Electromagnetic fingerprints of the Little Bang*

Ulrich Heinz
The Ohio State University

Hard Probes 2013

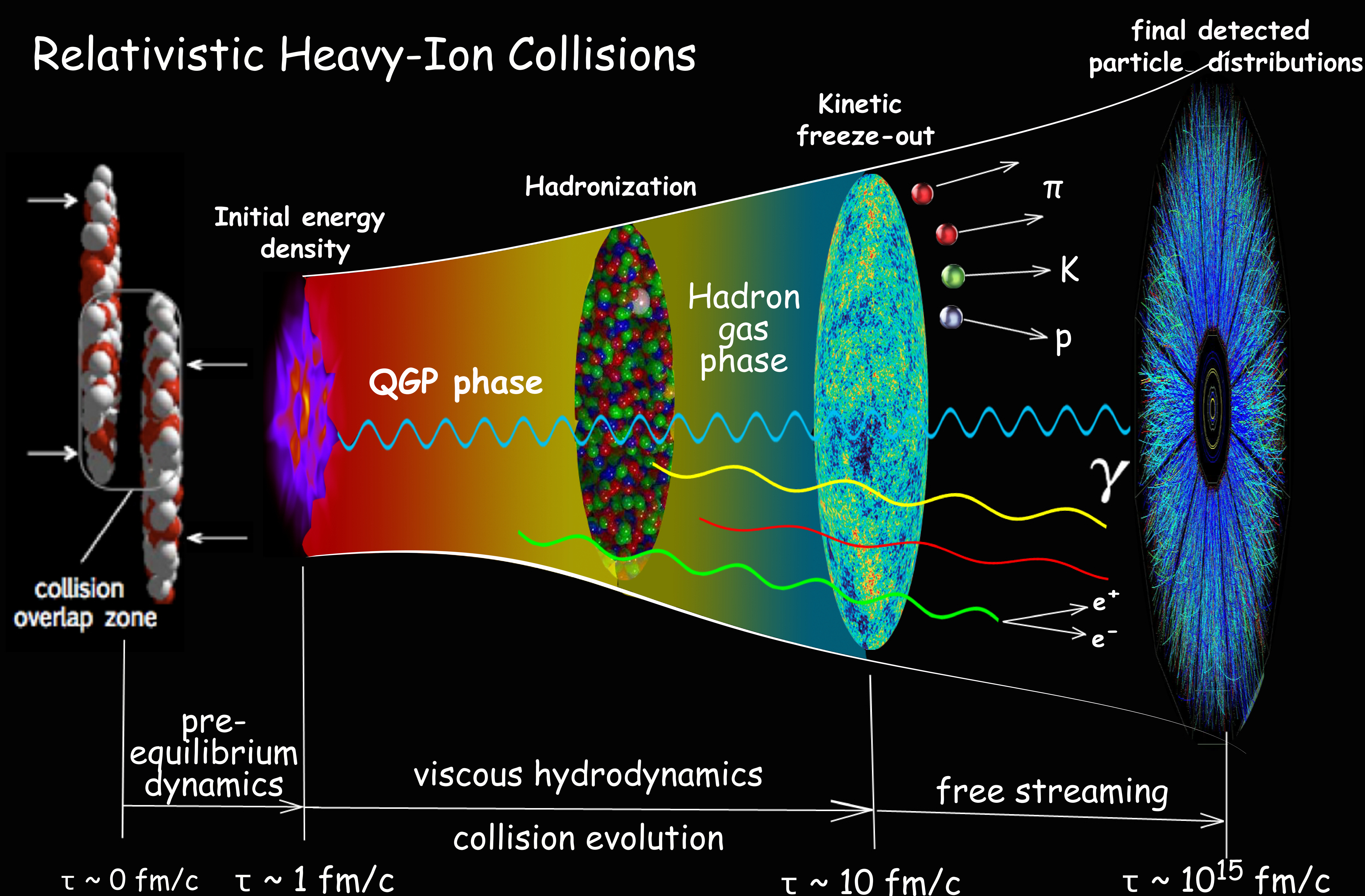
Stellenbosch Institute for Advanced Studies, 3-8 Nov. 2013

JET Collaboration

*Work supported by the US DOE

THE OHIO STATE UNIVERSITY DEPARTMENT OF PHYSICS

The Little Bang



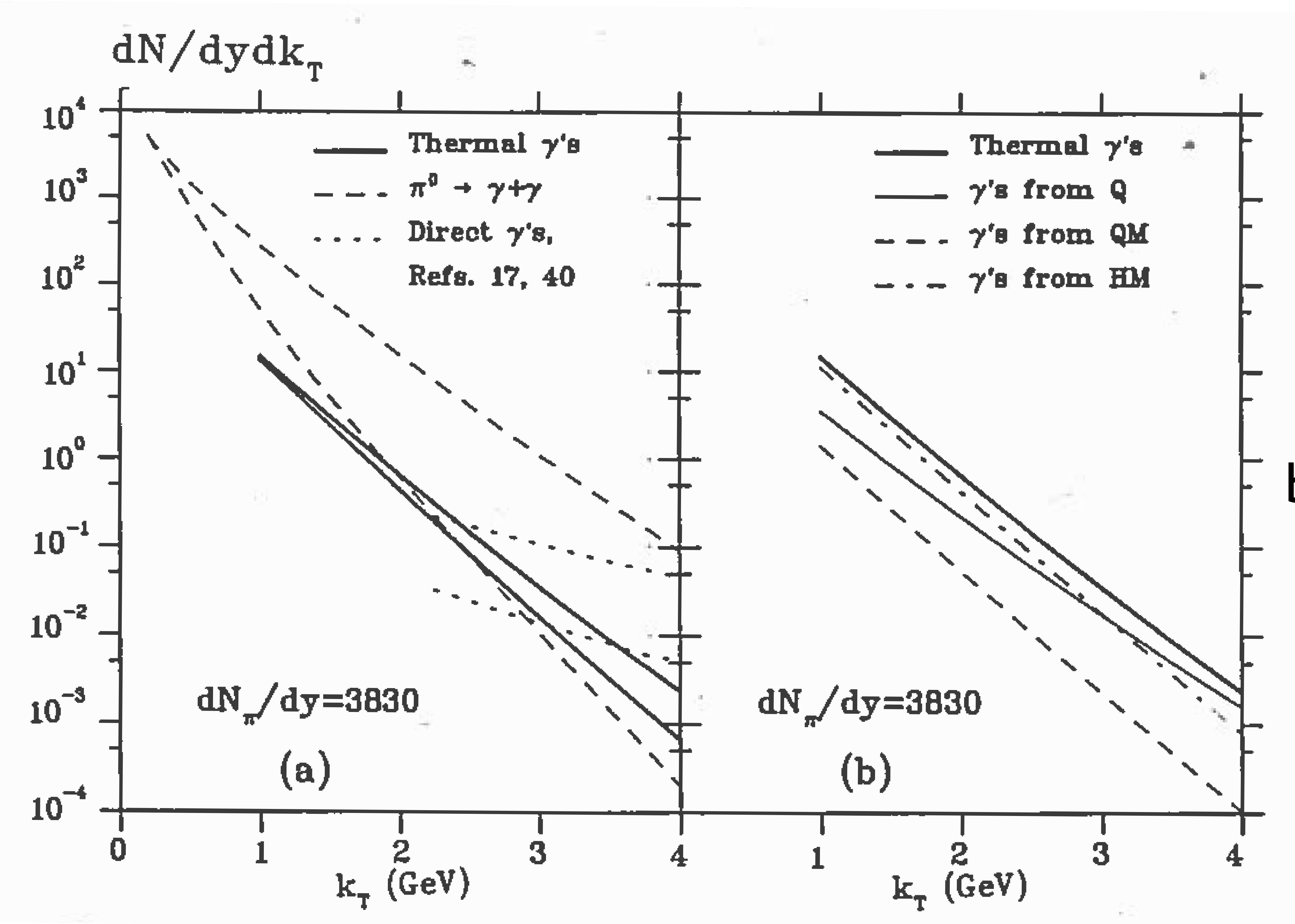
Disclaimer:

Only photons, no dileptons in this talk!

(Thermal) dileptons were/will be discussed by

Antonio Uras Tue 13:50
Gojko Vujanovic Tue 14:30
Mikko Laine Tue 15:10
Joey Butterworth Wed 11:00
Wolfgang Cassing Thu 15:40

It was a long way from first predictions .....

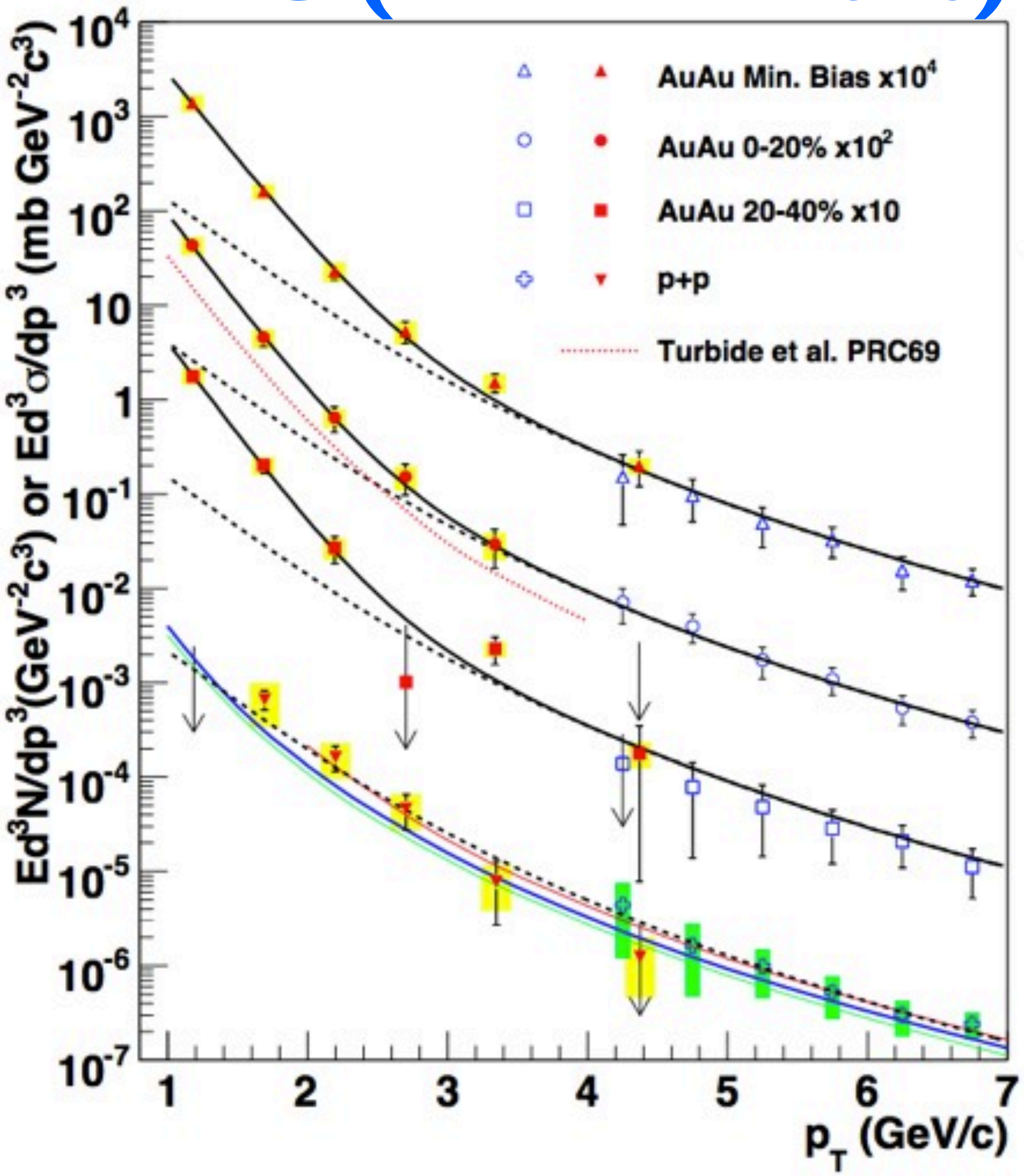


(1+1)-d ideal hydro with bag model EOS

Vesa Ruuskanen, Il Ciocco **1992** (based on work by S. Gupta)

..... to experimental data:

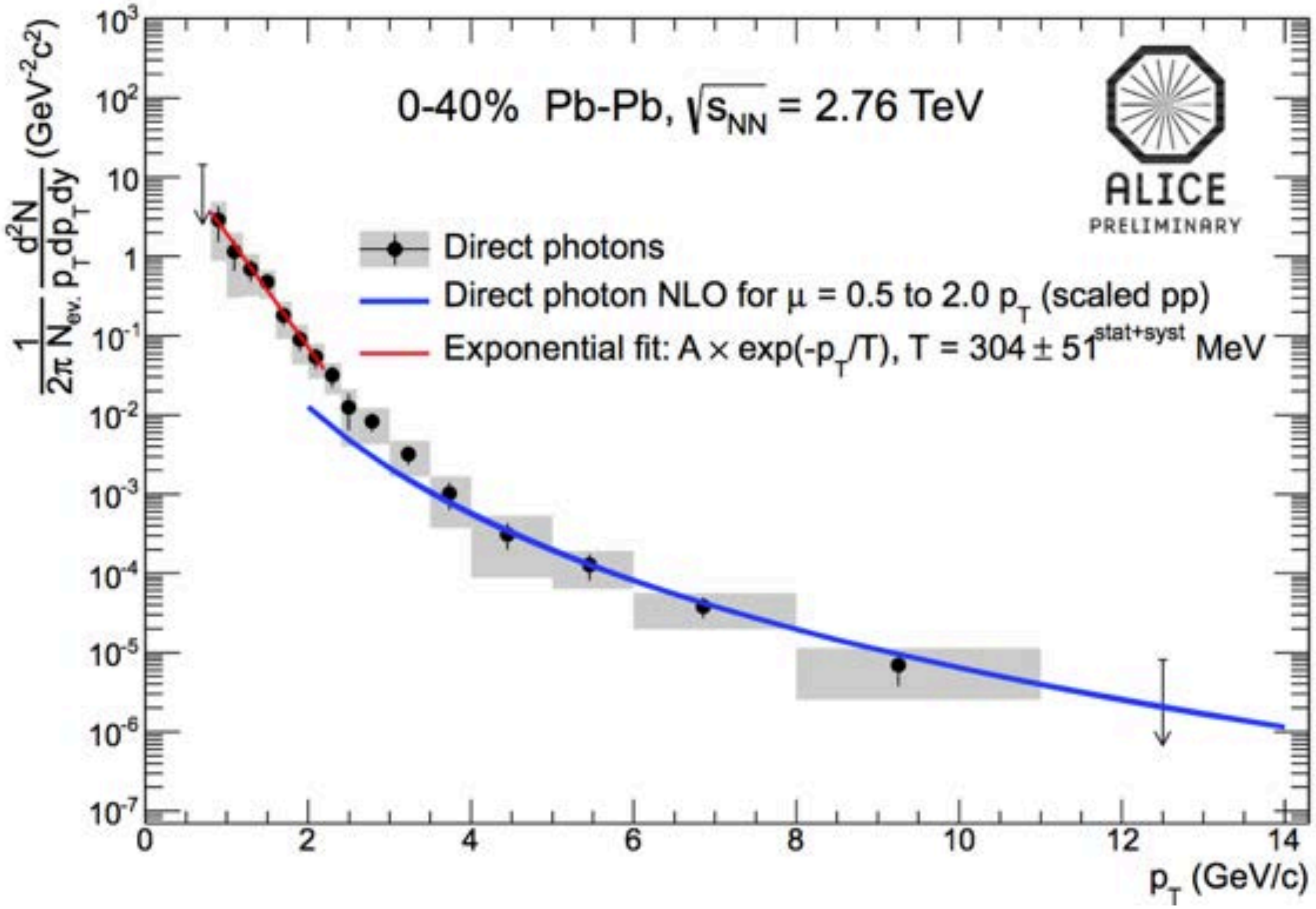
RHIC (PHENIX 2010)



$0-20\%$

$T = 221 \pm 19 \pm 19\,\mathrm{MeV}$

LHC (ALICE 2012)



