"THERMAL" PHOTONS FROM IDEAL AND VISCOUS MEDIA

OUTLINE

- Sources & EM emissivity
- Modelling the evolving system:
  - 3D hydro
  - 3D viscous hydro
  - Fluctuating initial states
- Are photons sensitive to all of the above?
  - If so, can we quantify this?

Charles Gale
McGill University

INFO CARRIED BY THE RADIATION

$$dR = -\frac{g^{\mu\nu}}{2\omega}\frac{d^3k}{(2\pi)^3}\frac{1}{Z}\sum_i e^{-\beta K_i}\sum_f (2\pi)^4\delta(p_i - p_f - k)$$
$$\times\langle j \mid J_\mu \mid i\rangle\langle i \mid J_\nu \mid j\rangle$$

Thermal ensemble average of the current-current correlator

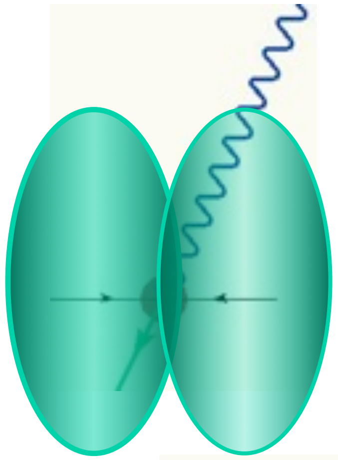
Emission rates:

$$\omega\frac{d^3R}{d^3k} = -\frac{g^{\mu\nu}}{(2\pi)^3}\mathrm{Im}\Pi_{\mu\nu}(\omega,k)\frac{1}{e^{\beta\omega}-1} \quad \text{(photons)}$$

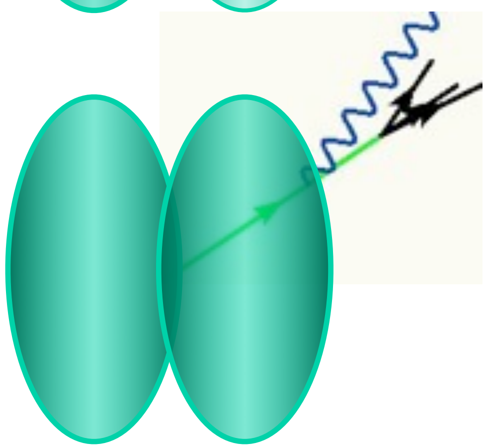
$$E_+E_-\frac{d^6R}{d^3p_+d^3p_-} = \frac{2e^2}{(2\pi)^6}\frac{1}{k^4}L^{\mu\nu}\,\mathrm{Im}\,\Pi^R_{\mu\nu}(\omega,k)\frac{1}{e^{\beta\omega}-1} \quad \text{(dileptons)}$$

McLerran, Toimela (85), Weldon (90), Gale, Kapusta (91)

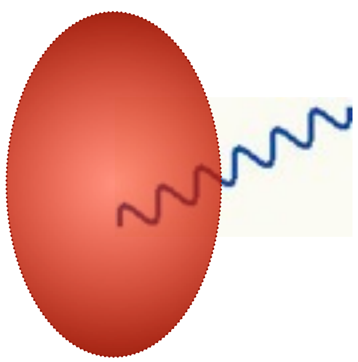
Sources of photons:



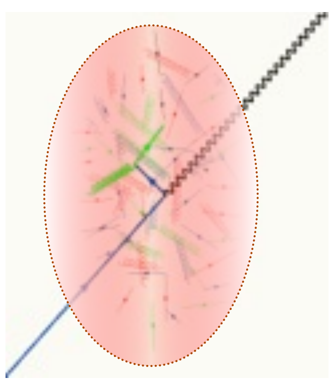
Hard direct photons. pQCD with shadowing
Non-thermal



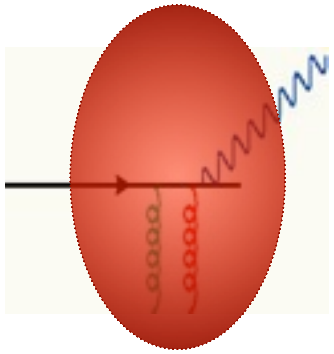
Fragmentation photons. pQCD with shadowing
Non-thermal



Thermal photons
Thermal

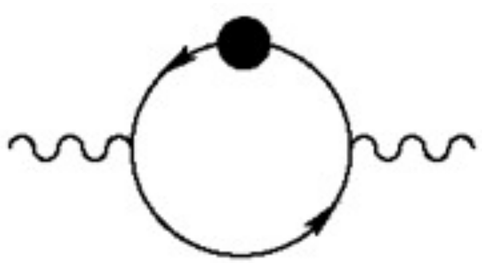


Jet-plasma photons
Thermal



Jet in-medium bremsstrahlung
Thermal

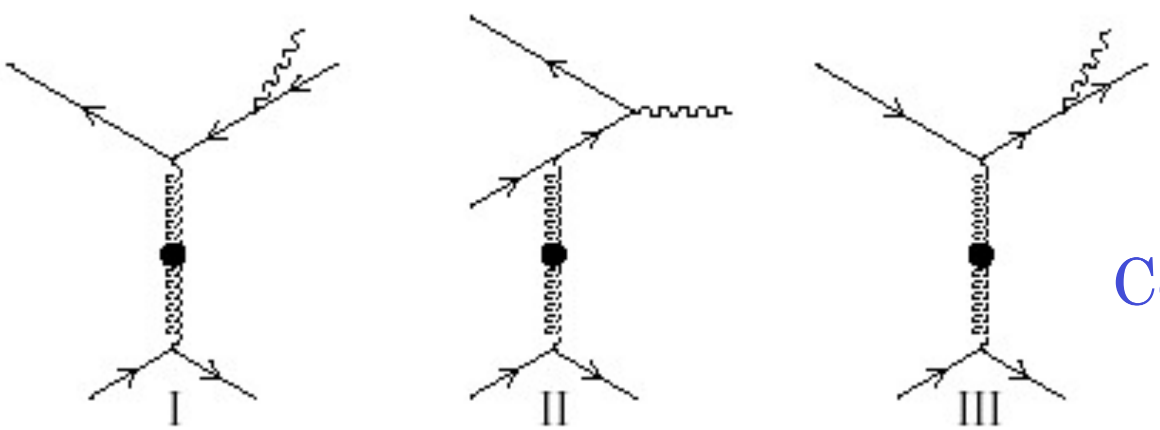
Thermal Photons from hot QCD: HTL program (Klimov (1981), Weldon (1982), Braaten & Pisarski (1990); Frenkel & Taylor (1990))



