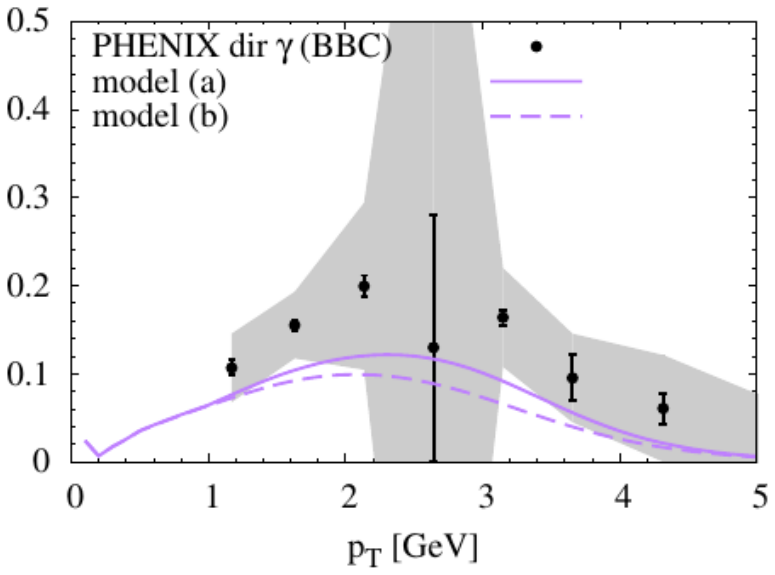
# Direct Photons at RHIC

RHIC:



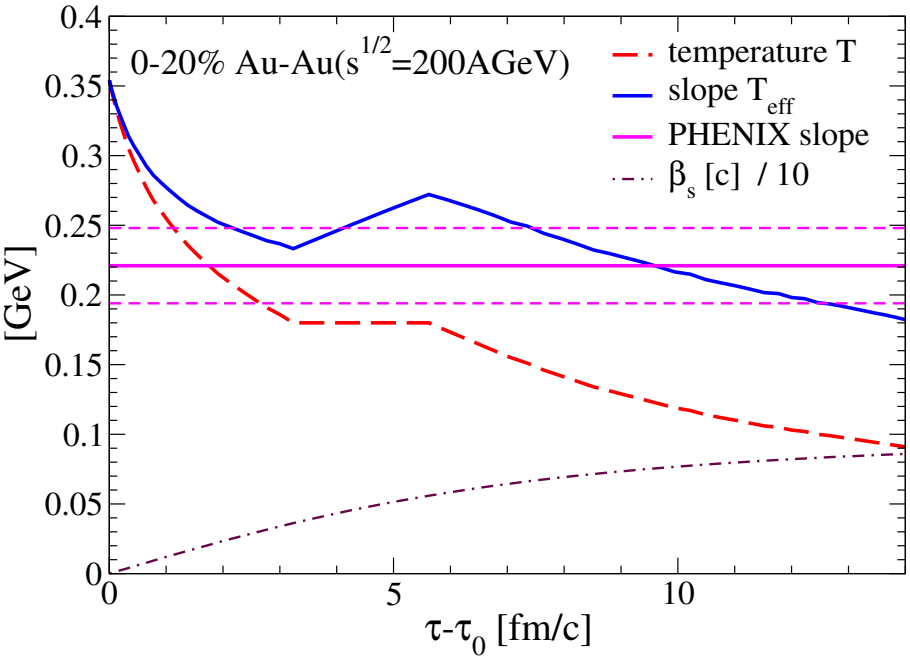



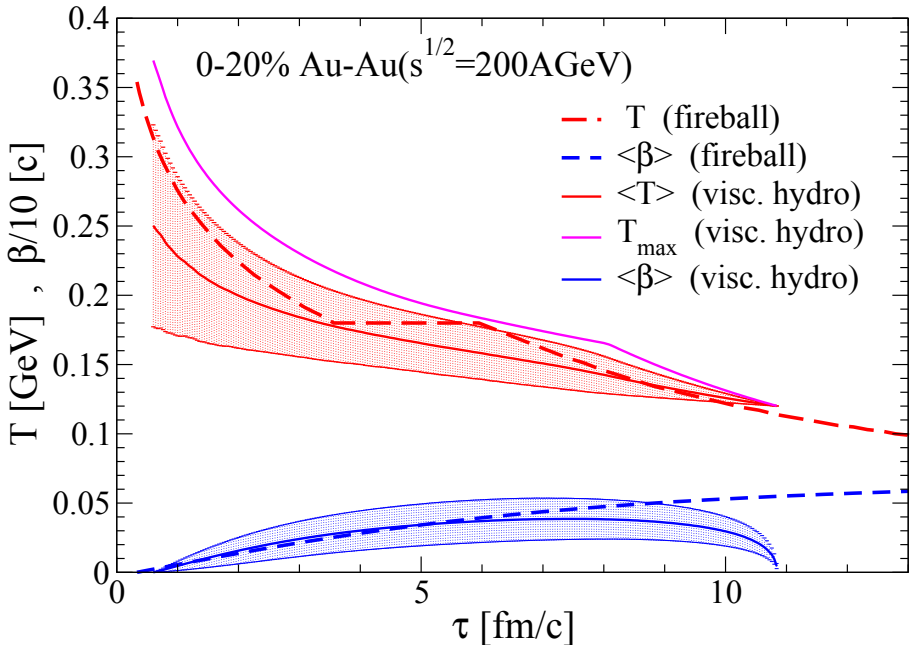




[HvH, Rapp, Gale, PRC **84**, 054906 (2011)]

# Temperature vs. effective Slope




[HvH, Rapp, Gale, PRC **84**, 054906 (2011)]



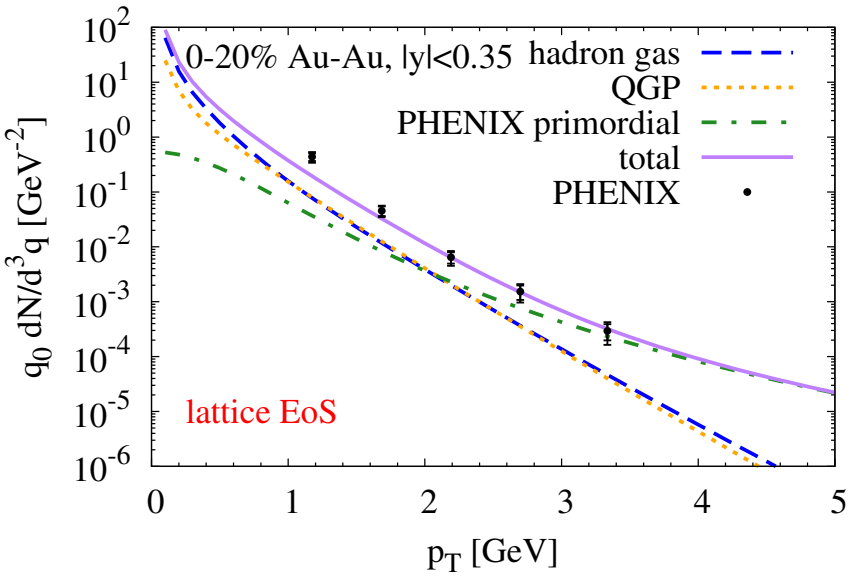

[C. Shen, U. W. Heinz, J.-F. Paquet, C. Gale]
[arXiv:1308.2440 [nucl-th]]

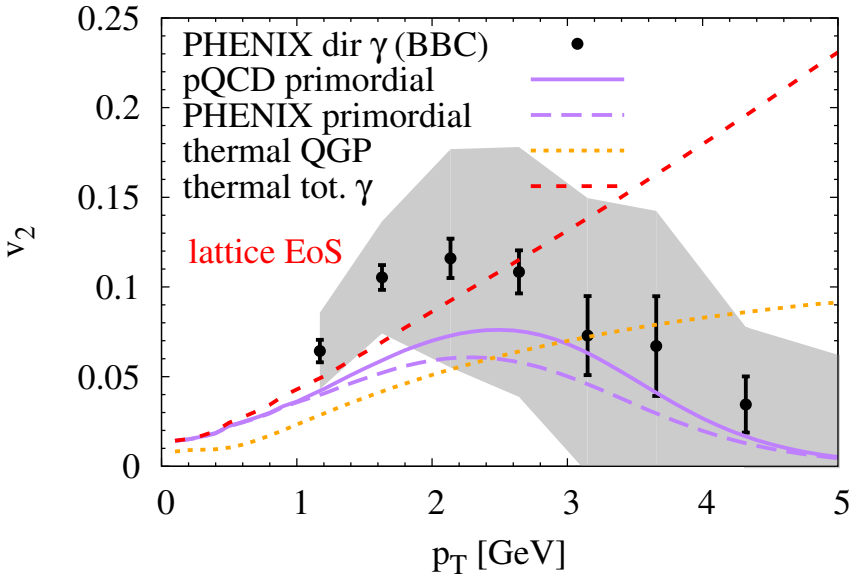
- blue-shift formula (Doppler effect) translates into