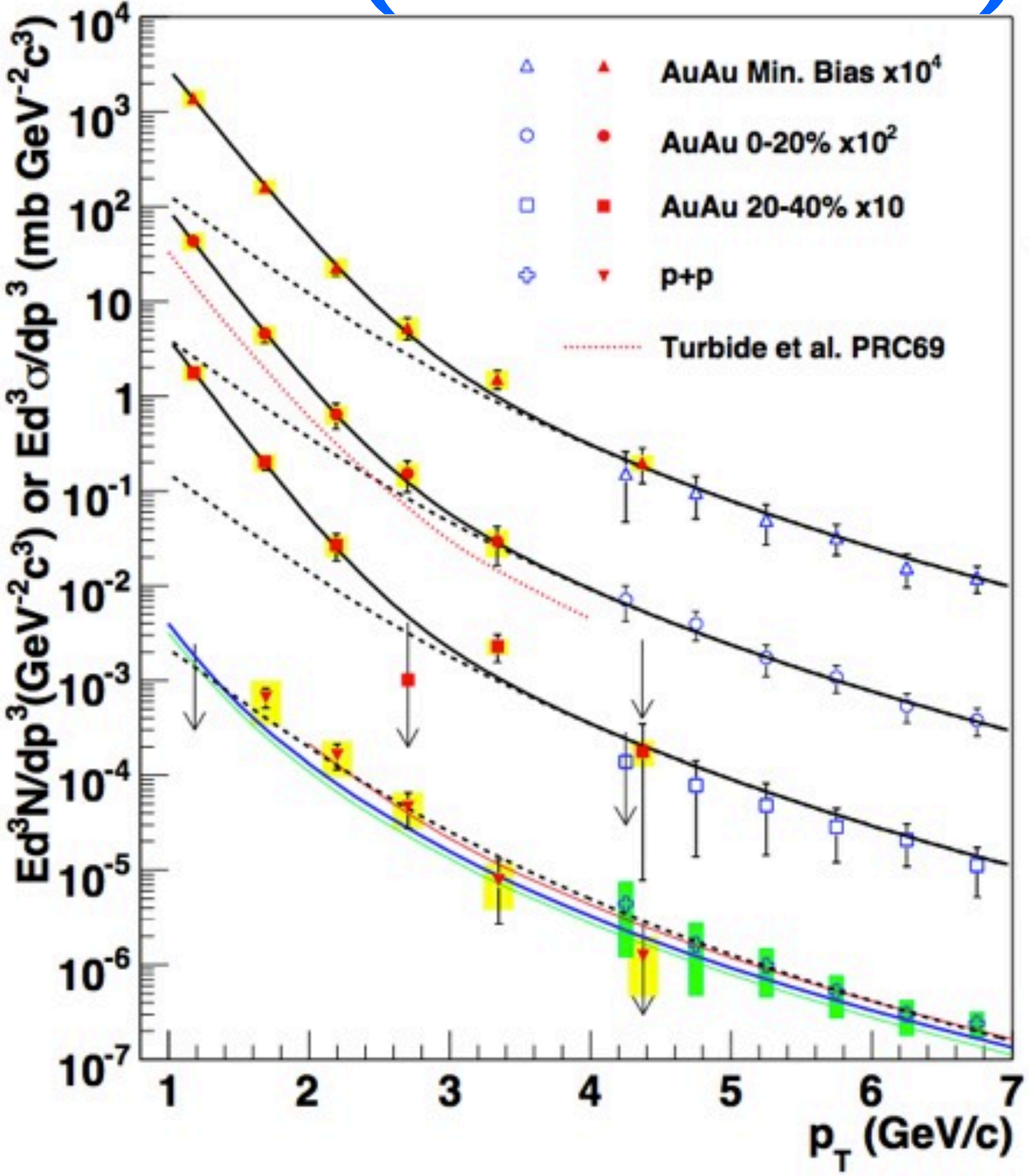
fit: $A\exp(-p_T/T)$

$T = 304 \pm 51^{\mathrm{stat+sys}}\,\mathrm{MeV}$

(see also new PHENIX analysis presented by B. Bannier Tue 13:30)

..... to experimental data:

RHIC (PHENIX 2010)



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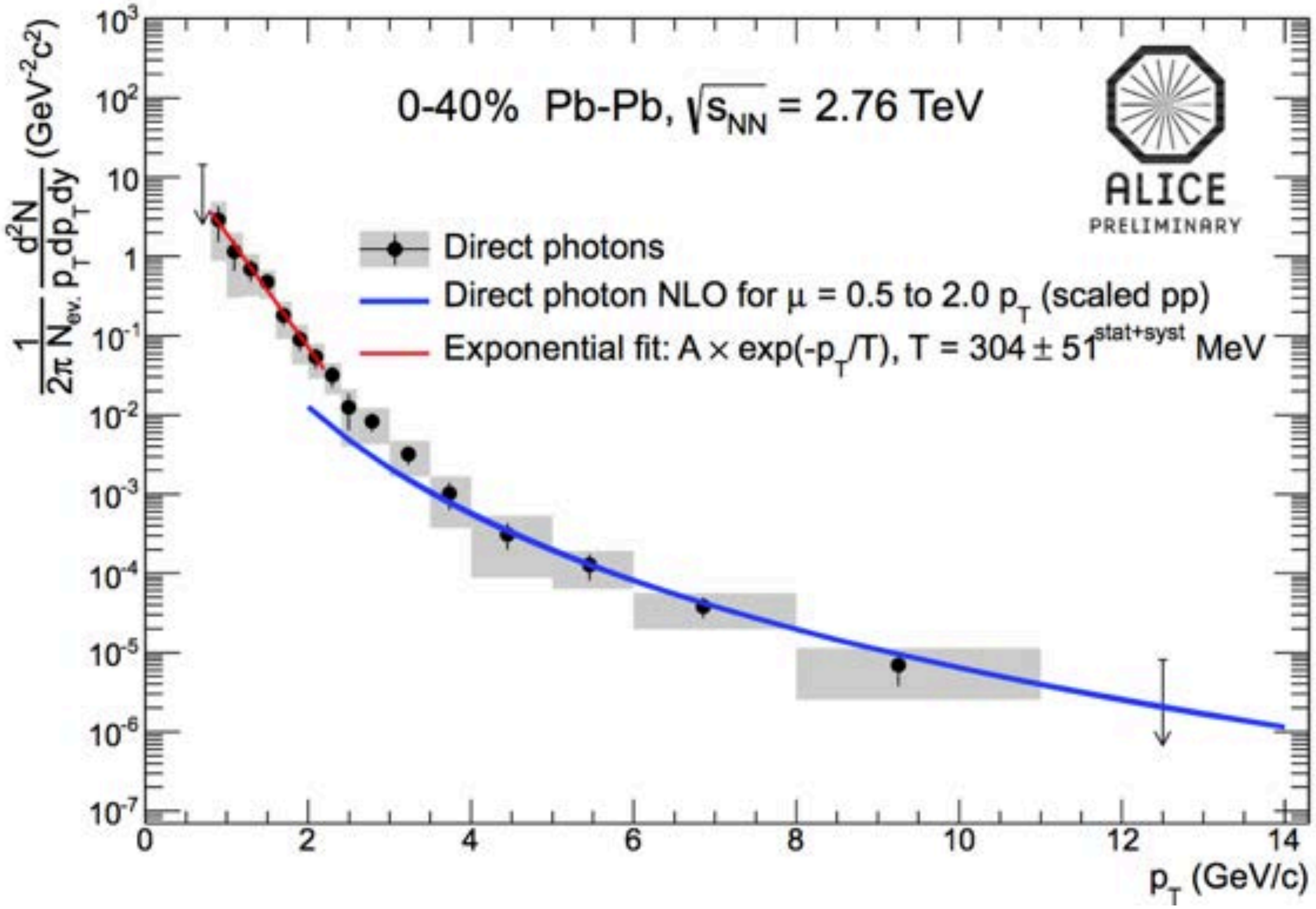
LHC (ALICE 2012)



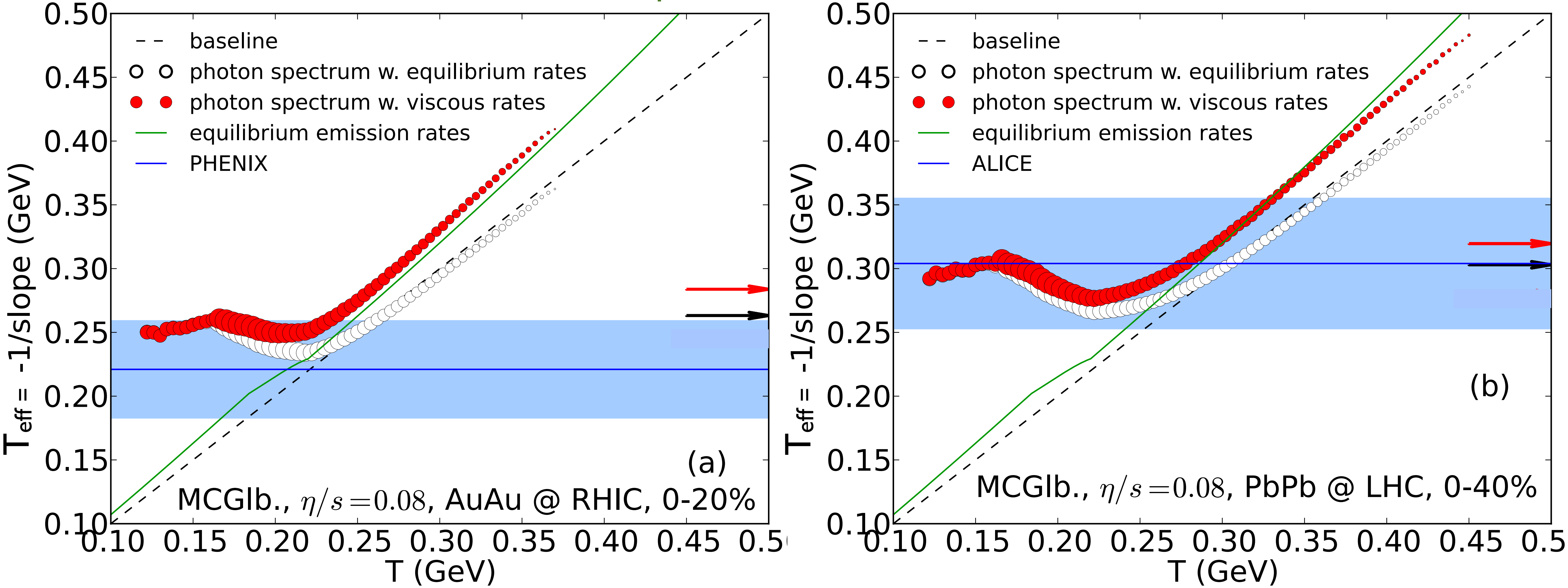
fit: $A\exp(-p_T/T)$

$T = 304 \pm 51^{\mathrm{stat+sys}}\,\mathrm{MeV}$

What does this T mean

Flow-boosted photons: T_{eff} vs. true temperature

Shen, UH, Paquet, Gale, arXiv:1308.2440

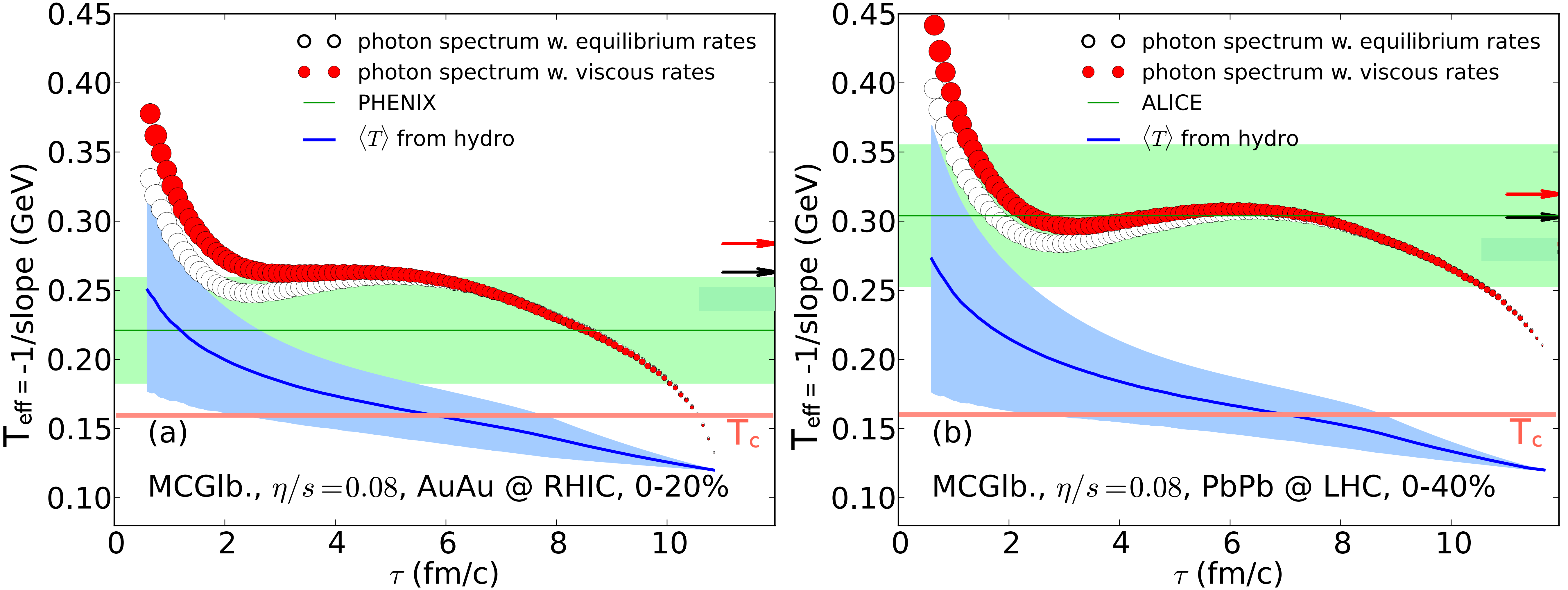


- Photon emission rates $\propto \exp(-E/T)\log(E/T) \Longrightarrow T_{\rm eff} > T$
- **All** cells with T < 250 MeV at RHIC and T < 300 MeV at LHC contribute photon spectra with T_{eff} in the experimental fit range
- About **50-60%** of all photons are emitted from T = 165~250 MeV; they are strongly blue-shifted by radial flow

$$T_{\rm eff} = T\sqrt{\frac{1+v}{1-v}}$$

T_{eff} = -1/slope vs. emission time

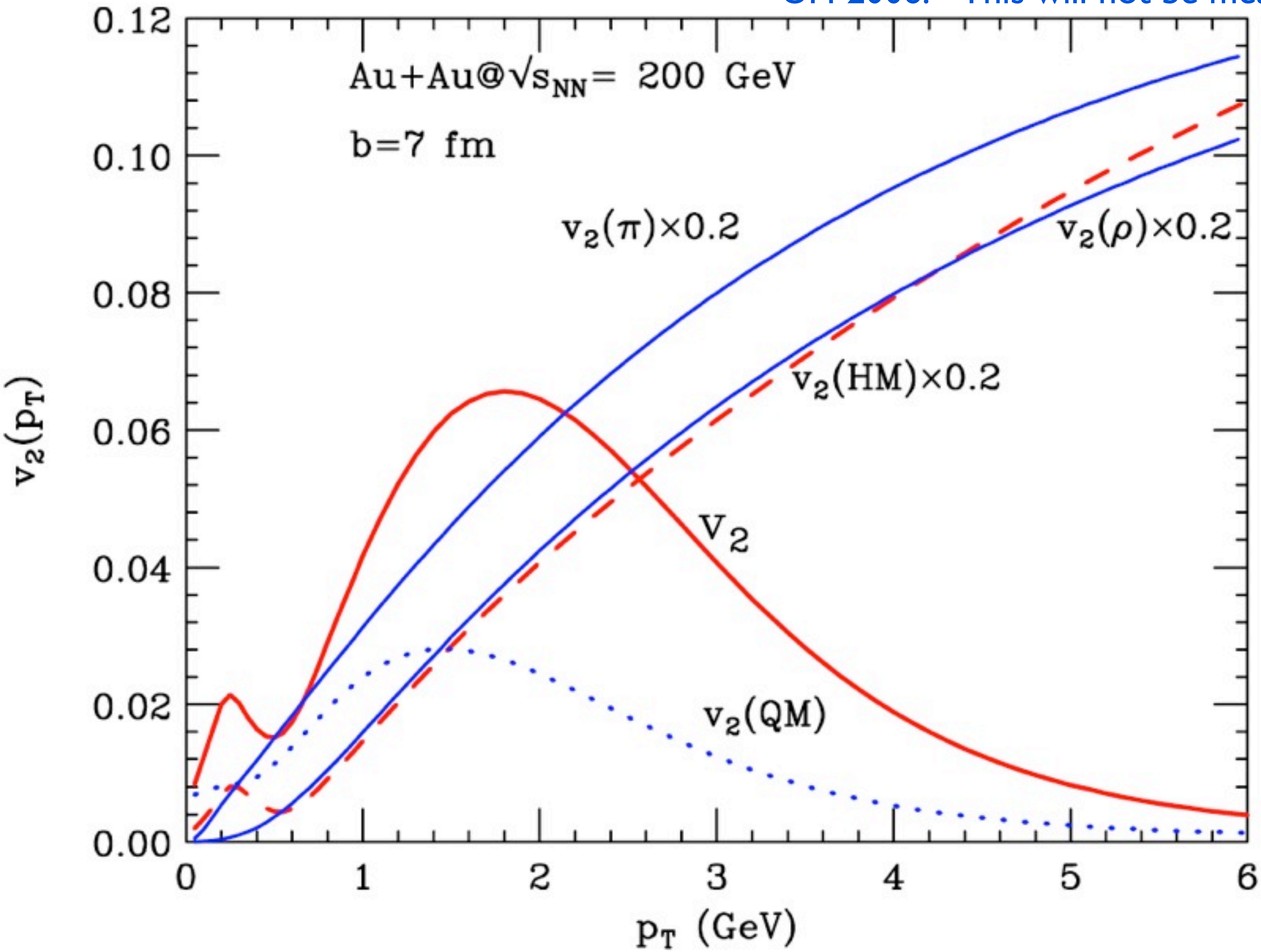
Shen, UH, Paquet, Gale, arXiv:1308.2440 (see also van Hees et al., PRC84 (2011) 054906)



- About 25% of thermal photons are emitted in the first 2 fm/c
- After 2 fm/c, thermal photons are significantly blue shifted by radial flow
- Viscous corrections to the slope of photon spectra are stronger during the early part of the evolution

A "safe" prediction (2006): thermal photon v_2

UH 2006: "This will not be measured in my lifetime!"