$$\mathrm{Im}\,\Pi^{\mu}_{R\mu} \sim \ln\left(\frac{\varpi T}{\left(m_{th}\left(\sim gT\right)\right)^{2}}\right)$$

Kapusta, Lichard, Seibert (1991)
Baier, Nakkagawa, Niegawa, Redlich (1992)

Going to two loops: Aurenche, Kobes, Gelis, Petitgirard (1996)
Aurenche, Gelis, Kobes, Zaraket (1998)



Co-linear singularities: $\alpha_s^2\left(\frac{T^2}{m_{th}^2}\right) \sim \alpha_s$

2001: Results complete at $O(\alpha_s)$

Arnold, Moore, and Yaffe JHEP **12**, 009 (2001); JHEP **11**, 057 (2001)
Incorporate LPM; Inclusive treatment of collinear enhancement, photon and gluon emission

Electromagnetic radiation from hadrons

Chiral, Massive Yang-Mills:

O. Kaymakcalan, S. Rajeev, J. Schechter, PRD 30, 594 (1984)

$$L = \frac{1}{8} F_\pi^2 \,\mathrm{Tr}\, D_\mu U D^\mu U^\dagger + \frac{1}{8} F_\pi^2 \,\mathrm{Tr}\, M \left(U + U^\dagger \right)$$

$$- \frac{1}{2} \mathrm{Tr} \left(F_{\mu\nu}^L F^{L\mu\nu} + F_{\mu\nu}^R F^{R\mu\nu} \right) + m_0^2 \mathrm{Tr} \left(A_\mu^L A^{L\mu} + A_\mu^R A^{R\mu} \right)$$

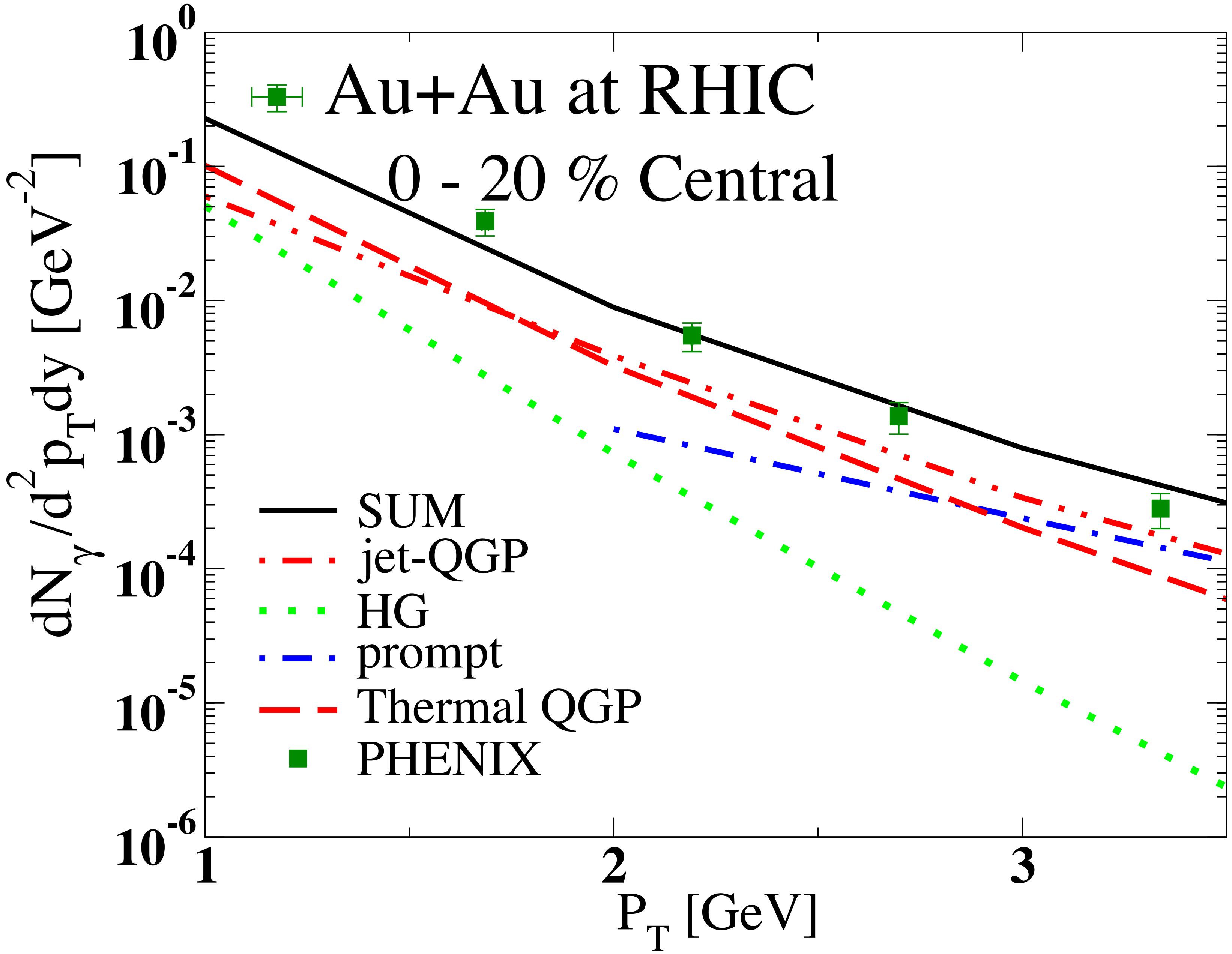
$$+ \text{ non-minimal terms}$$

Parameters and form factors are constrained by hadronic phenomenology:

- Masses & strong decay widths
- Electromagnetic decay widths
- Other hadronic observables:
  - *e.g.* $a_1 \to \pi\rho \quad D/S$ (See also, Lichard and Vojik, arXiv:1006.2919)

EM emissivities computed: Turbide, Rapp, Gale, PRC (2004); Turbide, McGill PhD (2006)

Applying this to the soft sector @ RHIC

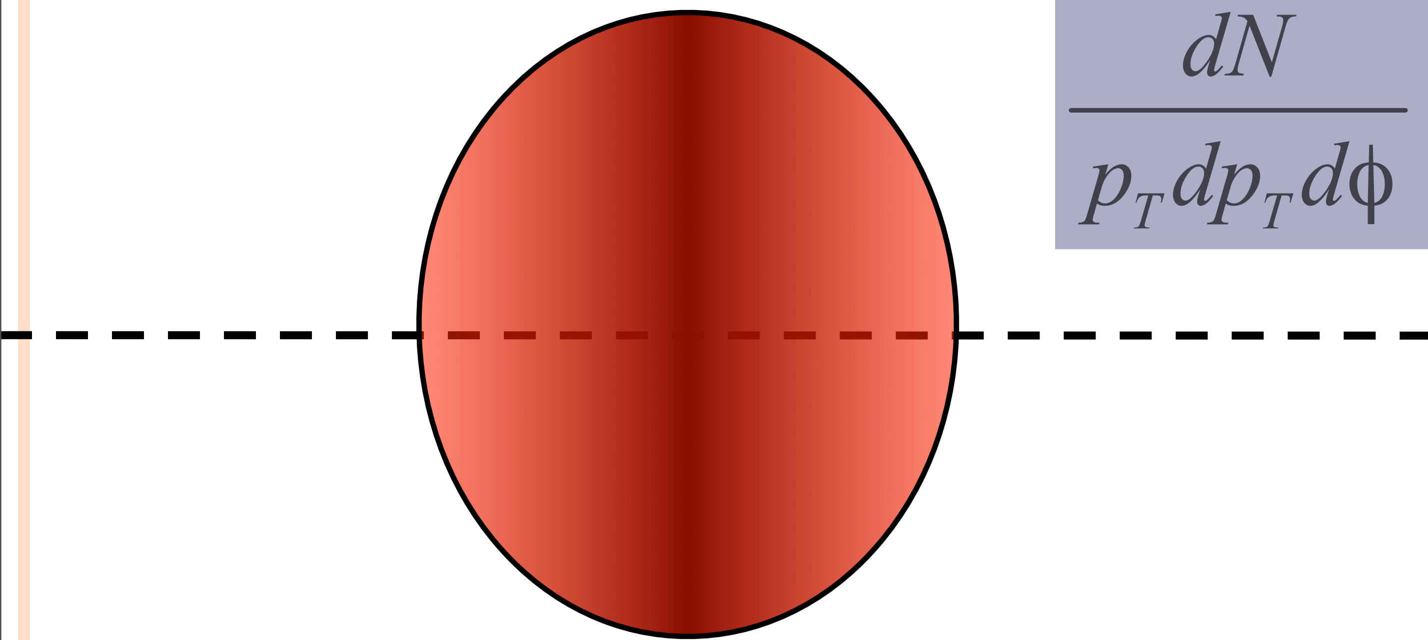


- At low p_T, spectrum dominated by thermal components (HG, QGP)
- At high p_T, spectrum dominated by pQCD
- Window for jet-QPG contributions at mid-p_T

Turbide, Gale, Frodermann, Heinz, PRC (2008);
Higher p_T: G. Qin et al., PRC (2009)