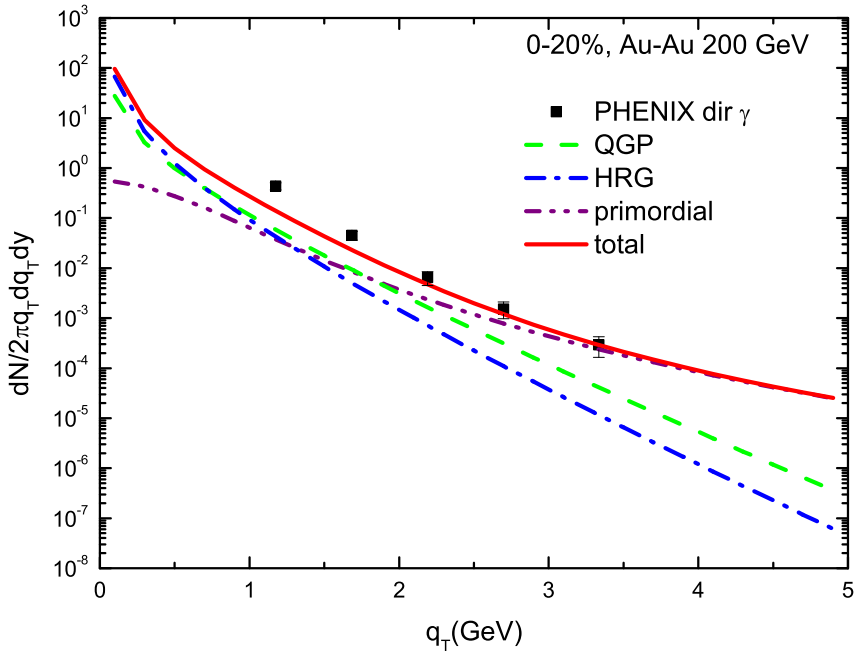
$$T_{\rm eff} \simeq T\sqrt{\frac{1+\langle v_{\rm T}\rangle}{1-\langle v_{\rm T}\rangle}}, \qquad v_{\rm T}: \quad \text{transverse fluid flow}$$

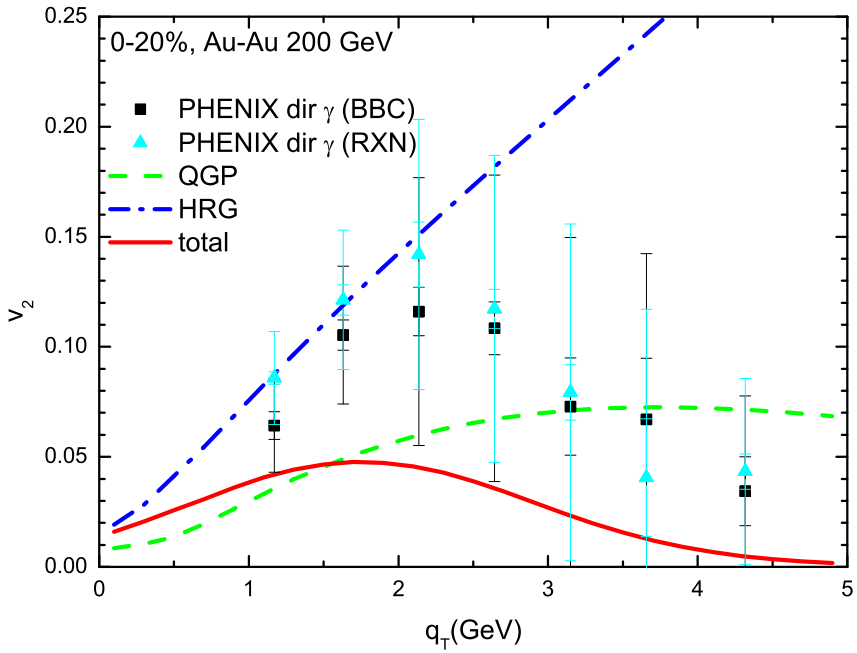
- measured slope indicates emission from source around $T_{\rm c}$