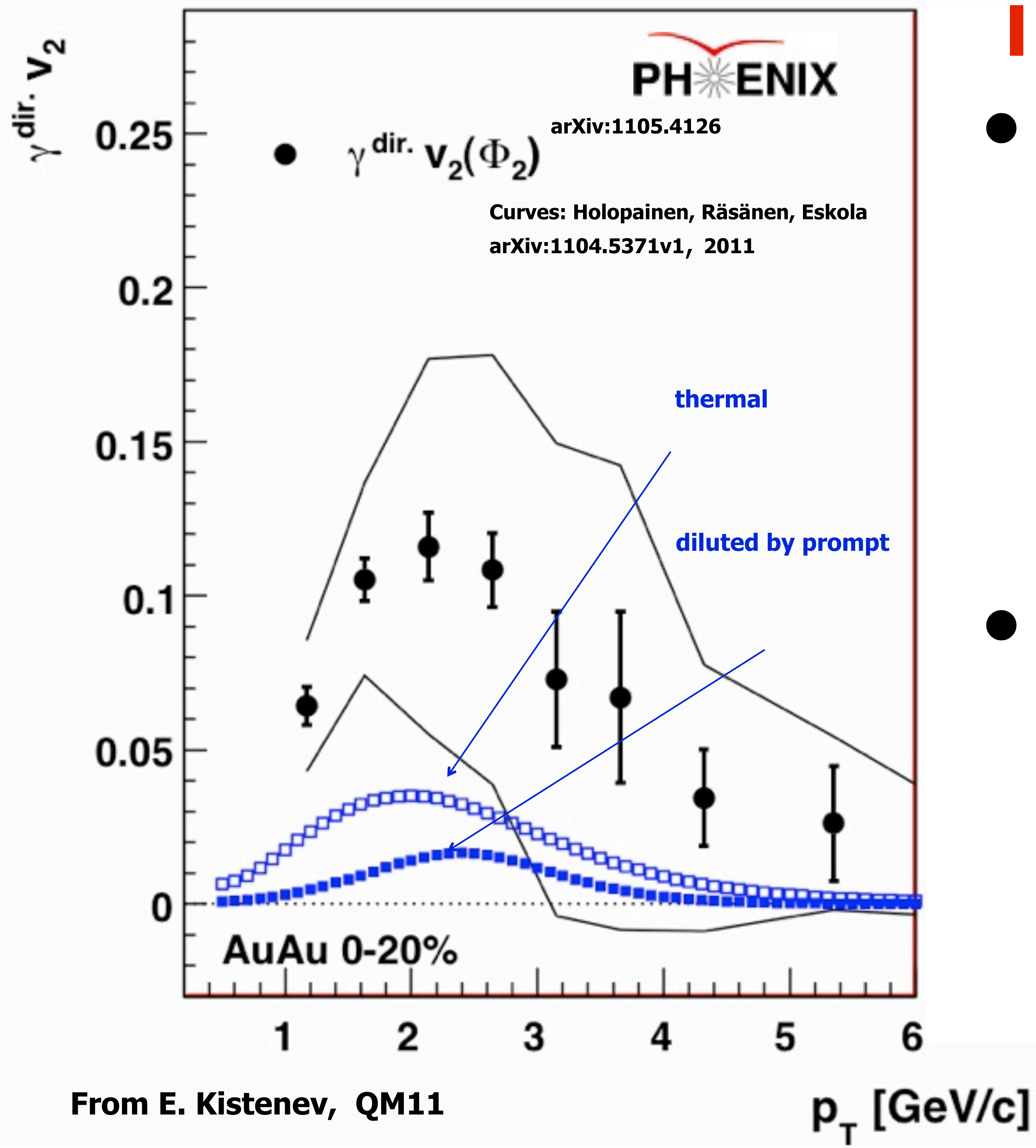


(2+1)-d ideal hydro with 1st order phase trans.

no prompt photons!

Chatterjee, Frodermann, UH, Srivastava, PRL 96 (2006) 202302

Boy, was I wrong!



From E. Kistenev, QM11

PHENIX did it in 2011!

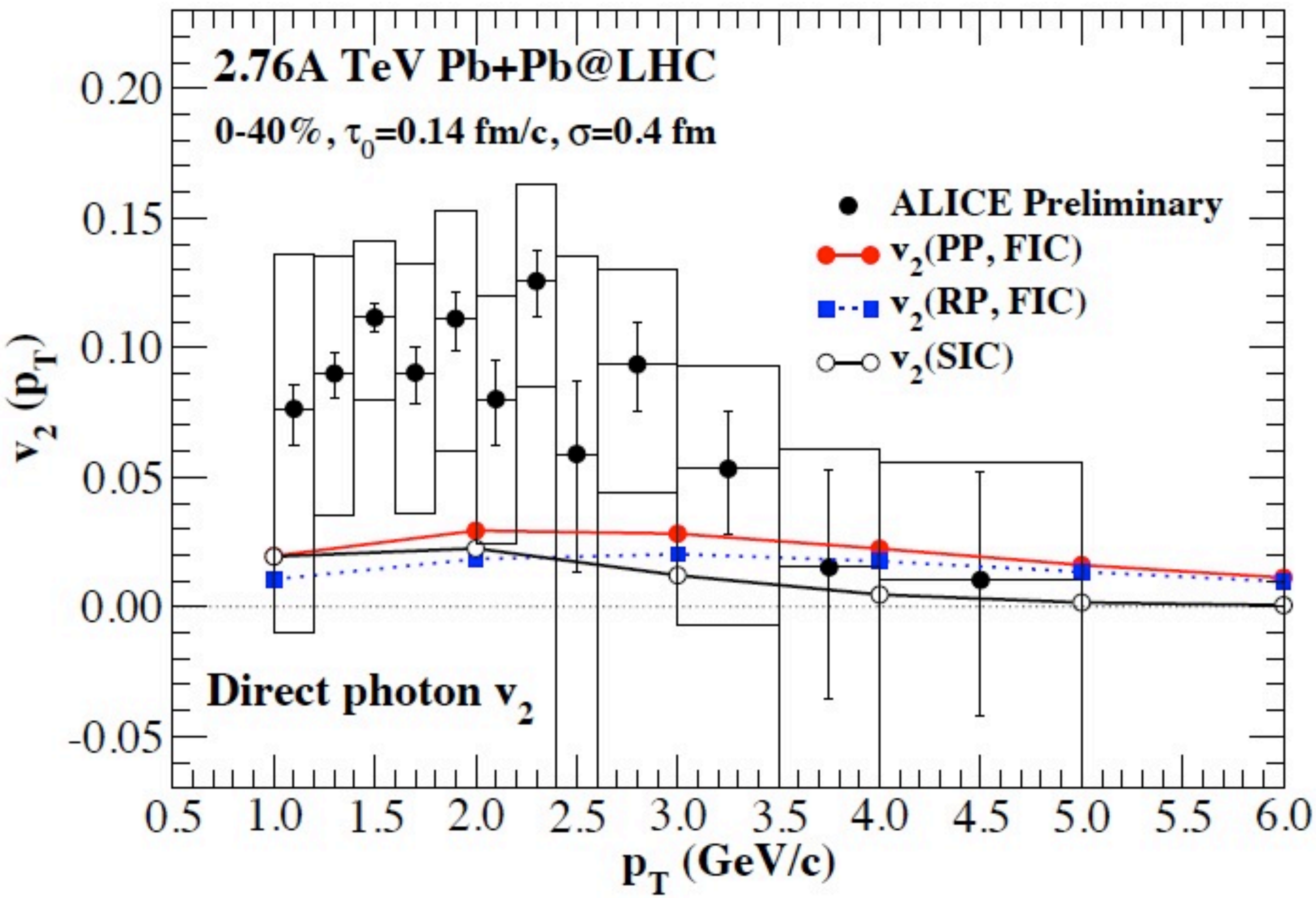
- PHENIX measurements show large direct photon v_2 at $p_T < 4$ GeV

But:

- State-of-the-art calculations underestimate the experimental data by a factor of 5!

Similar problems with ALICE data (QM2012):

Chatterjee et al., PRC 88 (2013) 034901

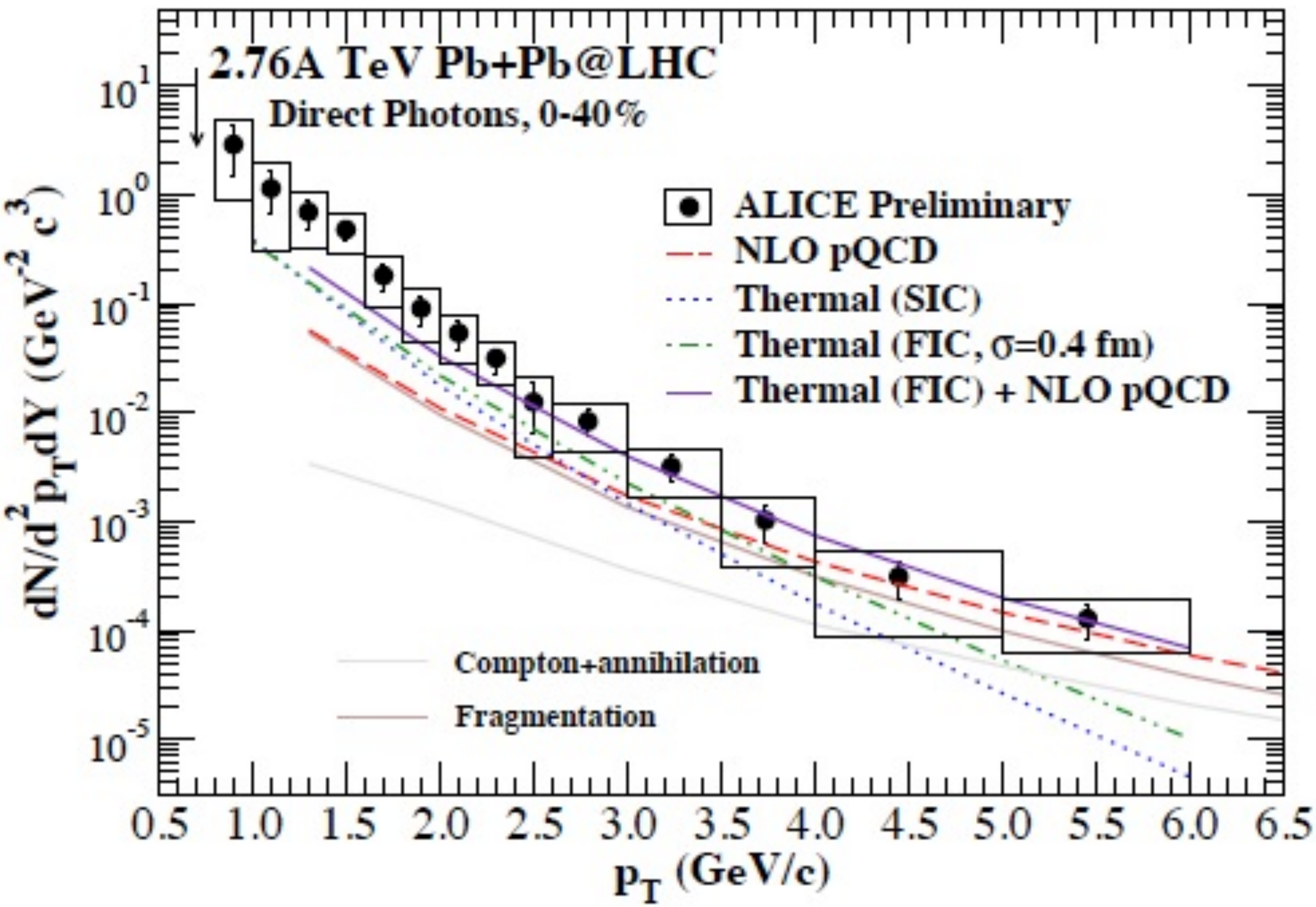


(2+1)-d ideal e-by-e hydro with fluctuating initial conds. and a lattice-motivated EOS

v_2 underpredicted by factor 3 in the hydrodynamic region

Similar problems with ALICE data (QM2012):

Chatterjee et al., PRC 88 (2013) 034901

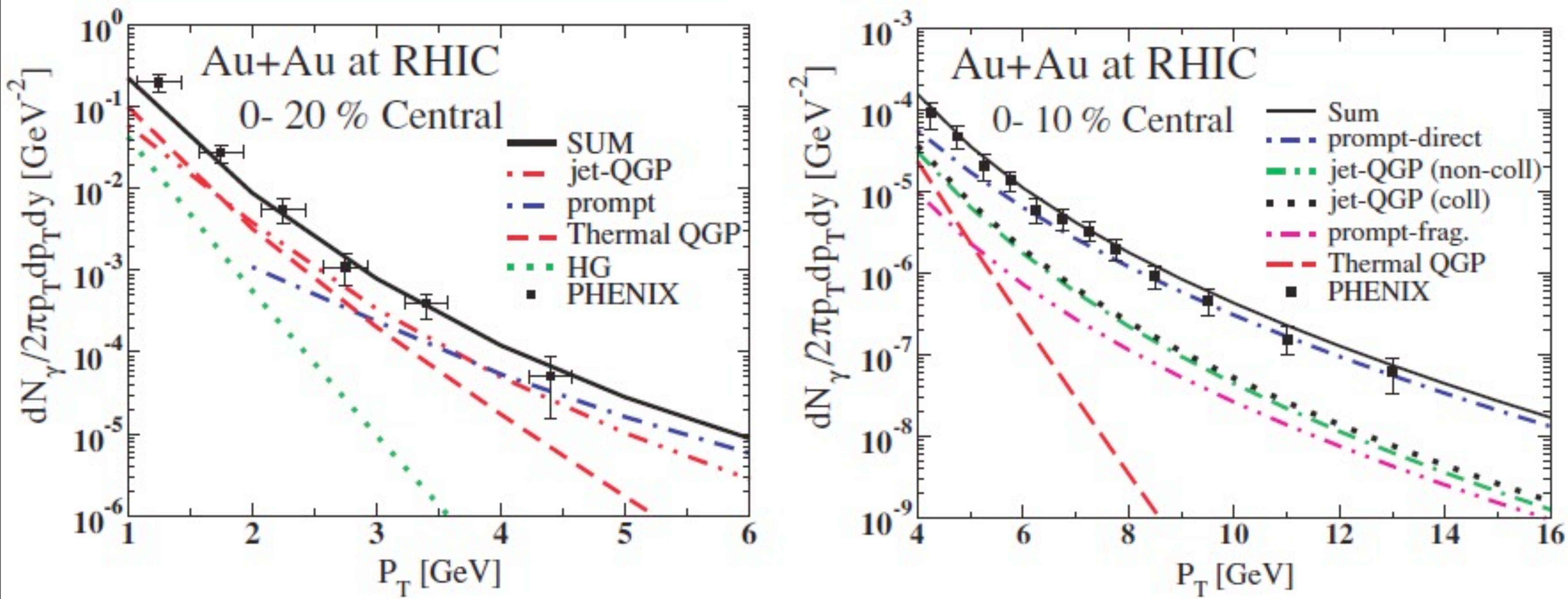


(2+1)-d ideal e-by-e hydro with fluctuating initial conds. and a lattice-motivated EOS

Missing photon yield at low p_T (also true at RHIC)

Hard photon production appears to be under control:

Turbide et al., PRC 77 (2008) 024909



But thermal radiation component is not.

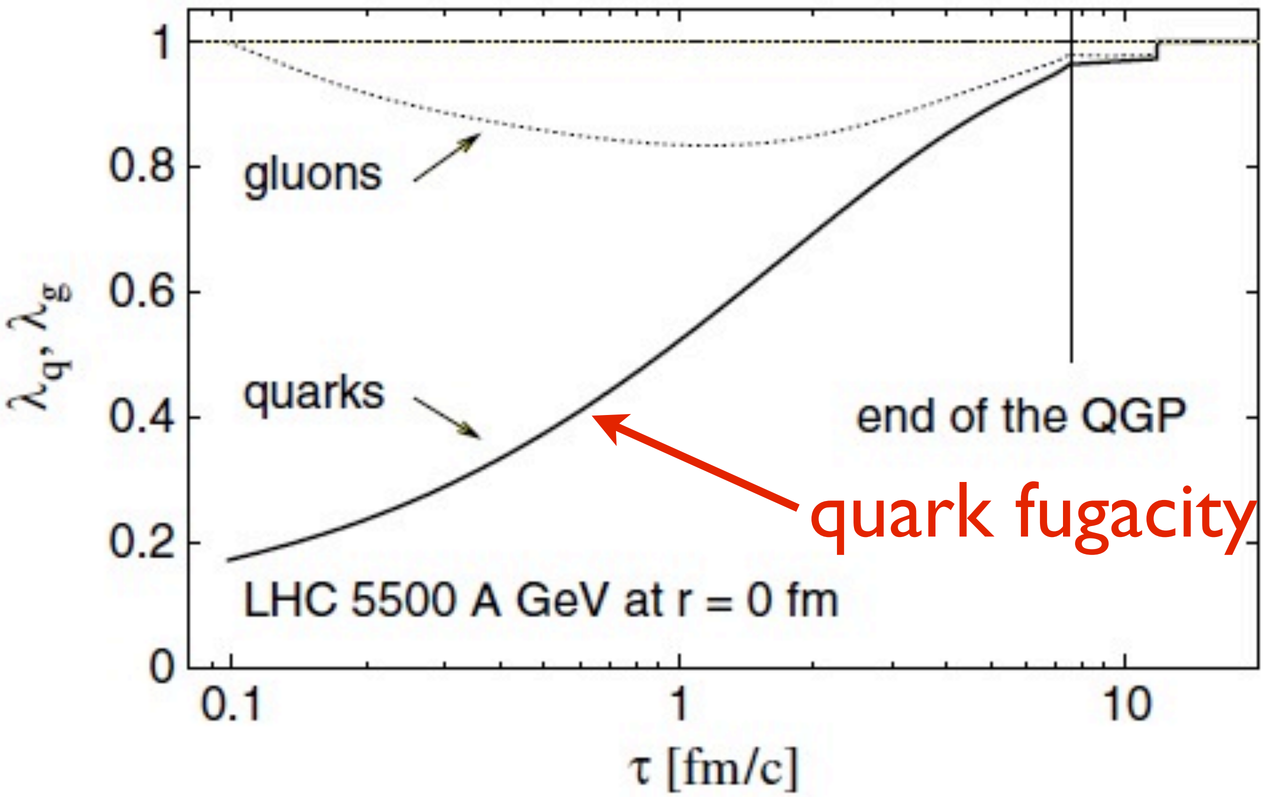
Ingredients in s.o.t.a. thermal photon calculations:

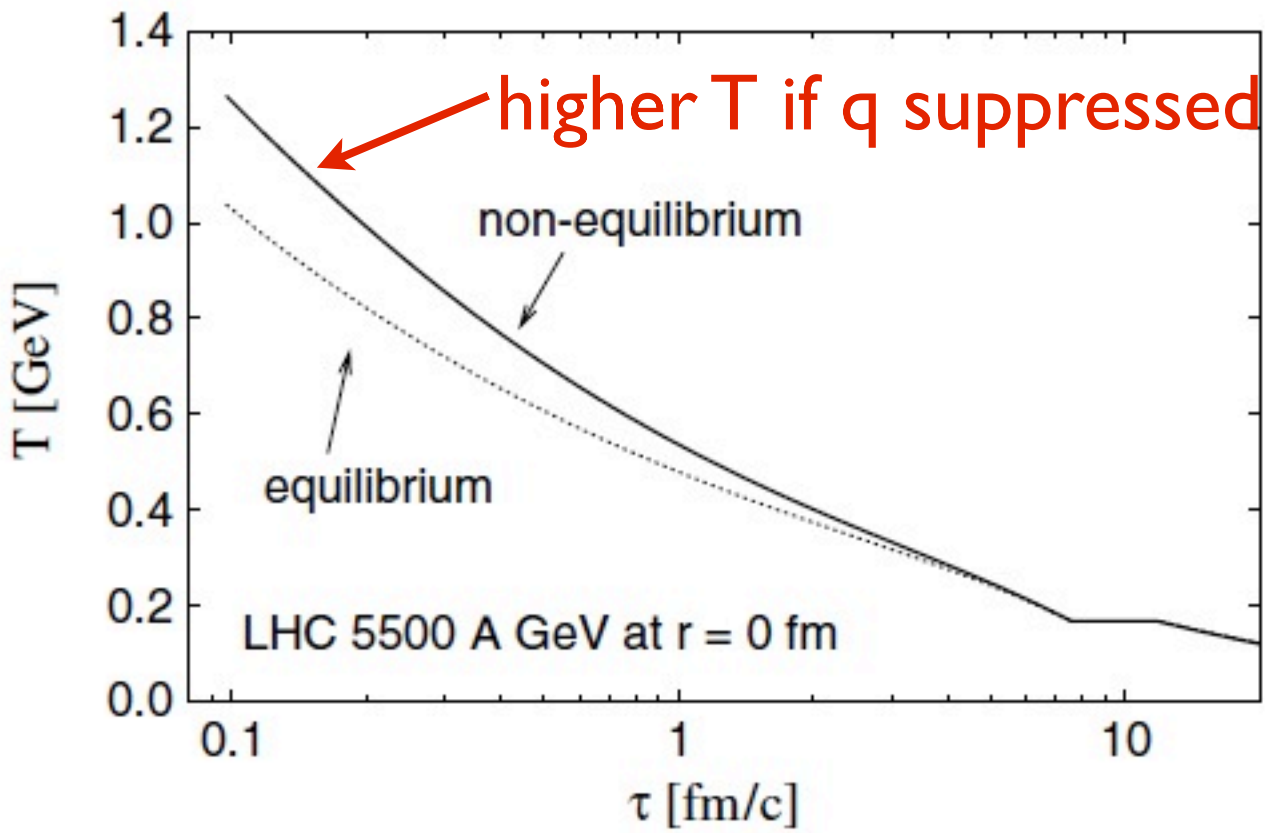
- Initial-state e-by-e temperature fluctuations
- Event-by-event (2+1)-d or (3+1)-d hydro-dynamic evolution
- Realistic lattice QCD-based EOS
- Viscous effects on hydrodynamic evolution and electromagnetic emission rates
- Addition of hard photon production channels
- Delayed chemical q-g equilibrium in QGP

iEBE

JET Collaboration

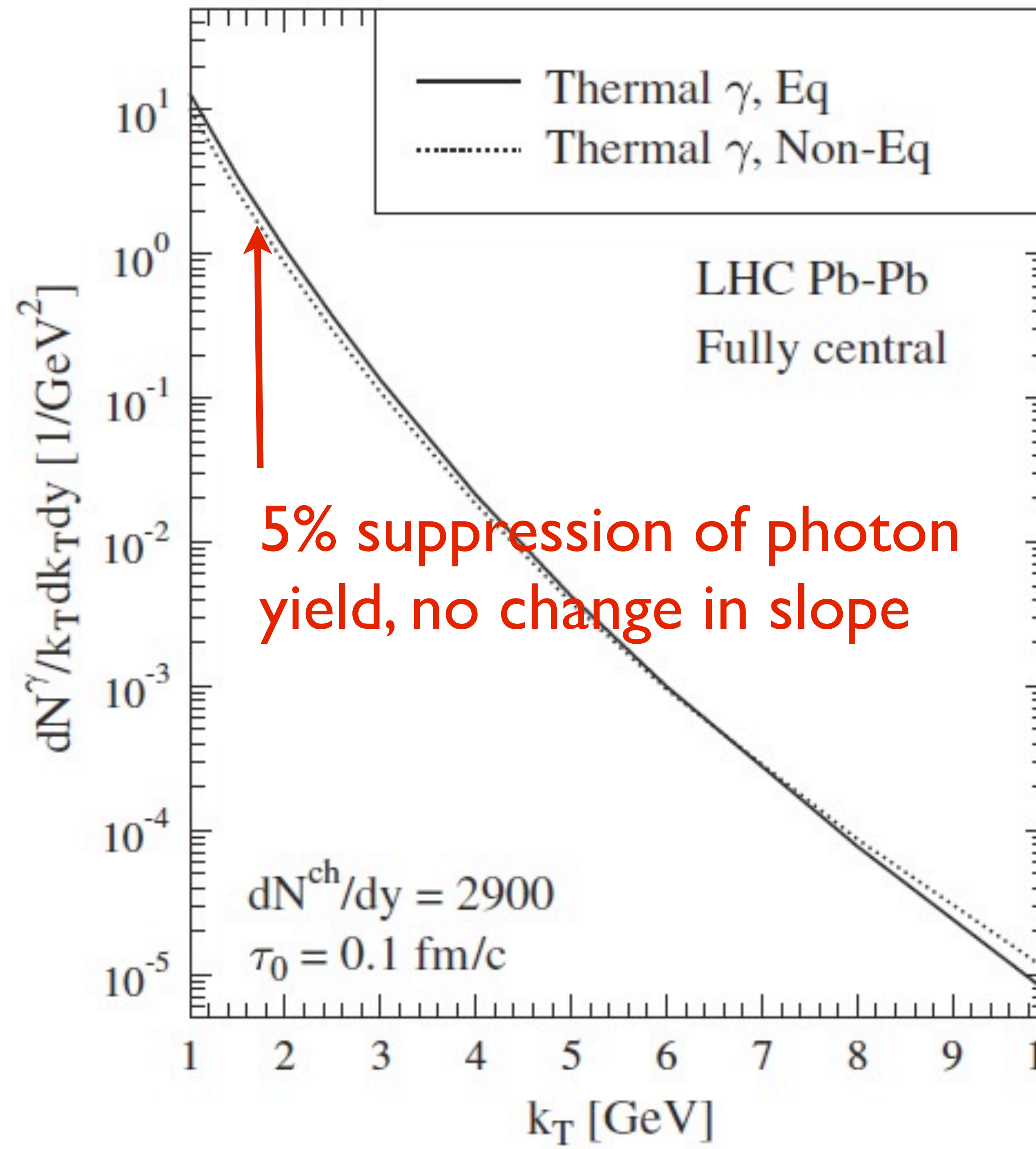
Delayed chemical QGP equilibration doesn’t much affect the photon spectra:





Gelis et al., JPG30 (2004) S1031

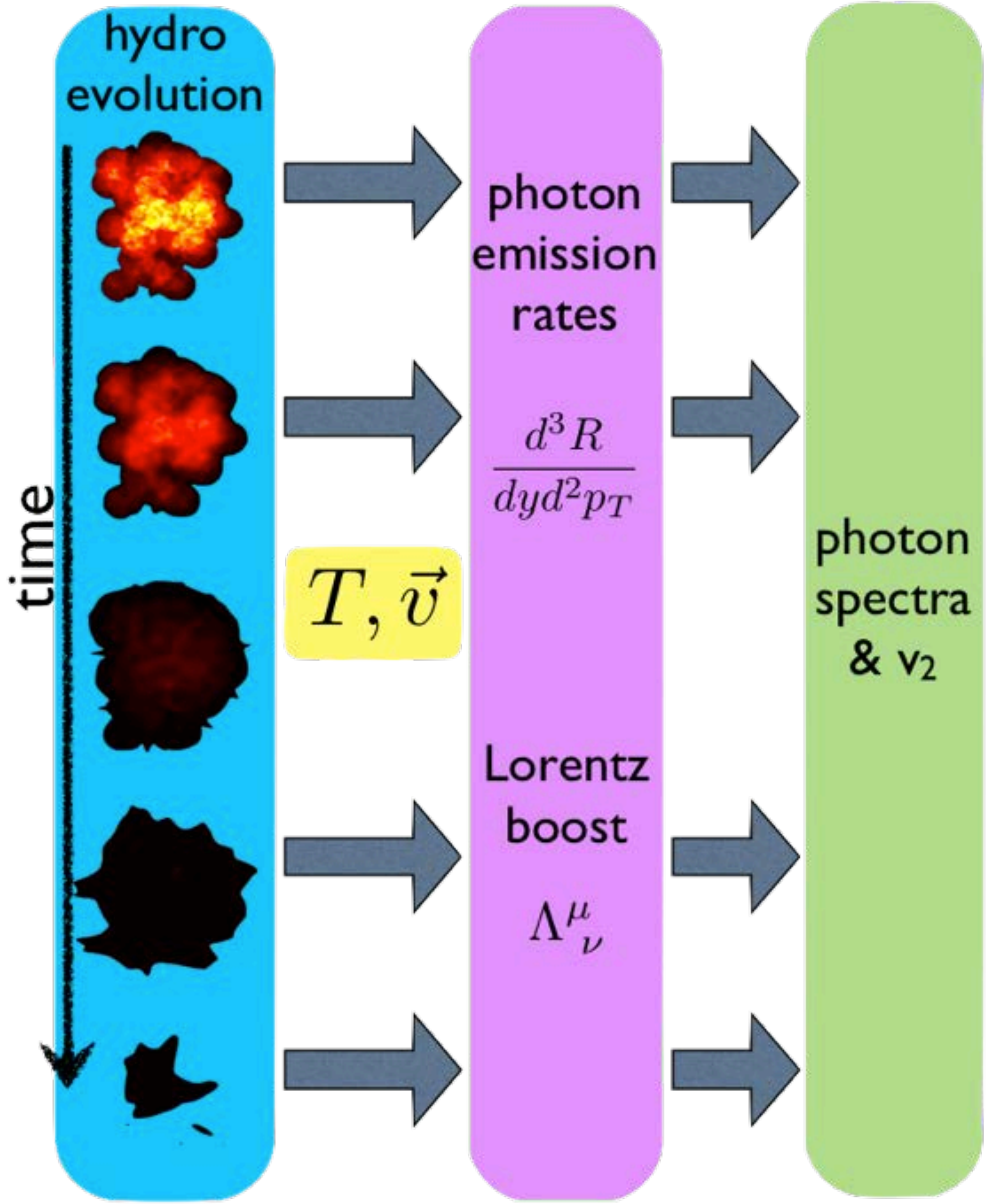
(see also Biro et al., PRC48 (1993) 1275)



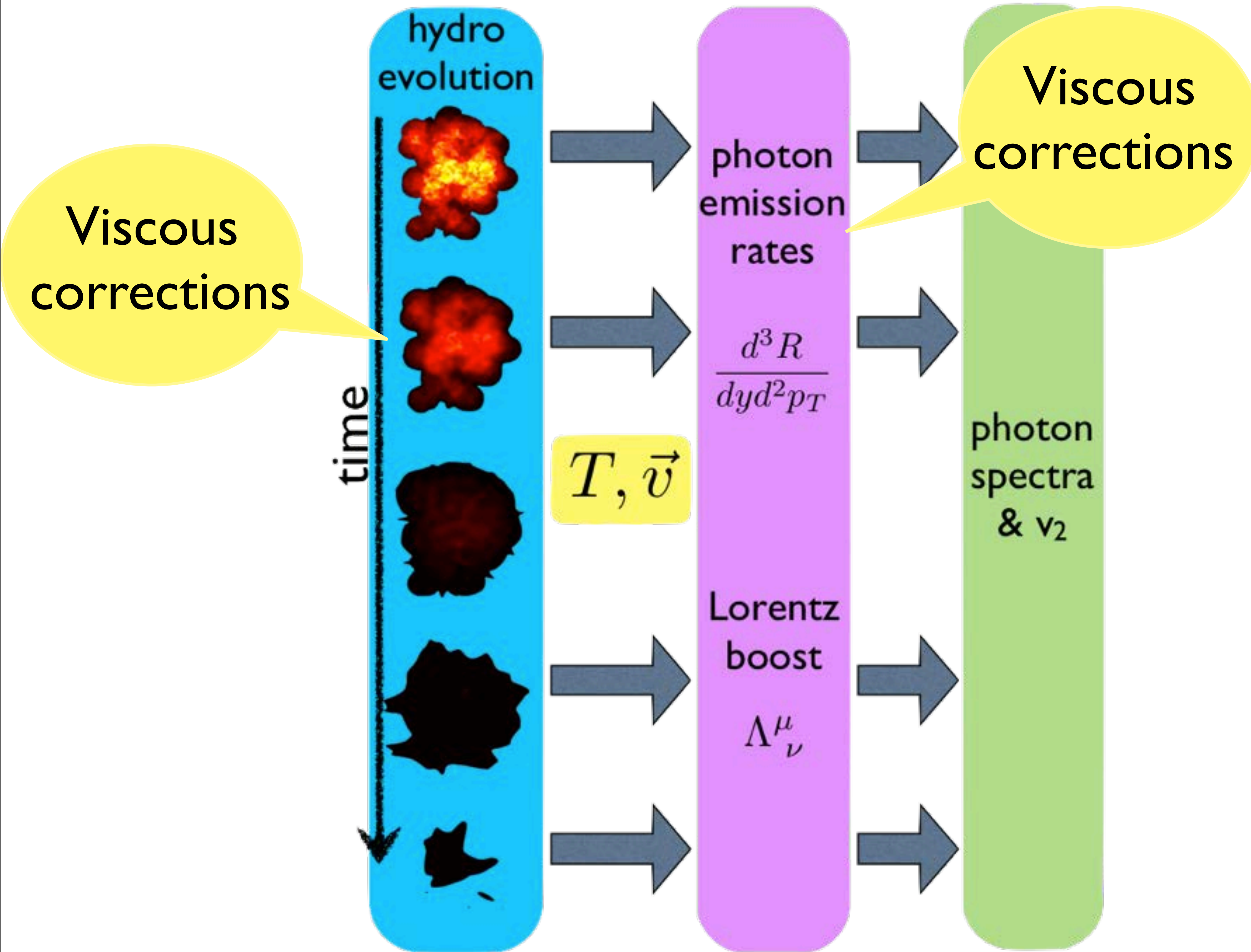
How to deal with viscosity in thermal photon emission

Shen Mo 17:20
Vujanovic Tue 14:30

Setting up the calculation

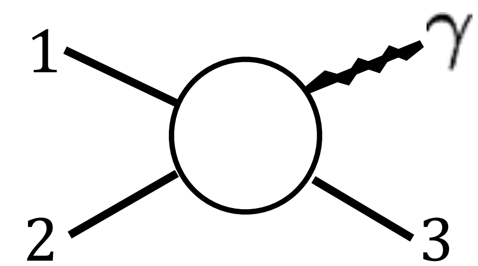


Setting up the calculation



Computing thermal photon emission rates

Kinetic Approach:



$$E_q \frac{dR}{d^3q} = \int \frac{d^3p_1}{2E_1(2\pi)^3} \frac{d^3p_2}{2E_2(2\pi)^3} \frac{d^3p_3}{2E_3(2\pi)^3} \frac{1}{2(2\pi)^3} |\mathcal{M}|^2$$
$$\times f_1(E_1) f_2(E_2)(1 \mp f_3(E_3))(2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - q)$$

At weak coupling these are equivalent in thermal equilibrium (KMS reln.)