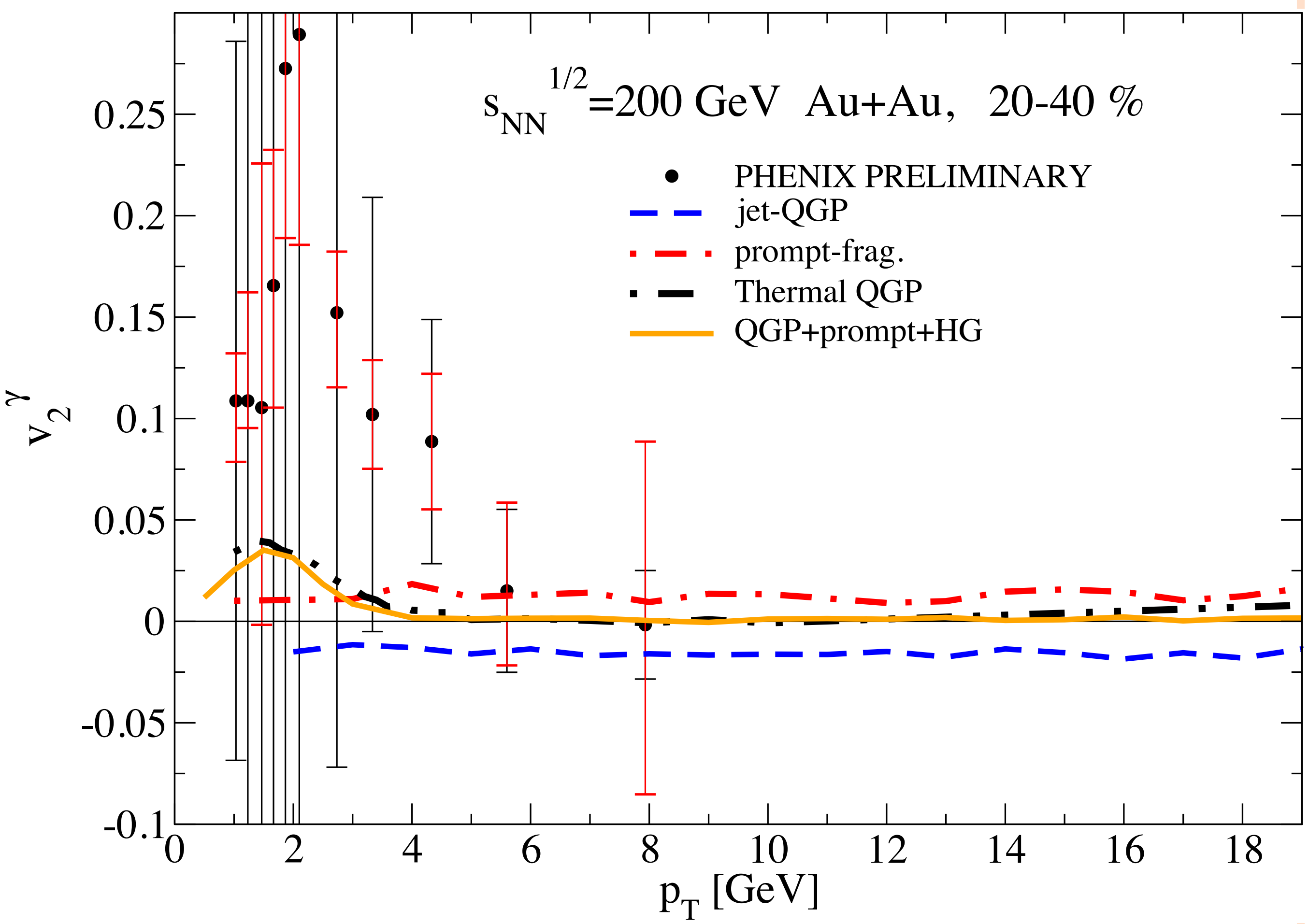
BEYOND ONE-BODY DATA: FLOW AND CORRELATIONS

$$\frac{dN}{p_T dp_T d\phi} = \frac{dN}{2\pi\, p_T dp_T}\left[1 + \sum_n 2v_n \cos(n\phi)\right]$$



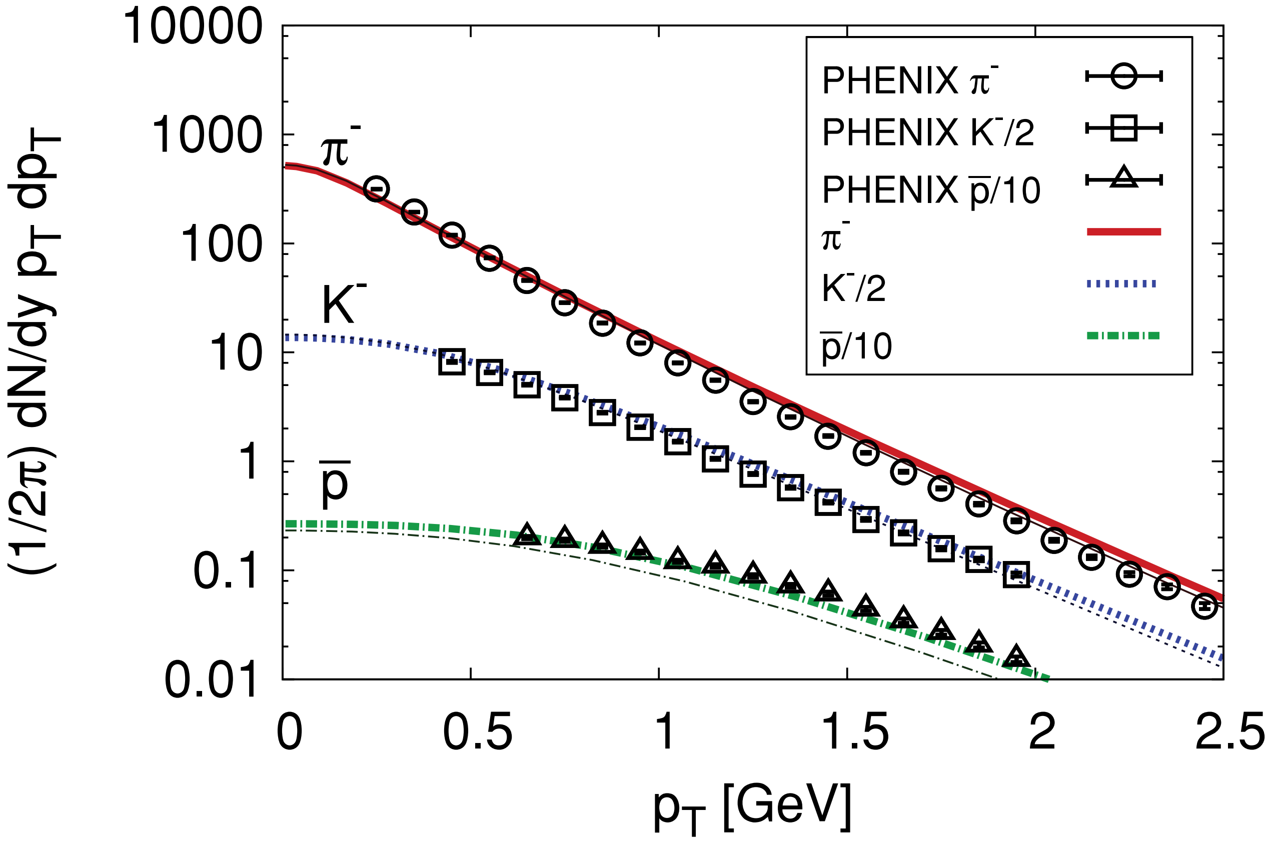
- Soft photons will go with the flow
- Jet-plasma photons: a negative v_2
- Details will matter: flow, T(t). . .