# Direct Photons with cross-over EoS: fireball vs. hydro



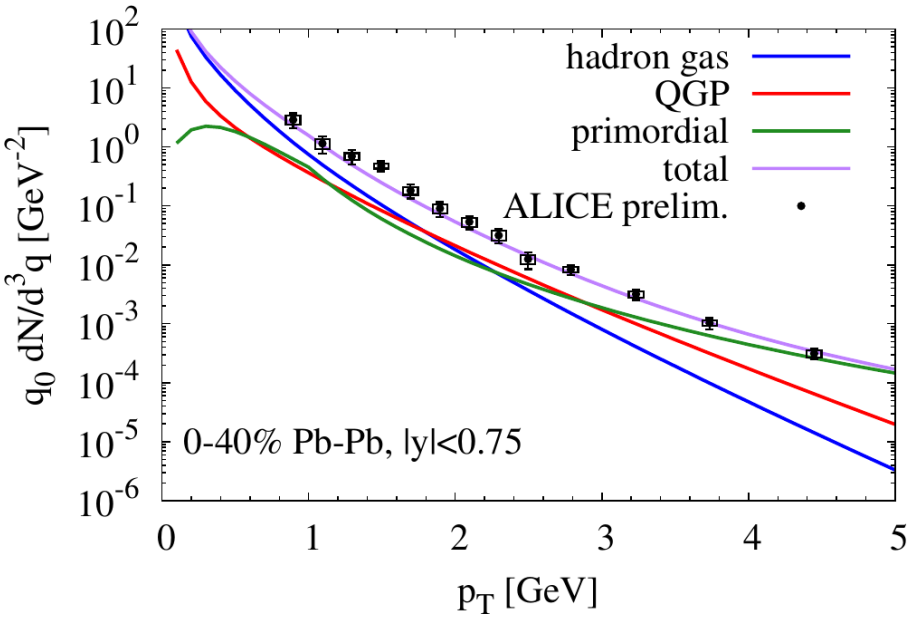



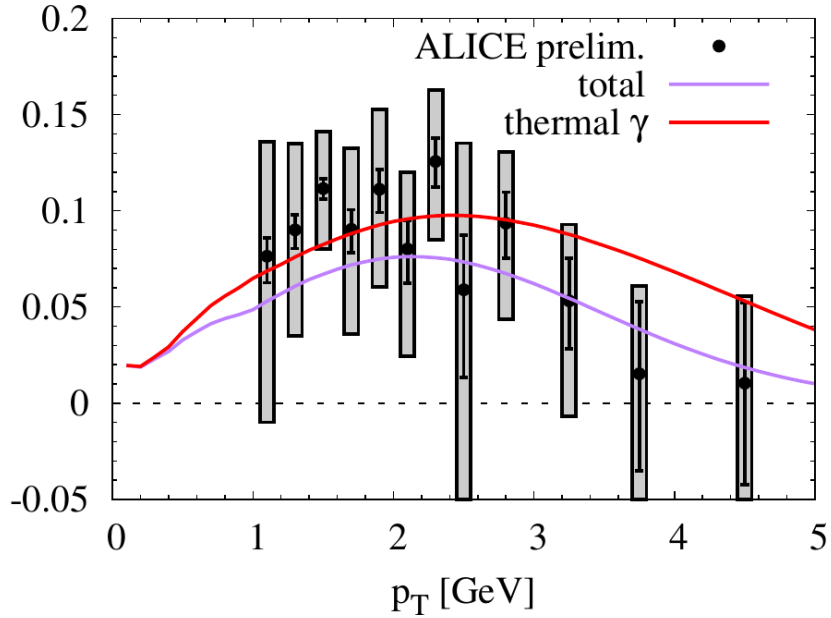



# Direct Photons at the LHC

LHC: same model, fireball adapted to hadron data from ALICE




[HvH, Rapp, Gale, unpublished]

# Conclusions

- explanation for large direct photon $v_2$
- emission from QGP and hadronic matter from hadronic many-body theory
- pretty large photon yield from hadronic thermal sources (RHIC)
- emission from thermal QGP dominates at LHC for $p_T \gtrsim 2$ GeV
  - same model successful for description of dileptons in HICs!

  [HvH, Rapp, NPA **806**, 339 (2008); Rapp, Wambach, HvH, Landolt-Börnstein, Volume **I/23**, 4-1 (2010)]
- large $p_T$ slope: blue shift due to flowing medium
- sequential hadron freeze-out: multistrange hadrons at $T_c$
- $\Rightarrow$ early buildup of $v_2$ of the bulk
- significant em. radiation from hadronic phase of fireball evolution
- outlook to further studies for discussion during the workshop
  - sensitivity to EoS (implementation of "lattice+HG cross-over EoS")
  - details of fireball flow
  - sensitivity to thermal-photon sources (QGP vs. hadrons)
  - comparison of fireball parameterization vs. hydro/transport