Diagrammatic Approach:

$$E_q \frac{dR}{d^3q} = \frac{i}{2(2\pi)^3} \Pi_\mu^{<\mu}(Q)$$

Laine Tue 15:10

C. Shen (2013): At weak coupling, high T, equivalence continues to hold to first order in viscous corrections

Including viscous corrections in the rates:

E. g. in the kinetic approach

$$E_q \frac{dR}{d^3q} = \int \frac{d^3p_1}{2E_1(2\pi)^3} \frac{d^3p_2}{2E_2(2\pi)^3} \frac{d^3p_3}{2E_3(2\pi)^3} \frac{1}{2(2\pi)^3} |\mathcal{M}|^2$$

$$\times f_1(p_1^\mu) f_2(p_2^\mu)(1 \pm f_3(p_3^\mu))(2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - q)$$

Viscous corrections arise from momentum anisotropies in the dist. fct.:

$$f(p^\mu) = f_0(E) + f_0(E)(1 \pm f_0(E)) \frac{\pi^{\mu\nu} \hat{p}_\mu \hat{p}_\nu}{2(e+p)} \chi\left(\frac{p}{T}\right)$$

Expanding the rate around thermal equilibrium to first order in $\pi^{\mu\nu}$:

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu \hat{q}_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta},$$

work out in global (hydro) frame [$\pi^{\mu\nu}\hat{q}_\mu \hat{q}_\nu$]

work out and tabulate as fct. of q/T in l.r.f. aligned with photon mom. [$a_{\alpha\beta}\Gamma^{\alpha\beta}$]

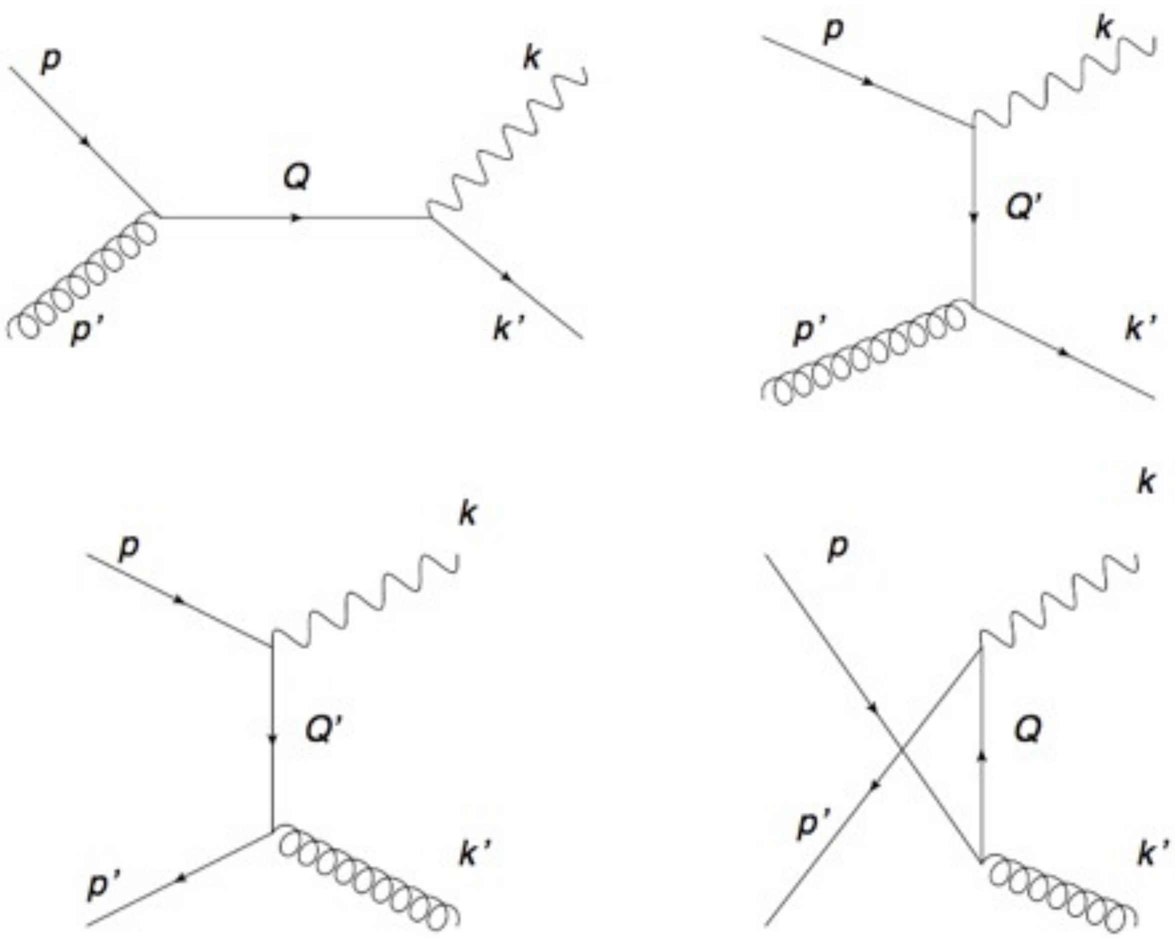
$$a_{\mu\nu} = \frac{3}{2(u\cdot\hat{q})^4}\hat{q}_\mu\hat{q}_\nu + \frac{1}{(u\cdot\hat{q})^2}u_\mu u_\nu + \frac{1}{2(u\cdot\hat{q})^2}g_{\mu\nu} - \frac{3}{2(u\cdot\hat{q})^3}(\hat{q}_\mu u_\nu + \hat{q}_\nu u_\mu).$$

Including viscous corrections in the rates:

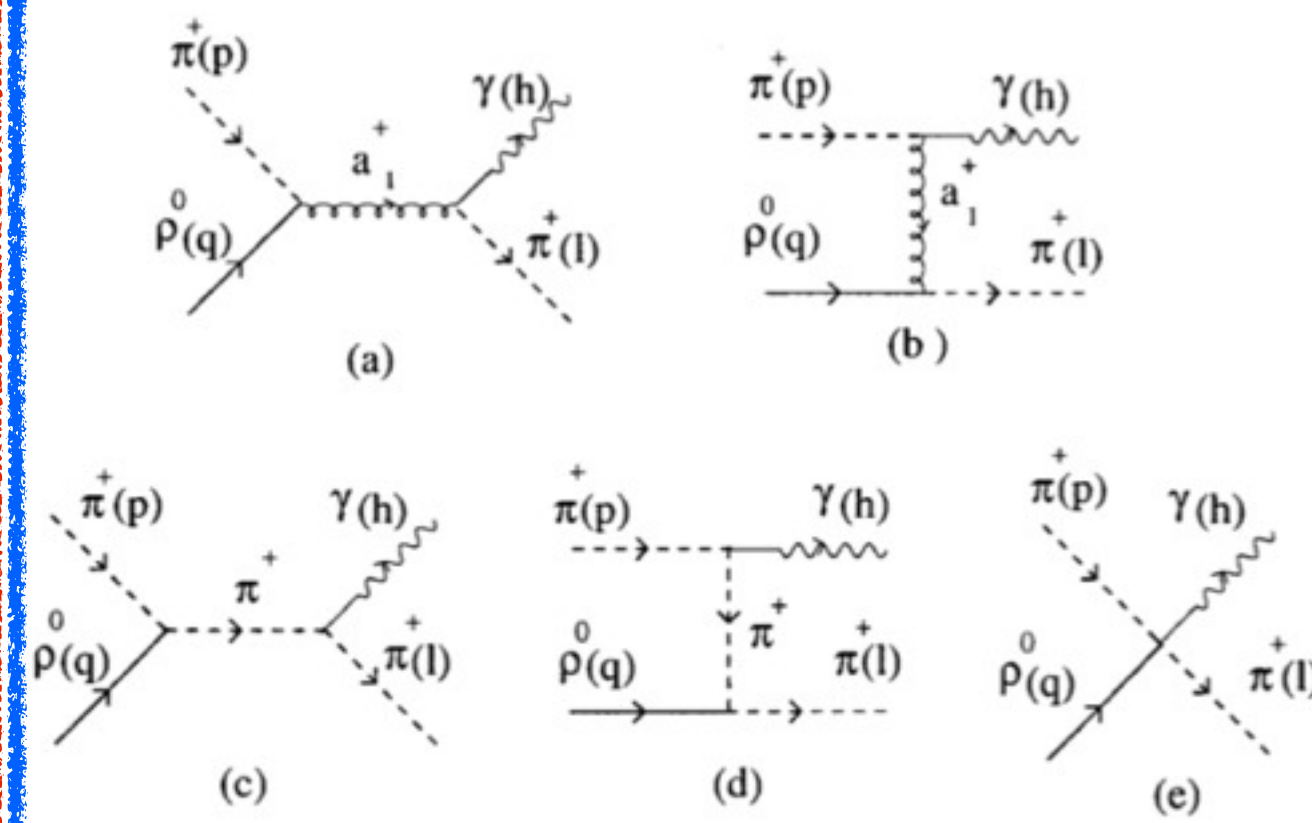
$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu\hat{q}_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta}$$

Equilibrium rates

QGP



Hadron Gas

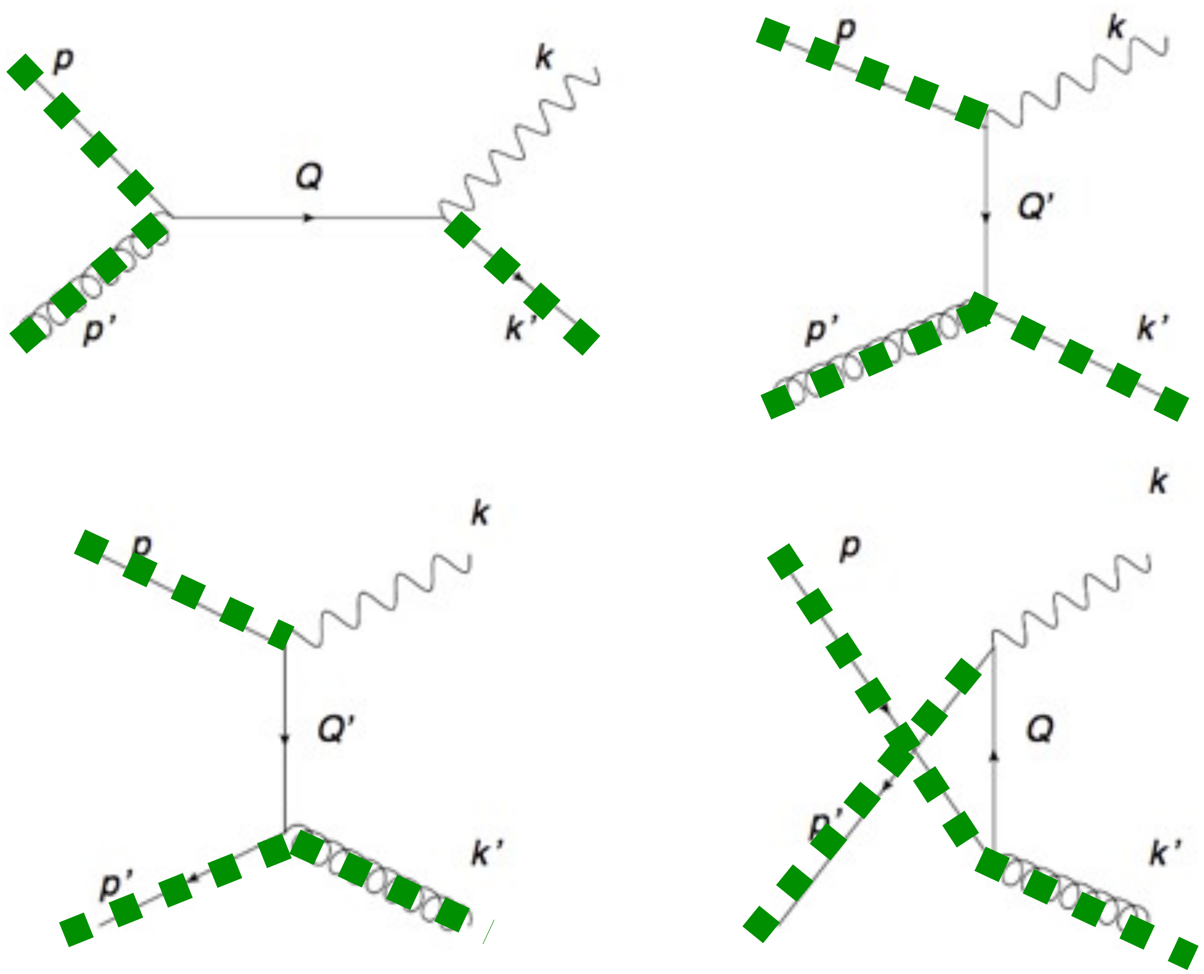


Including viscous corrections in the rates:

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu\hat{q}_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta}$$

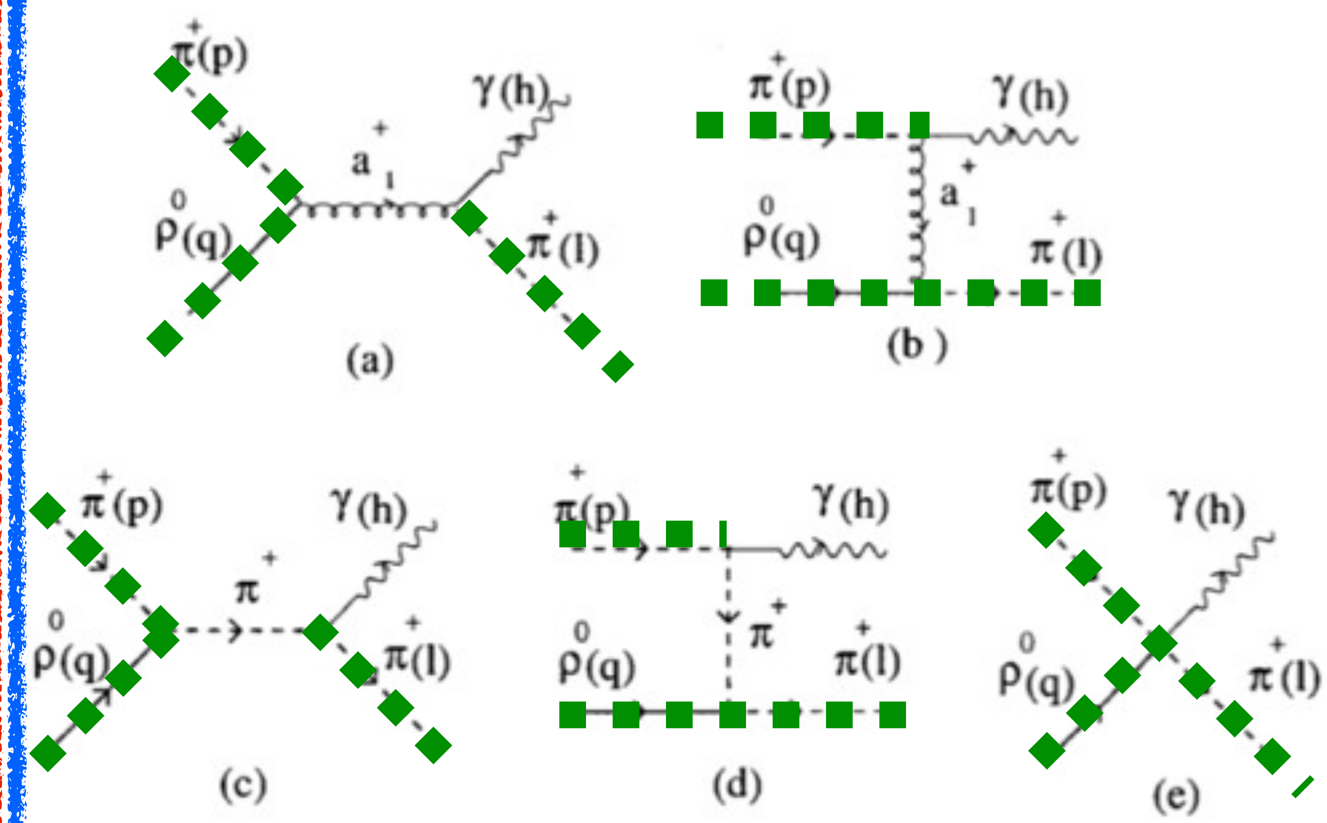
Equilibrium rates   off-equilibrium δf corrections

QGP



Dusling NPA839 (2010) 70

Hadron Gas



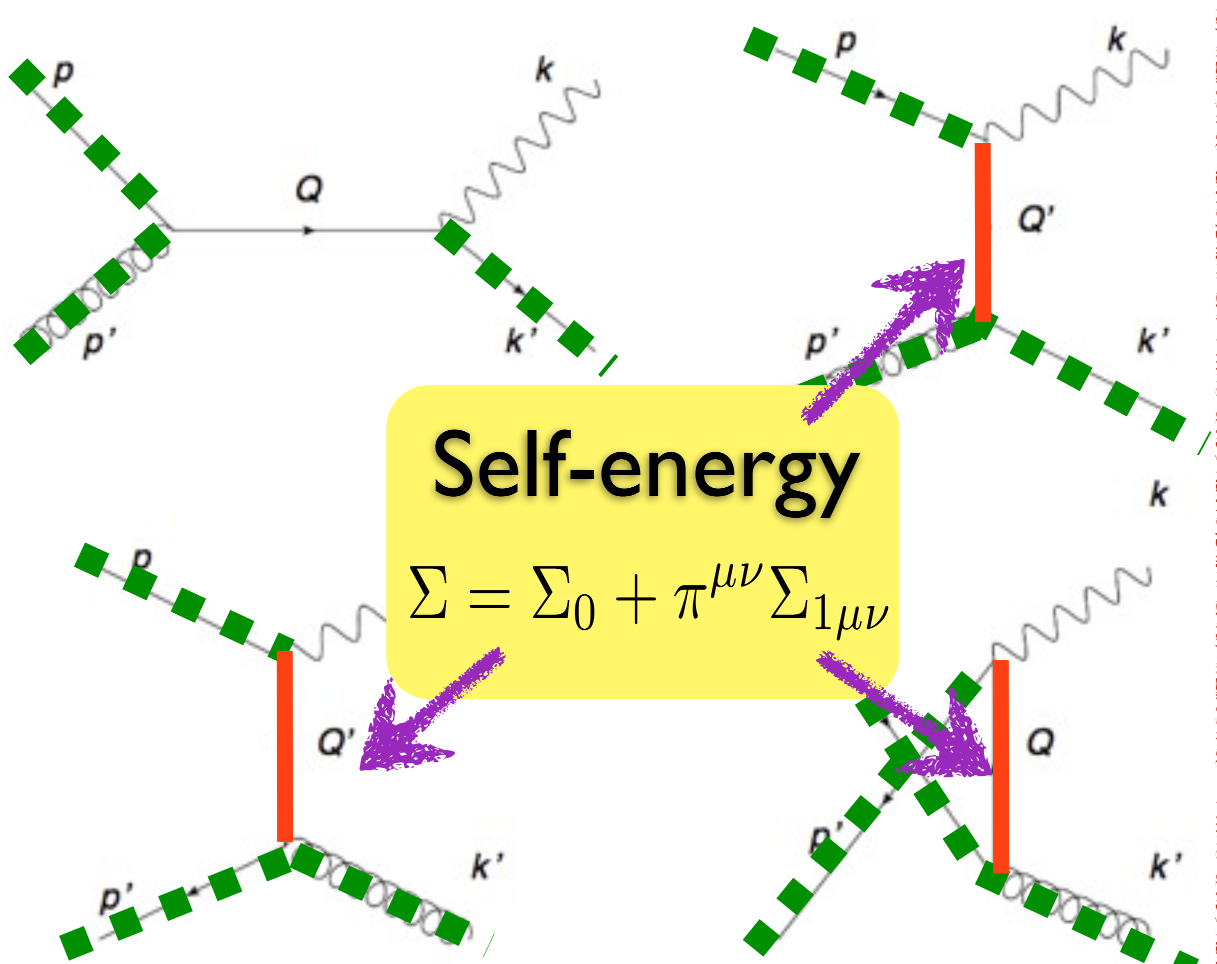
Dion et al. PRC84 (2011) 064901

Including viscous corrections in the rates:

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu\hat{q}_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta}$$