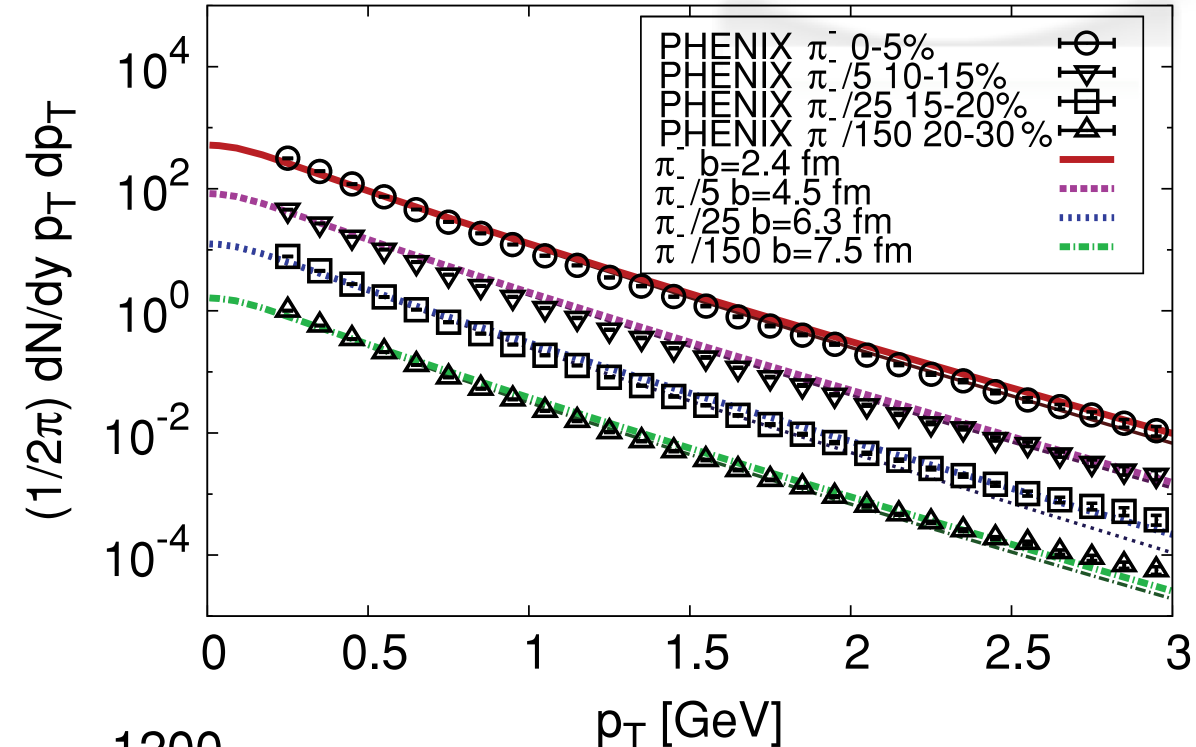
Turbide, Gale, Fries PRL (2006)
Low p_T: Chatterjee *et al.*, PRL (2006)
All p_T: Turbide *et al.*, PRC (2008)

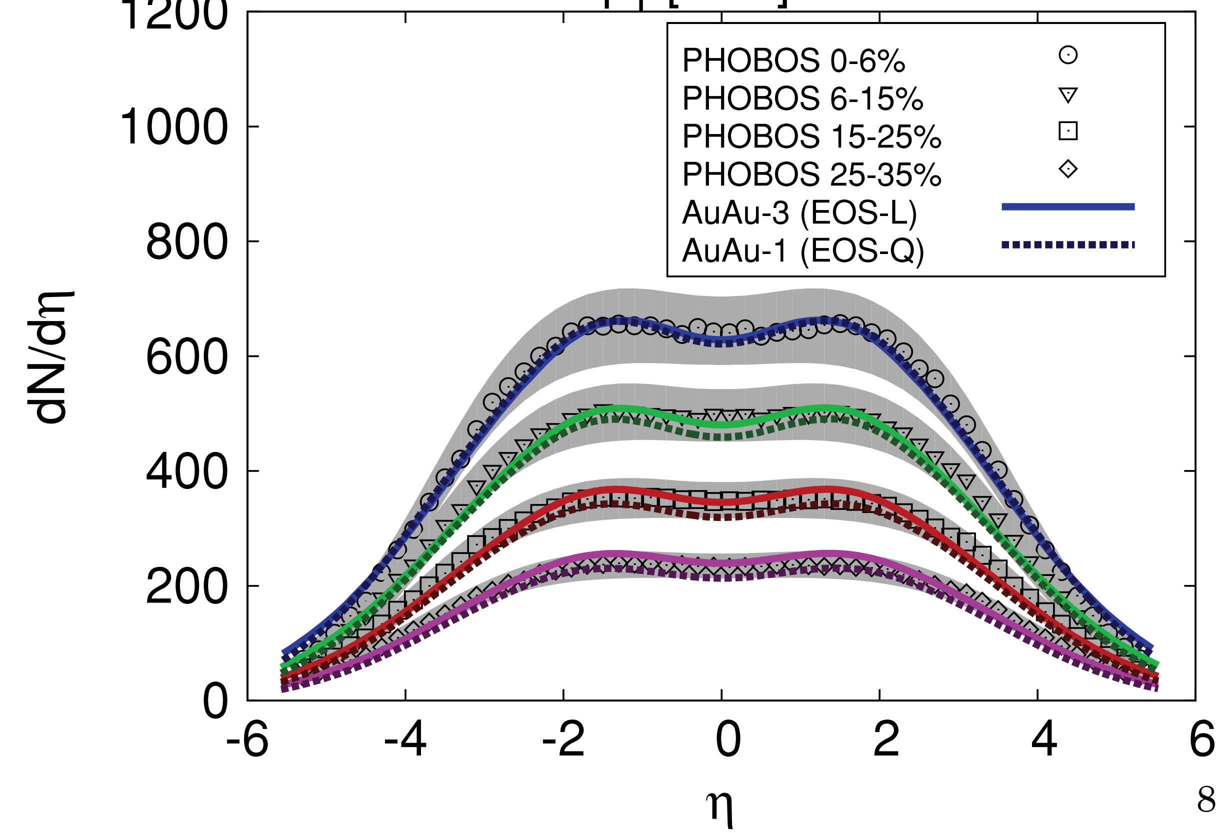


Charles Gale

3D Relativistic Hydrodynamics: MUSIC:







- MUSIC: 3D relativistic hydro
  - Ideal: Schenke, Jeon, and Gale, PRC (2010)
  - FIC and Viscous: Schenke, Jeon, Gale, PRL (2011)

The effects of shear viscosity on bulk dynamics

$$T^{\mu\nu}_{\text{ideal}} = (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu}$$

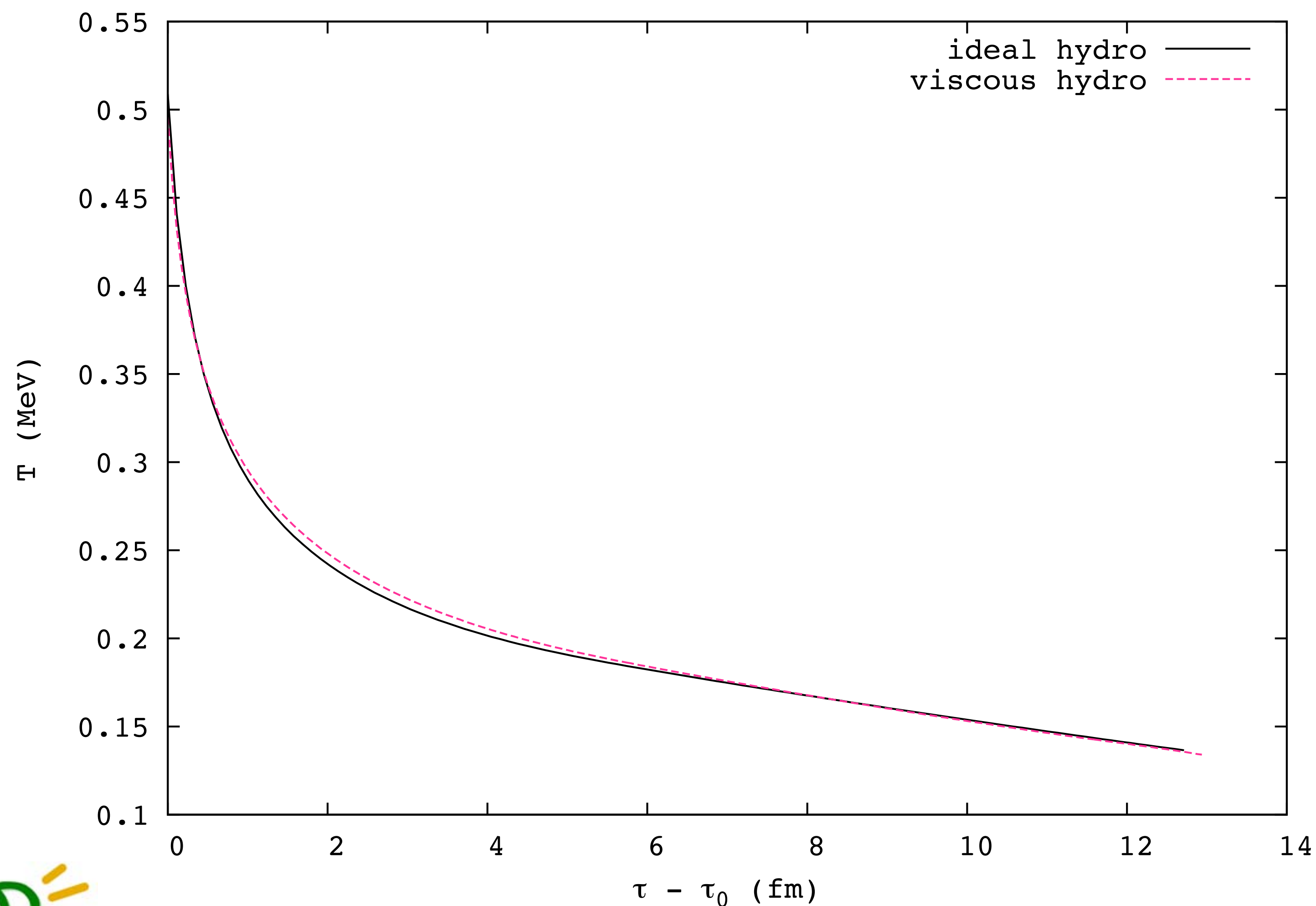
$$T^{\mu\nu} = T^{\mu\nu}_{\text{ideal}} + W^{\mu\nu}$$

Israël & Stewart, Ann. Phys. (1979), Baier et al., JHEP (2008), Luzum and Romatschke, PRC (2008)

$$\partial_\mu T^{\mu\nu} = 0, \quad \Delta^\mu_\alpha \Delta^\upsilon_\beta u^\sigma \partial_\sigma W^{\alpha\beta} = -\frac{1}{\tau_\pi}(W^{\mu\upsilon} - S^{\mu\upsilon}) - \frac{4}{3} W^{\mu\upsilon}(\partial_\alpha u^\alpha)$$

$$\partial_\mu (s u^\mu) \propto \eta$$

(c.f. Talk by B. Schenke)



- Viscous evolution starts with a lower T
- T drop is slower than ideal case

Charles Gale

The effects of shear viscosity on bulk dynamics

$$T^{\mu\nu}_{\text{ideal}} = (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu}$$