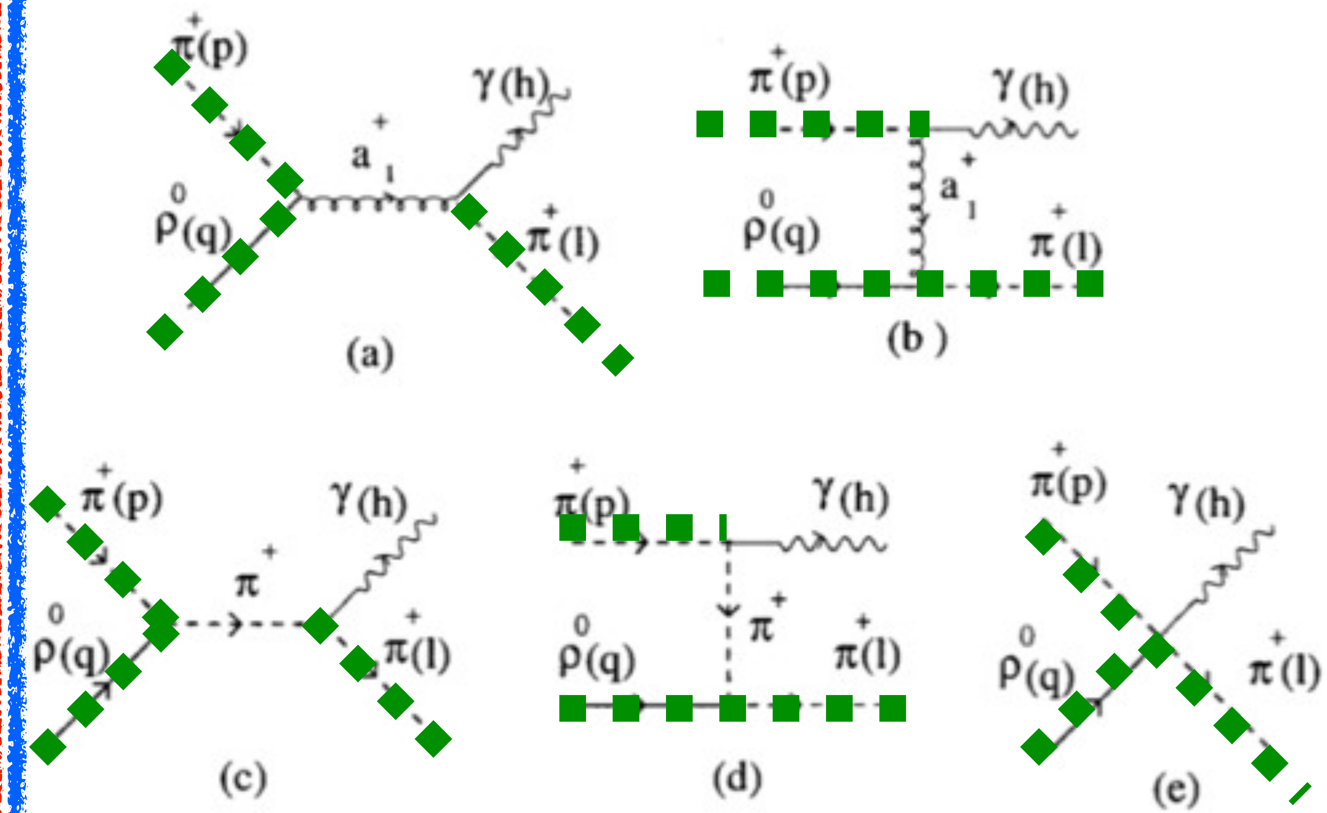
Equilibrium rates — off-equilibrium δf corrections

QGP



Shen, Paquet et al. (2013)

Hadron Gas



Present status of the calculation:

(i) 2 to 2 processes in Hadron Gas ✓

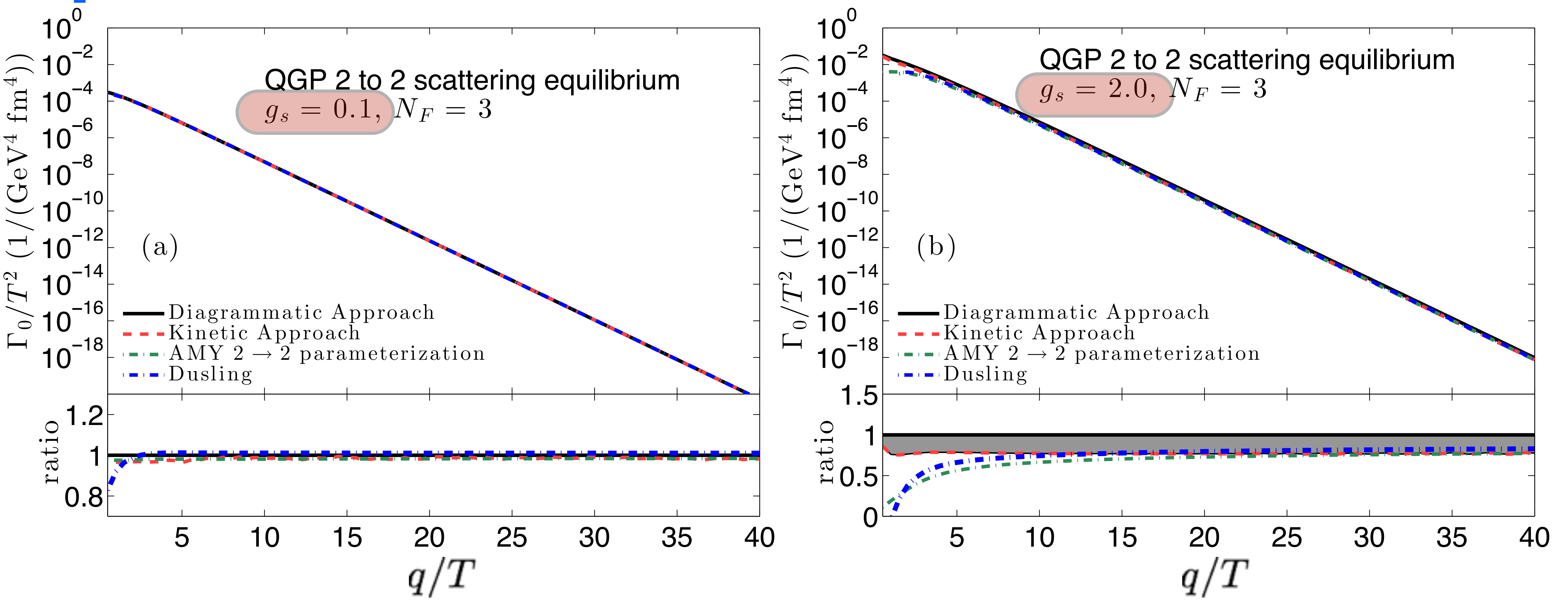
QGP ✓

(ii) Equivalence of diagrammatic and kinetic approaches for 2 to 2 processes in weakly coupled QGP ✓

(iii) Viscous corrections to resummed AMY kernel for collinear photon emissions --- in progress (Shen, Paquet)

Equivalence of kinetic and diagrammatic approaches:

Equilibrium rates:



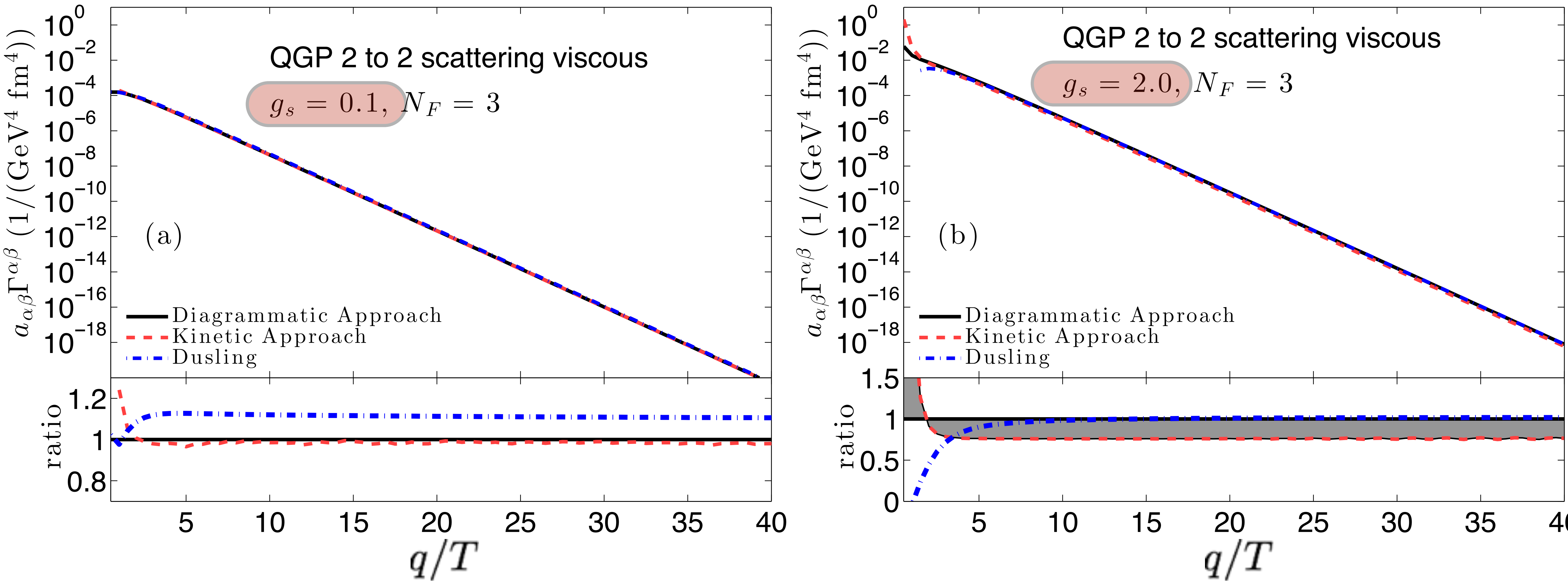
-- Diagrammatic approach requires matching soft and hard rates at gT < q* < T; kinetic approach doesn't (can use HTL matrix element everywhere).

-- For small g find broad matching window of insensitivity; window disappears for large g. Match at q* where sensitivity is minimal.

-- Equivalence holds only at leading order in g; for g=2, diagrammatic approach gives 25% larger yield than kinetic (irreducible systematic error at O(g))

Equivalence of kinetic and diagrammatic approaches:

Viscous corrections:



q/T

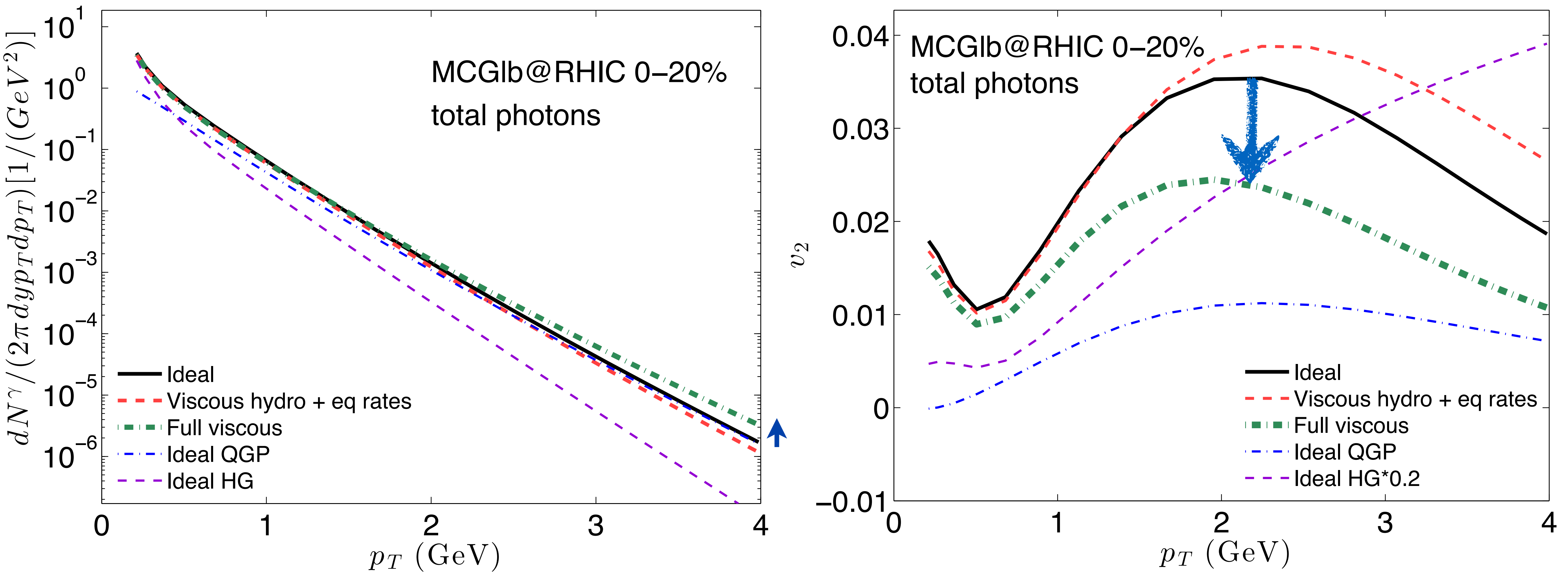
-- Viscous effects in HTL matrix element (not included by Dusling) reduce viscous rate corrections by 15% (g=0.1) to 25% (g=2) over most of q range.

-- For small g find broad matching window of insensitivity; window disappears for large g. Match at q* where sensitivity is minimal.

-- For g=2, O(25%) systematic uncertainty from different approaches.

Results

Example: Au+Au@200 AGeV w/ $\eta/s = 0.08$

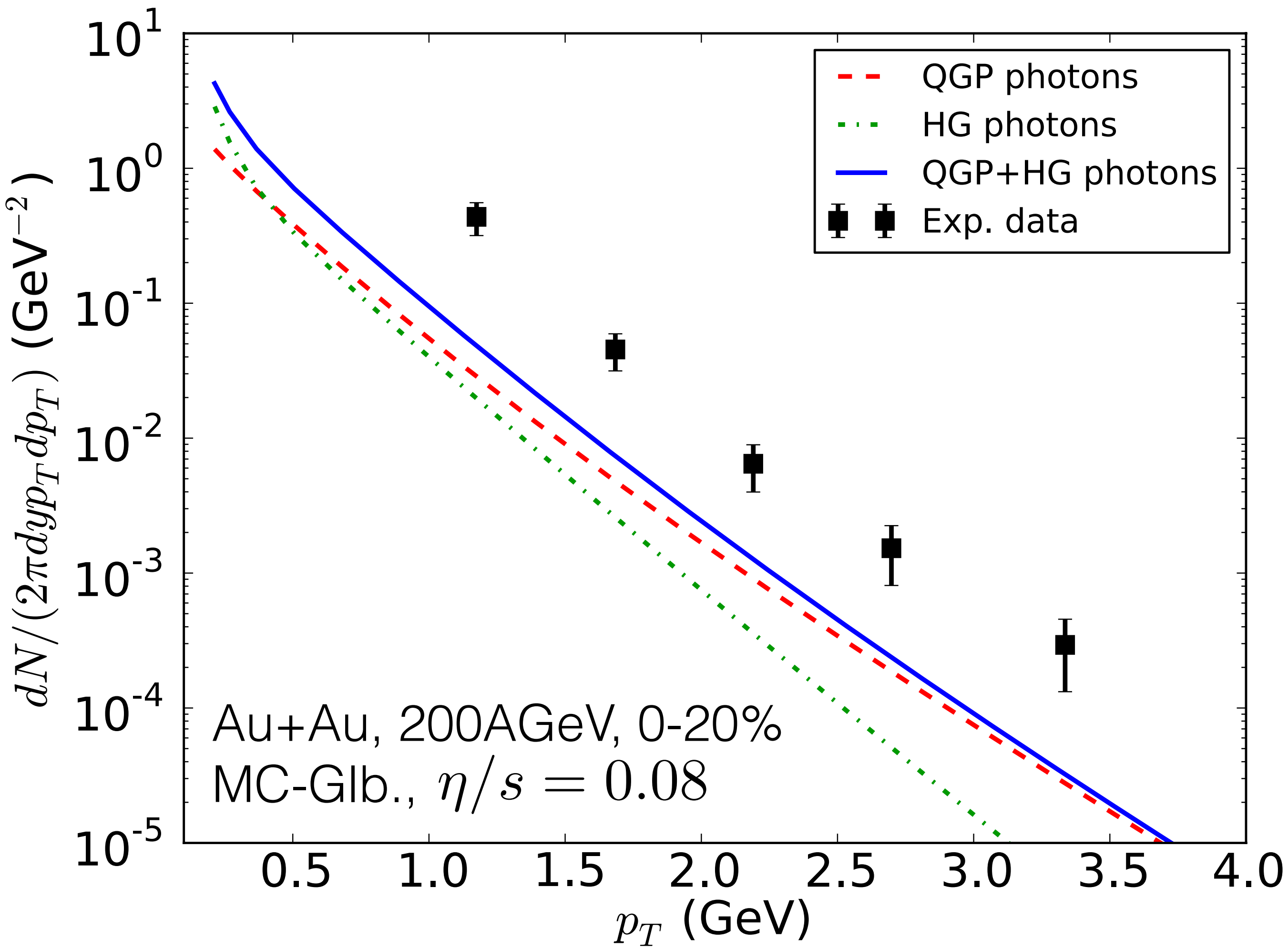


- Total photon spectrum dominated by QGP photons, except at very low p_T.
- Since QGP photons from early stage of hydrodynamic evolution carry small v_2, total photon v_2 remains small compared to that of hadrons