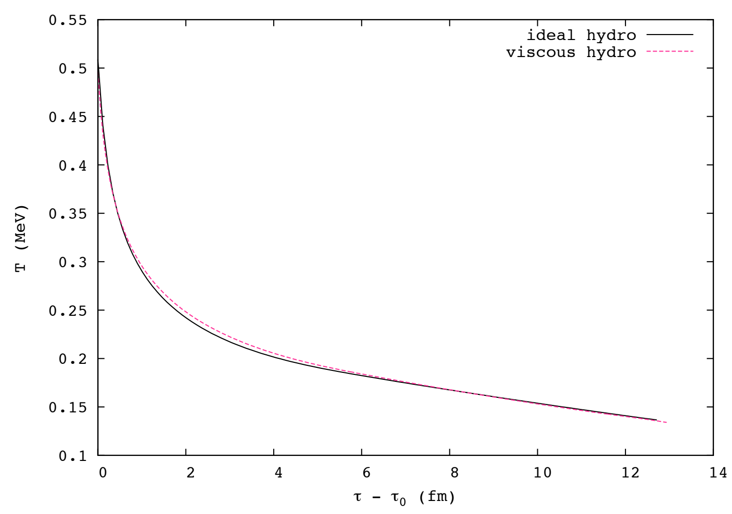
$$T^{\mu\nu} = T^{\mu\nu}_{\text{ideal}} + W^{\mu\nu}$$

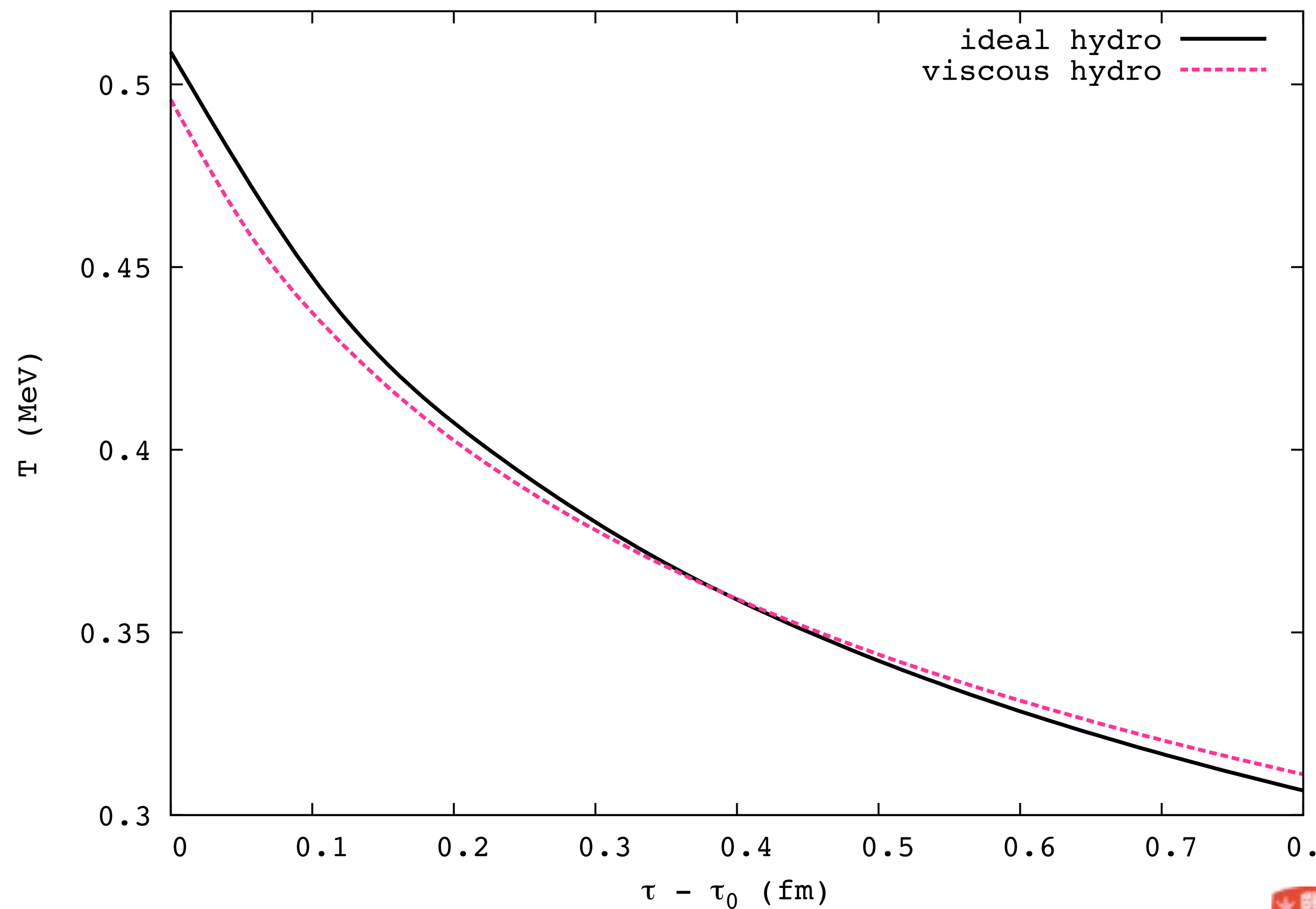
Israël & Stewart, Ann. Phys. (1979), Baier et al., JHEP (2008), Luzum and Romatschke, PRC (2008)

$$\partial_\mu T^{\mu\nu} = 0, \quad \Delta^\mu_\alpha \Delta^\upsilon_\beta u^\sigma \partial_\sigma W^{\alpha\beta} = -\frac{1}{\tau_\pi}(W^{\mu\upsilon} - S^{\mu\upsilon}) - \frac{4}{3} W^{\mu\upsilon}(\partial_\alpha u^\alpha)$$

$$\partial_\mu (s u^\mu) \propto \eta$$

(c.f. Talk by B. Schenke)