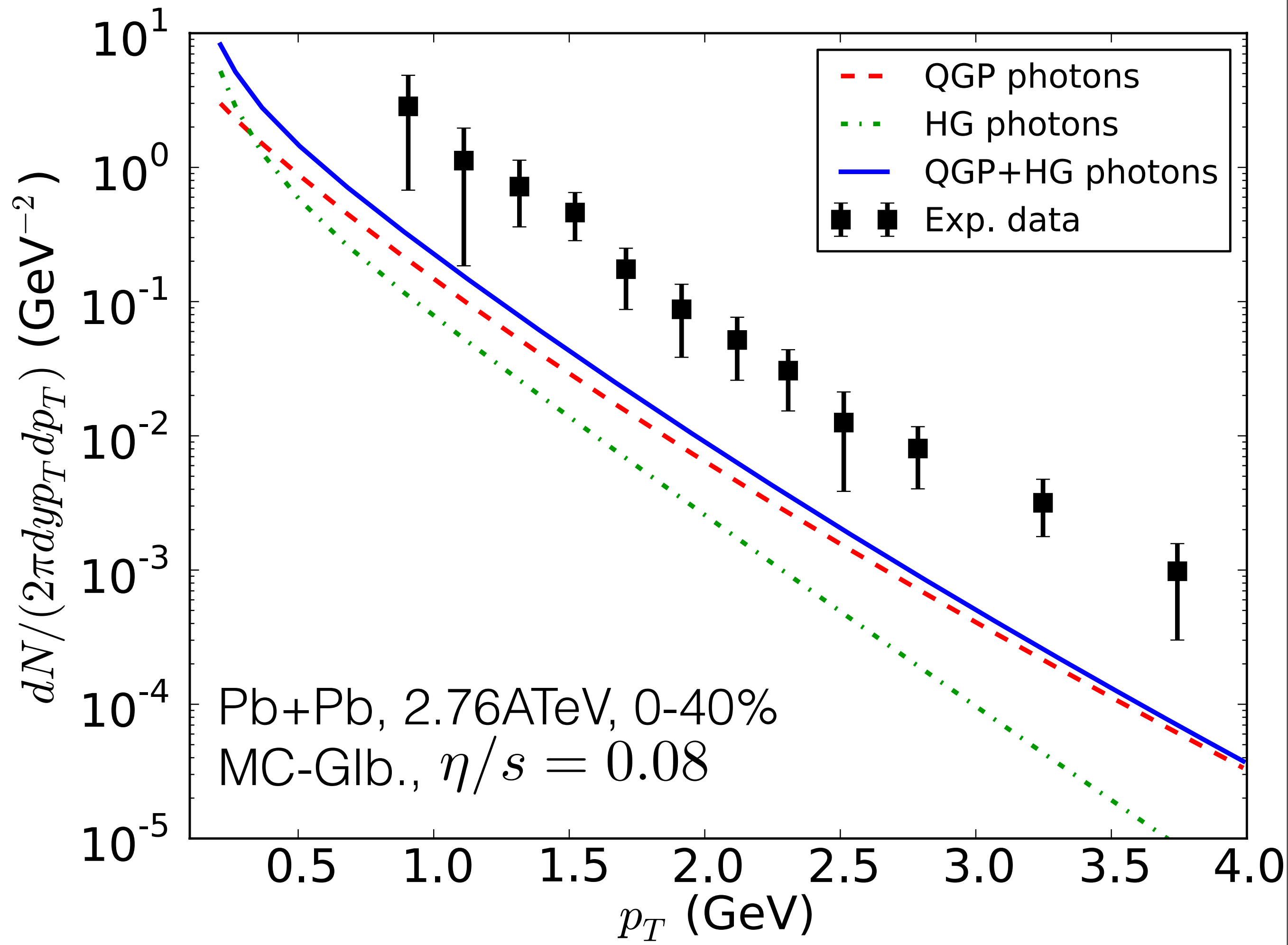
- Net effect of shear viscosity: even smaller photon v_2 !

Comparison with experiment
1. photon spectra: problems remain

RHIC (PHENIX)



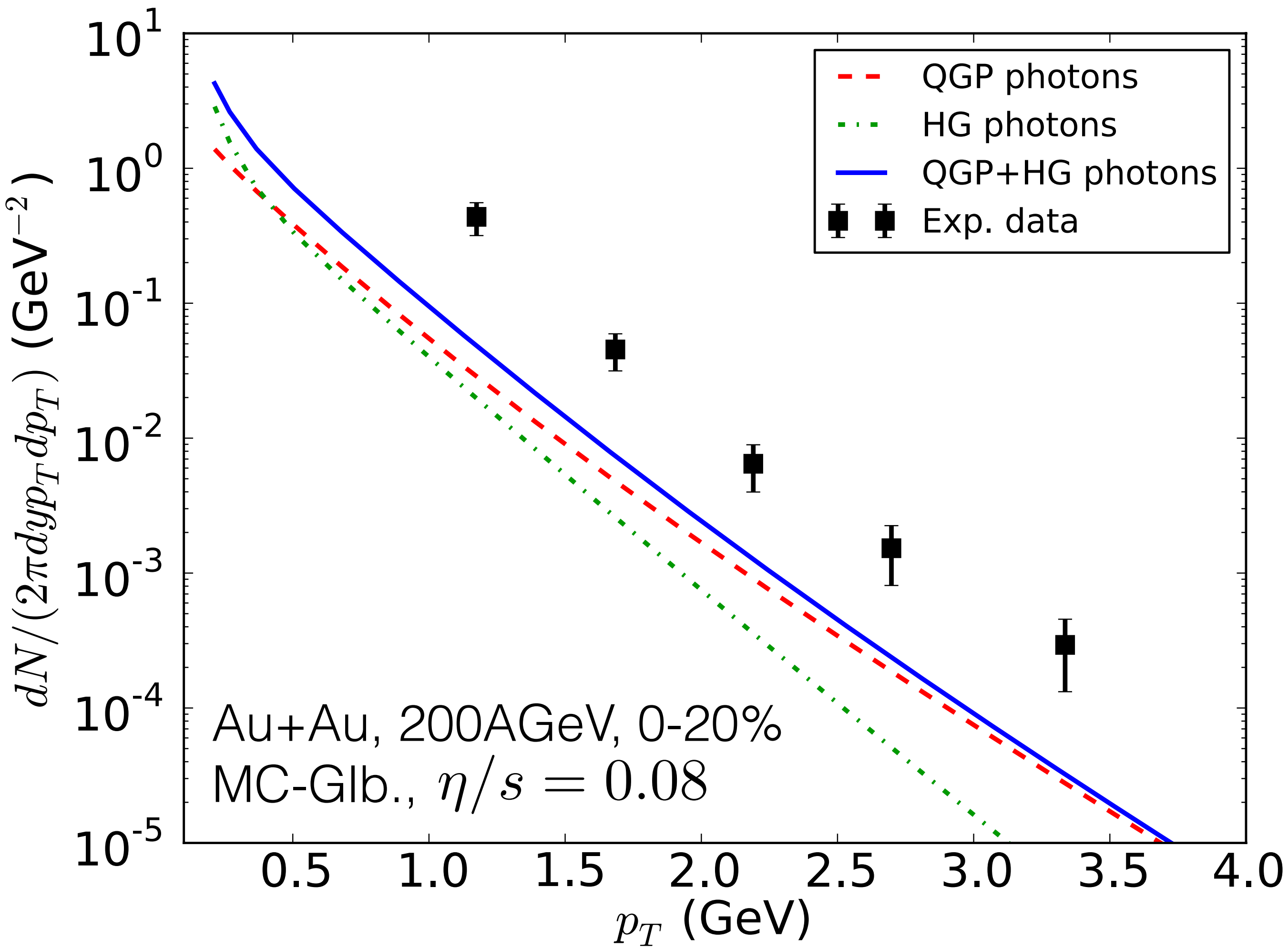
LHC (Alice)



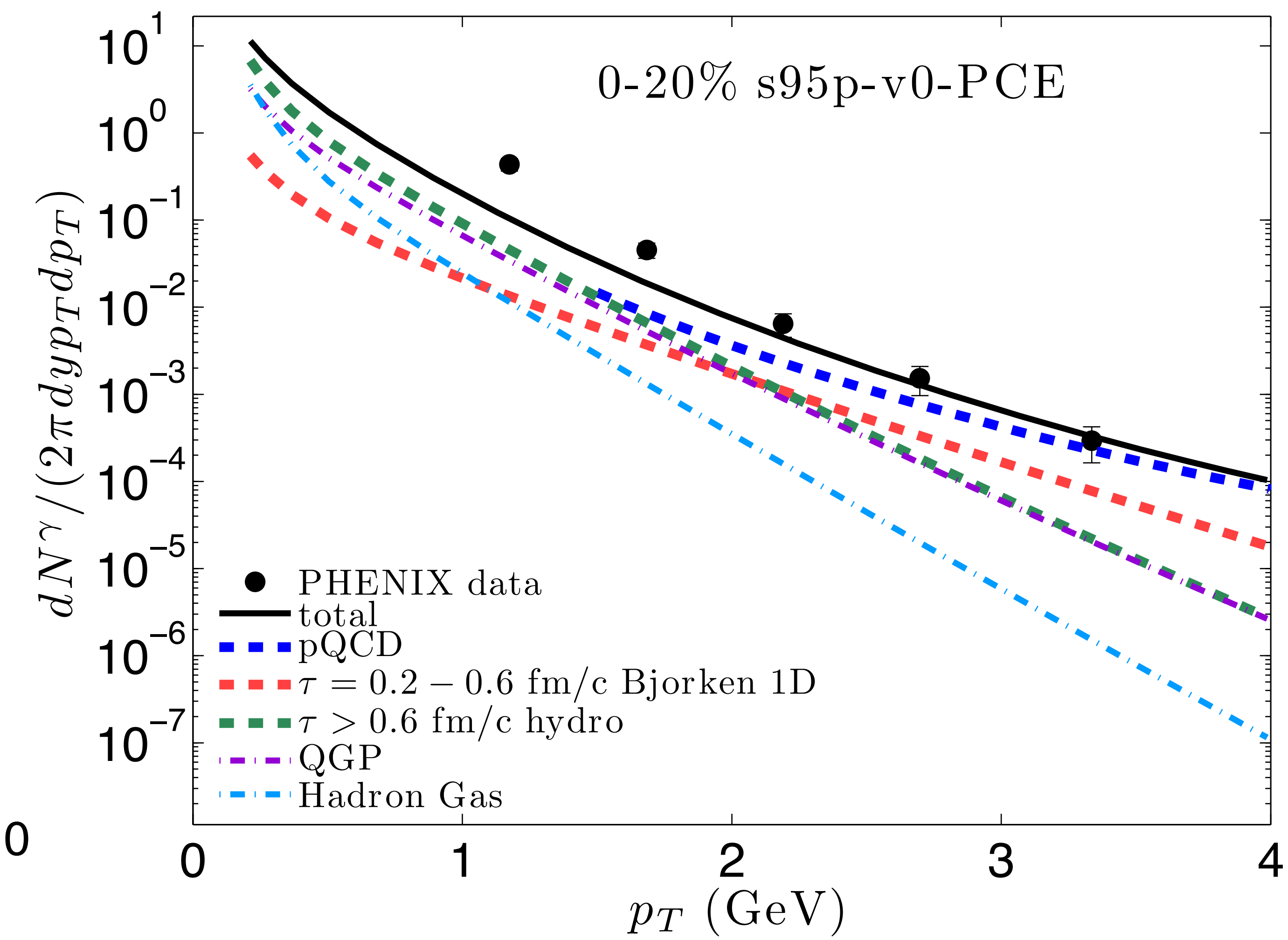
Thermal radiation too weak by factor 10 describe the data

Comparison with experiment
I. photon spectra: problems remain

thermal only



adding prompt+pre-eq

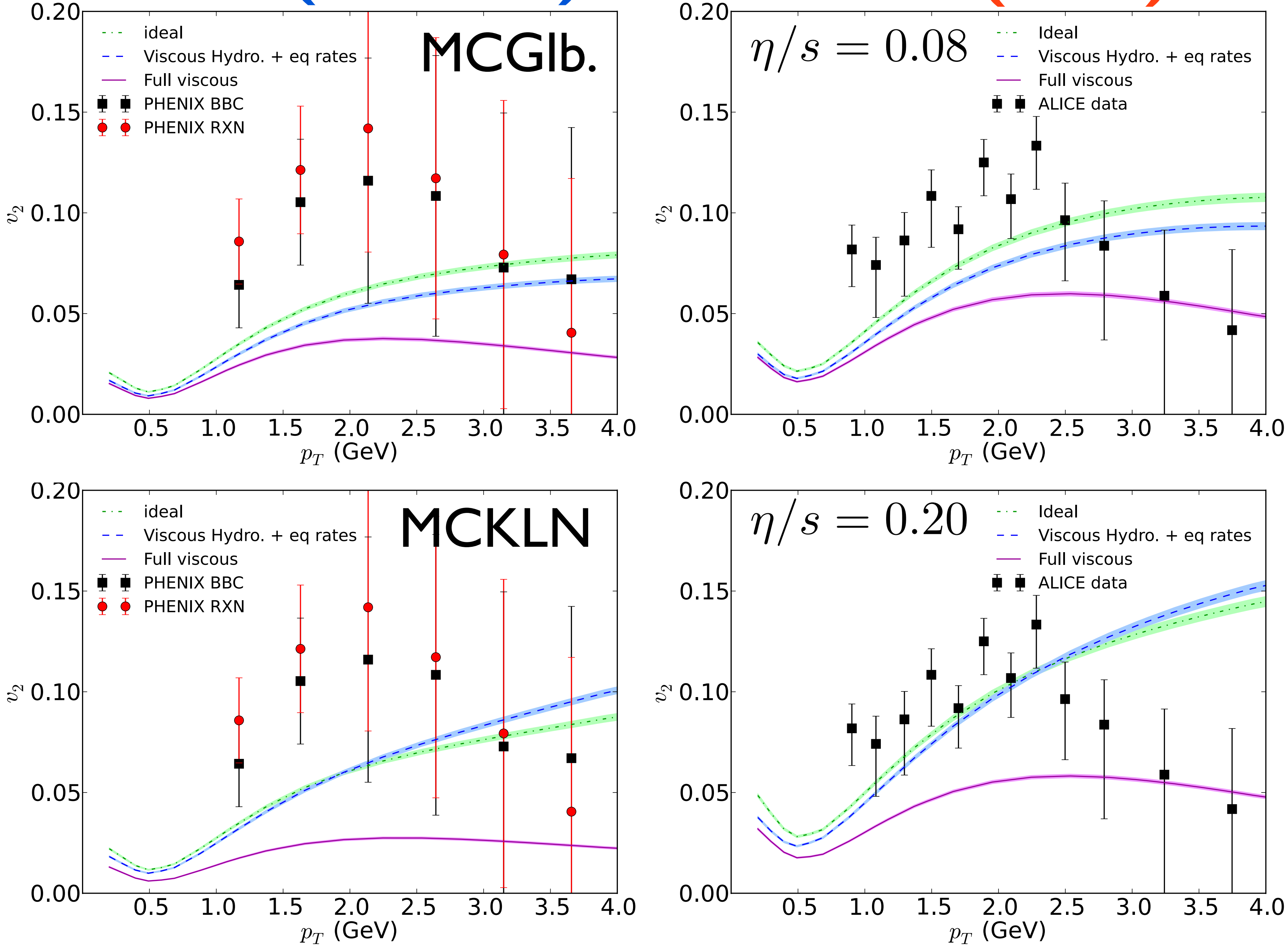


Still missing a large factor at p_T < 2 GeV ➡ need additional late-stage photon emission

see also new PHENIX data (Bannier Tue 13:30)

Comparison with experiment: v_2 worse than before! (note: theory does not include prompt photons)

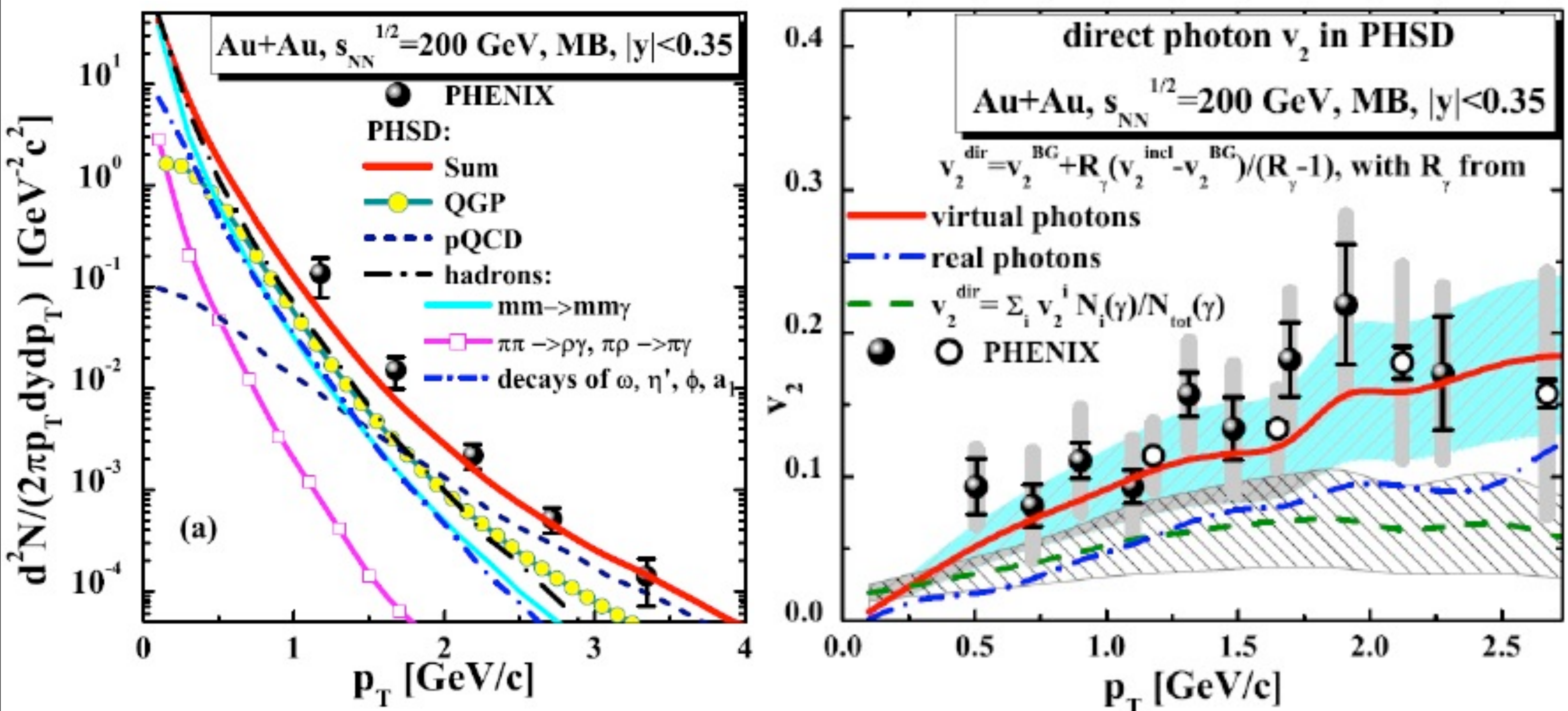
RHIC (PHENIX) **LHC (Alice)**



Missing rate at late times where v_2 is large!

Another approach: PHSD (Giessen)

O. Lynnik et al. , PRC88 (2013) 034904



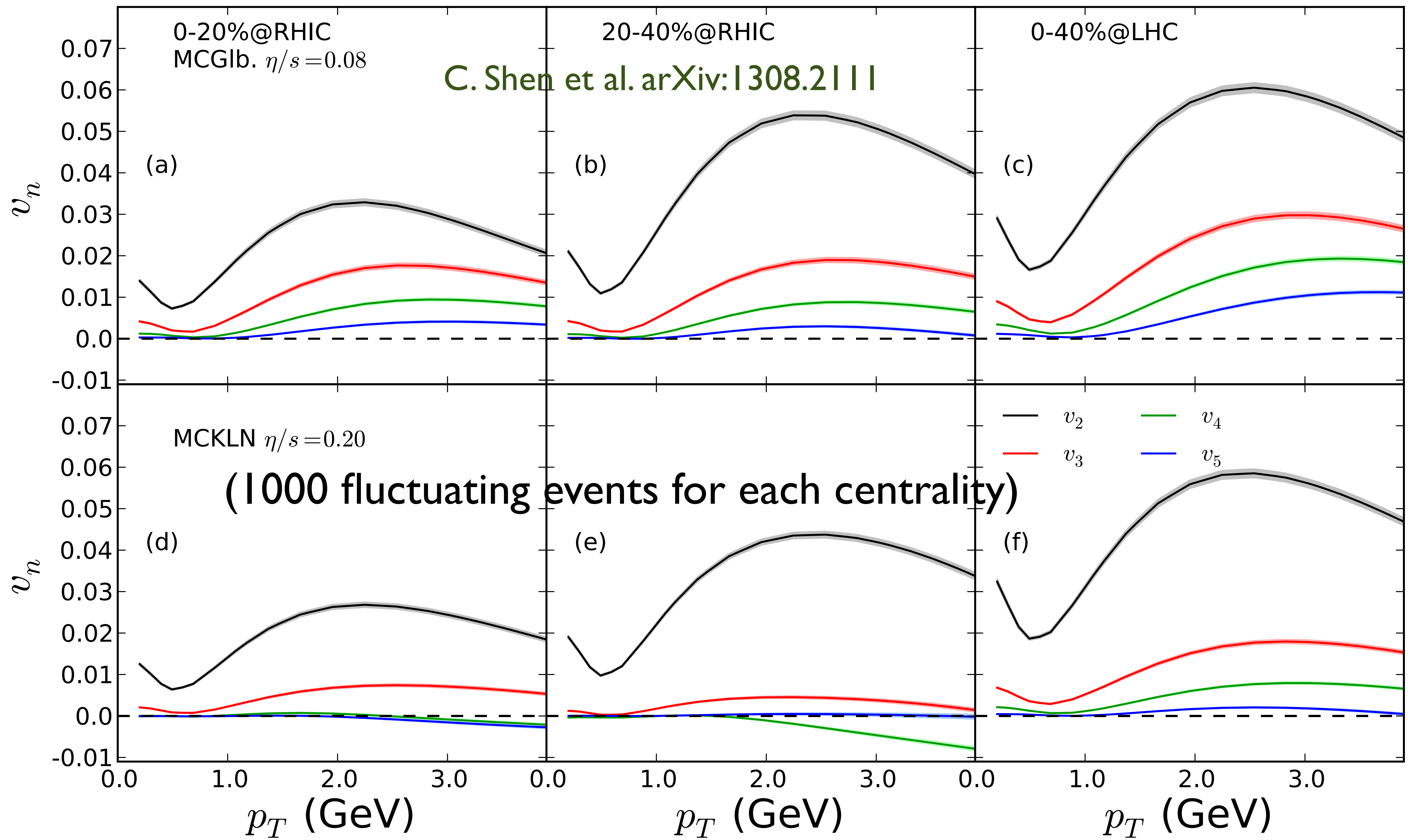
More hadronic radiation, steeper QGP and HG spectra at low pT than in hydro

Still, not enough v_2 for direct photons

W. Cassing Thu 15:40

Finally, some good news:

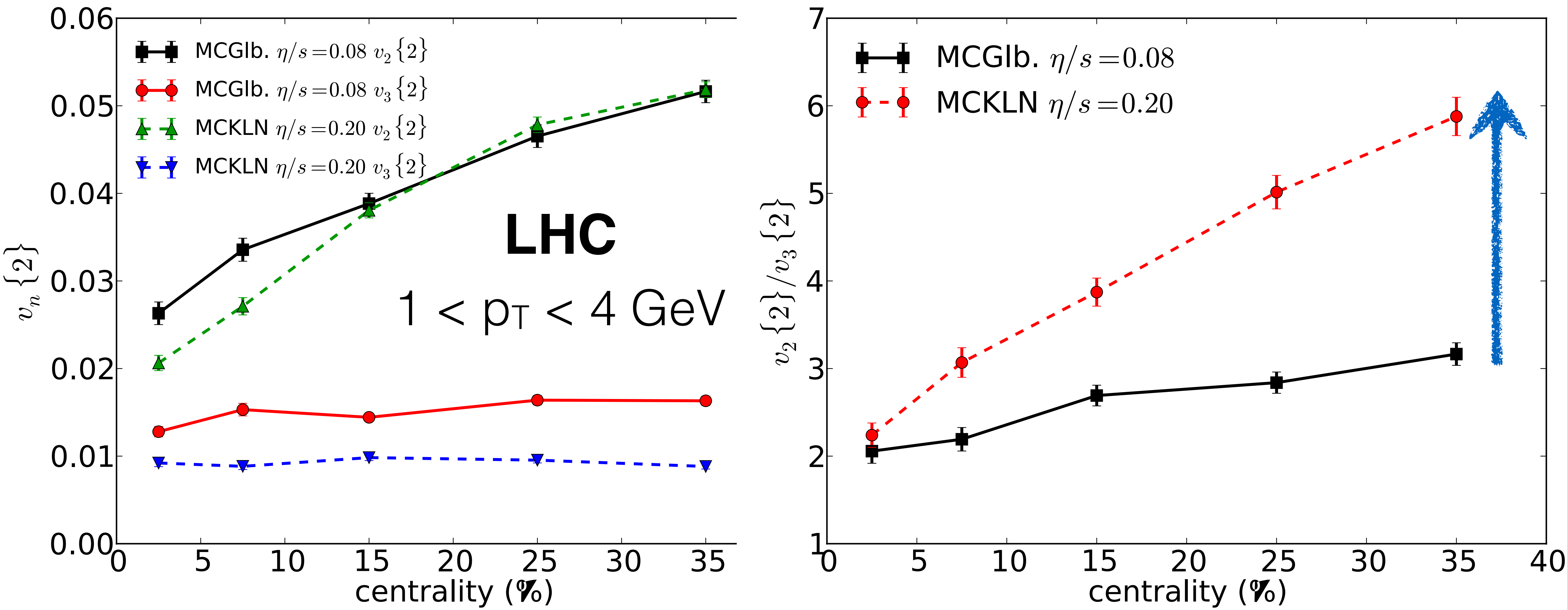
Event-by-event full viscous photon v_n



- E-by-e hydro allows to predict v_3, v_4, v_5, ...
- v_3 measurement can kill exotic production mechanisms for large v_2
- Size of photon v_3/v_2 can constrain shear viscosity at early times

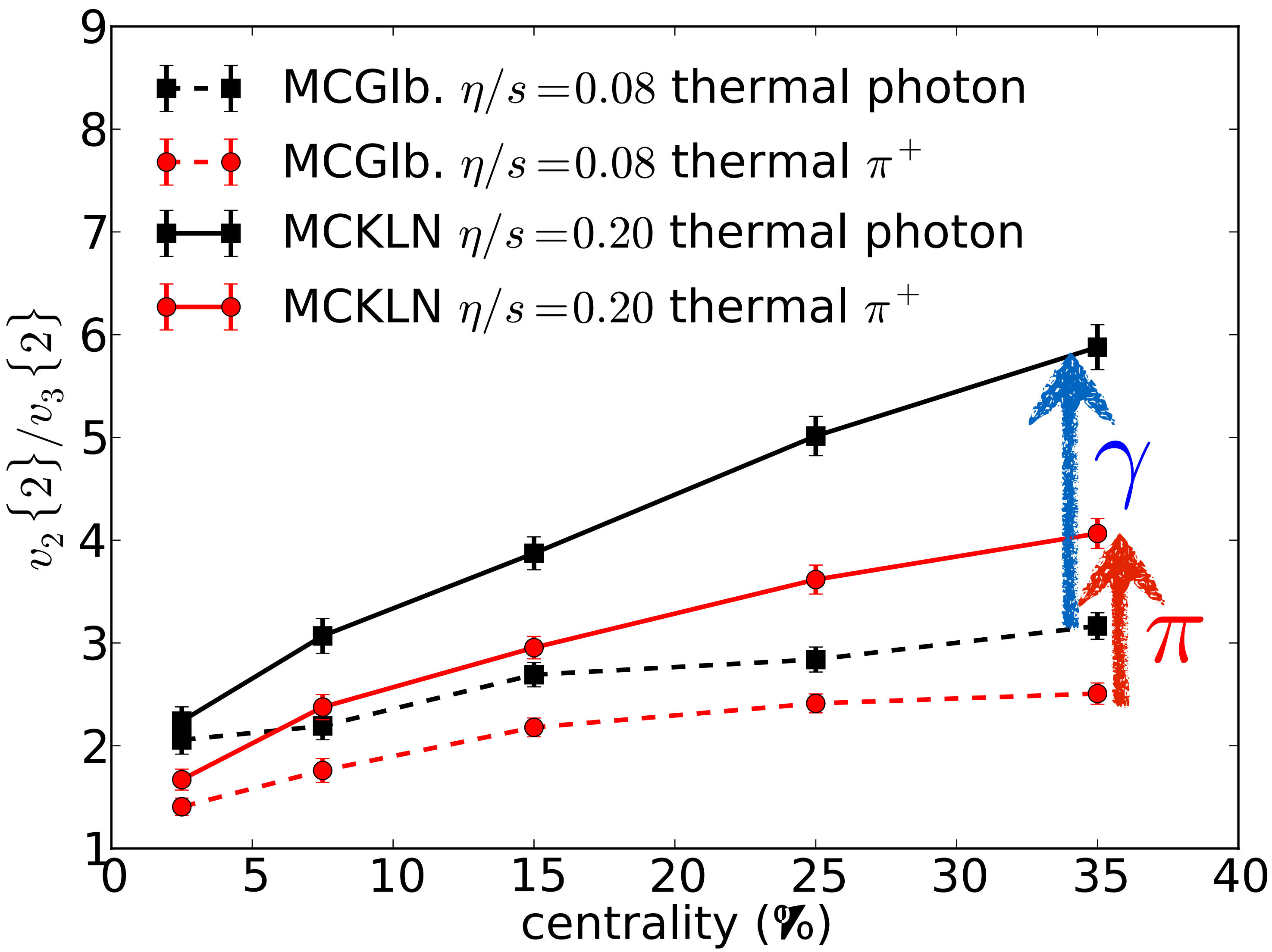
Shen Mo17:20

Event-by-event full viscous photon v_n



- Anisotropic photon flows show qualitatively similar centrality dependence as hadron flows
- The ratio v_2/v_3, and its slope as a function of centrality, increase with shear viscosity.

Event-by-event full viscous photon v_n



C. Shen

- Anisotropic photon flows show qualitatively similar centrality dependence as hadron flows
- The ratio of v_2/v_3, and its slope as a function of centrality, increase with shear viscosity.
- The centrality dependence of this ratio is stronger for photons than for hadrons, **due to stronger viscous effects at early times!**

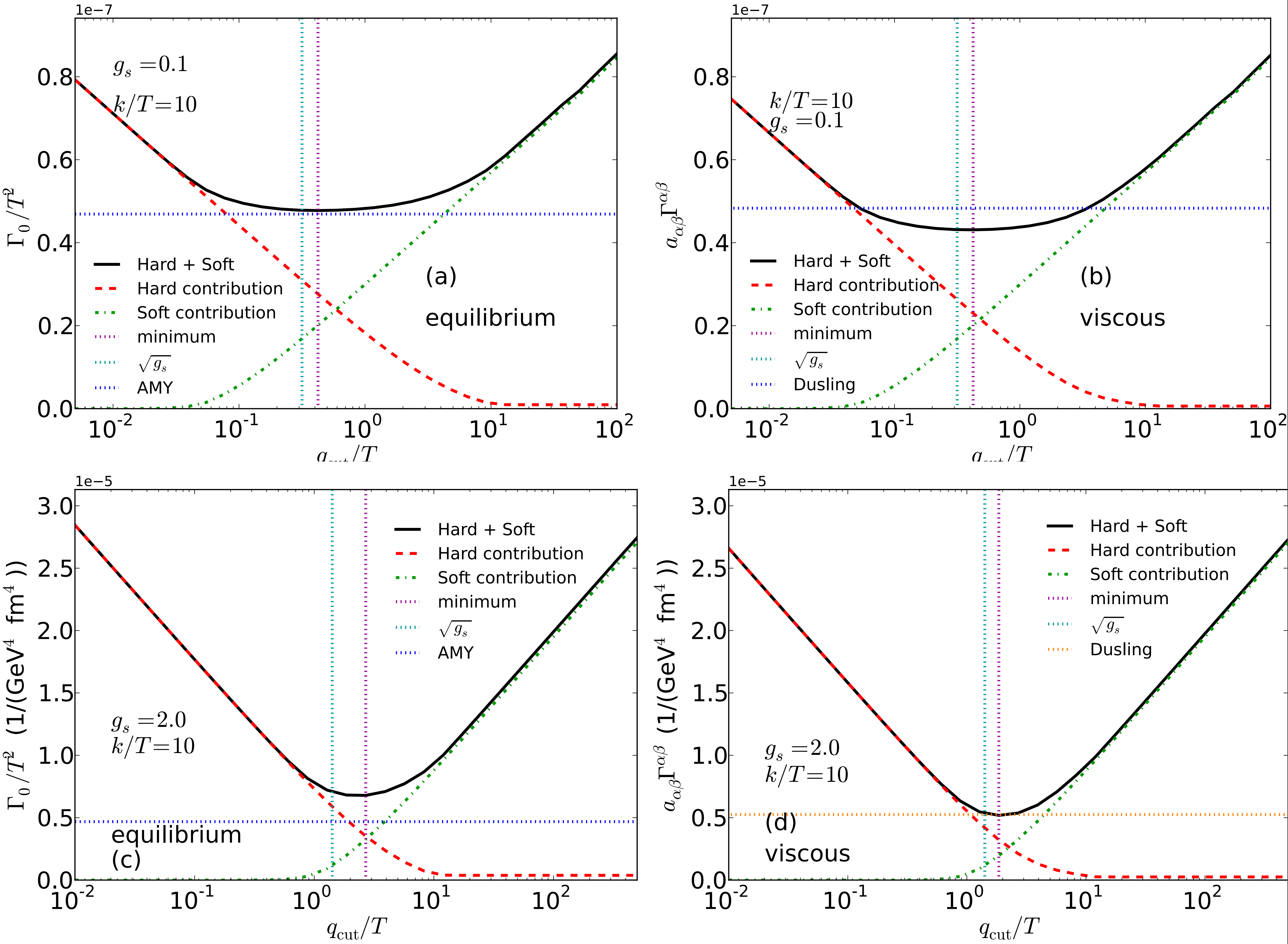
Conclusions

- The large measured photon v_2 continues to be a challenge for theory
- Hydrodynamic models produce too much radiation at early times and too little at late times to reproduce measured photon spectra and v_2 at low p_T -- are our emission rates wrong?
- Photons are more susceptible to shear viscosity than hadrons, and shear viscosity further reduces v_2
- Can use centrality dependence of photon vs. hadron v_2/v_3 ratio to constrain shear viscosity at early times

Thanks to:

Chun Shen,
Jean-Francois Paquet,
Evan Frodermann,
Zhi Qiu,
Rupa Chatterjee,
Dinesh Srivastava
Charles Gale

Back up



1e−7
$g_s = 0.1$
$k/T = 10$
0.8
0.6
0.4
0.2
0.0
Γ_0/T^2
Hard + Soft
Hard contribution
Soft contribution
minimum
$\sqrt{g_s}$
AMY
(a)
equilibrium
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}
q_{cut}/T
1e−7
$k/T = 10$
$g_s = 0.1$
$a_{\alpha\beta}\Gamma^{\alpha\beta}$
Hard + Soft
Hard contribution
Soft contribution
minimum
$\sqrt{g_s}$
Dusling
(b)
viscous
q_{cut}/T
1e−5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Γ_0/T^2 (1/(GeV^4 fm^4))
Hard + Soft
Hard contribution
Soft contribution
minimum
$\sqrt{g_s}$
AMY
$g_s = 2.0$
$k/T = 10$
equilibrium
(c)
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}
q_{cut}/T
1e−5
$a_{\alpha\beta}\Gamma^{\alpha\beta}$ (1/(GeV^4 fm^4))
Hard + Soft
Hard contribution
Soft contribution
minimum
$\sqrt{g_s}$
Dusling
$g_s = 2.0$
$k/T = 10$
(d)
viscous
q_{cut}/T