THE EFFECTS OF SHEAR VISCOSITY ON THE PHOTON DISTRIBUTION

In-medium **hadrons**:

$$f_0(u^\mu p_\mu) = \frac{1}{(2\pi)^3}\frac{1}{\exp[(u^\mu p_\mu - \mu)/T]\pm 1}$$

$$f \rightarrow f_0 + \delta f, \quad \delta f = f_0(1\pm f_0)p^\alpha p^\beta W_{\alpha\beta}\frac{1}{2(\varepsilon + P)T^2}$$

$$q_0\frac{d^3R}{d^3q} = \int \frac{d^3p_1}{2(2\pi)^3E_1}\frac{d^3p_2}{2(2\pi)^3E_2}\frac{d^3p_3}{2(2\pi)^3E_3}(2\pi)^4|M|^2\delta^4(\ldots)\frac{f(E_1)f(E_2)\left[1\pm f(E_3)\right]}{2(2\pi)^3}$$

One considers all the reaction and radiative decay channels of external state combinations of:

$\{\pi, K, \rho, K^*, a_1\}$ With hadronic form factors

+ QGP Photons

Charles Gale

The effects of shear viscosity on the photon distribution

In-medium **hadrons**:

Ansatz: Dusling, Moore, Teaney PRC (2010)

$$f_0(u^\mu p_\mu) = \frac{1}{(2\pi)^3}\frac{1}{\exp[(u^\mu p_\mu - \mu)/T]+1}$$

$$f \to f_0 + \delta f, \quad \delta f = f_0(1 \pm f_0) p^\alpha p^\beta W_{\alpha\beta}\frac{1}{2(\varepsilon + P)T^2}$$

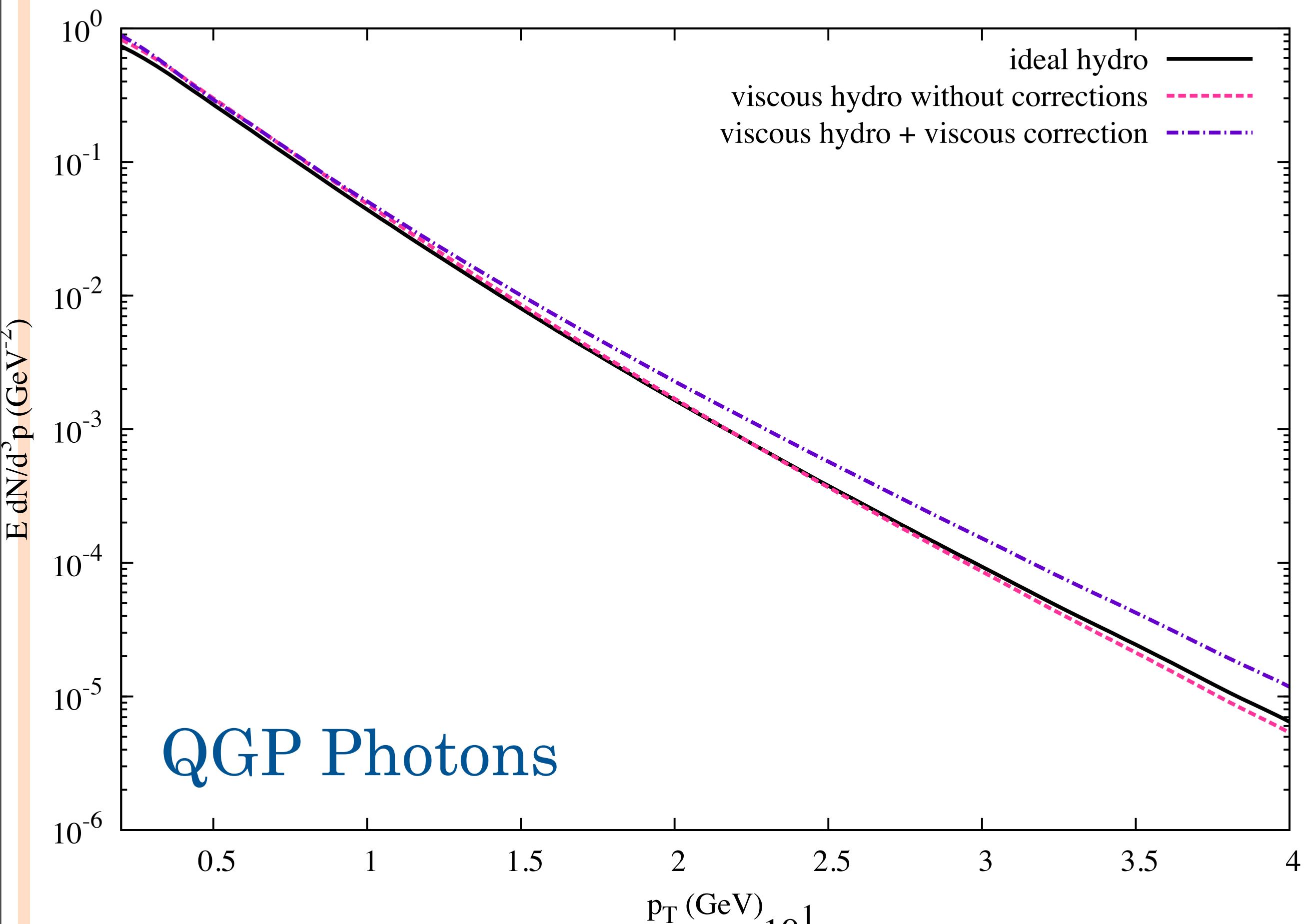
$$q_0 \frac{d^3R}{d^3q} = \int \frac{d^3p_1}{2(2\pi)^3 E_1}\frac{d^3p_2}{2(2\pi)^3 E_2}\frac{d^3p_3}{2(2\pi)^3 E_3}(2\pi)^4 |M|^2 \delta^4(\ldots)\frac{f(E_1)f(E_2)[1 \pm f(E_3)]}{2(2\pi)^3}$$

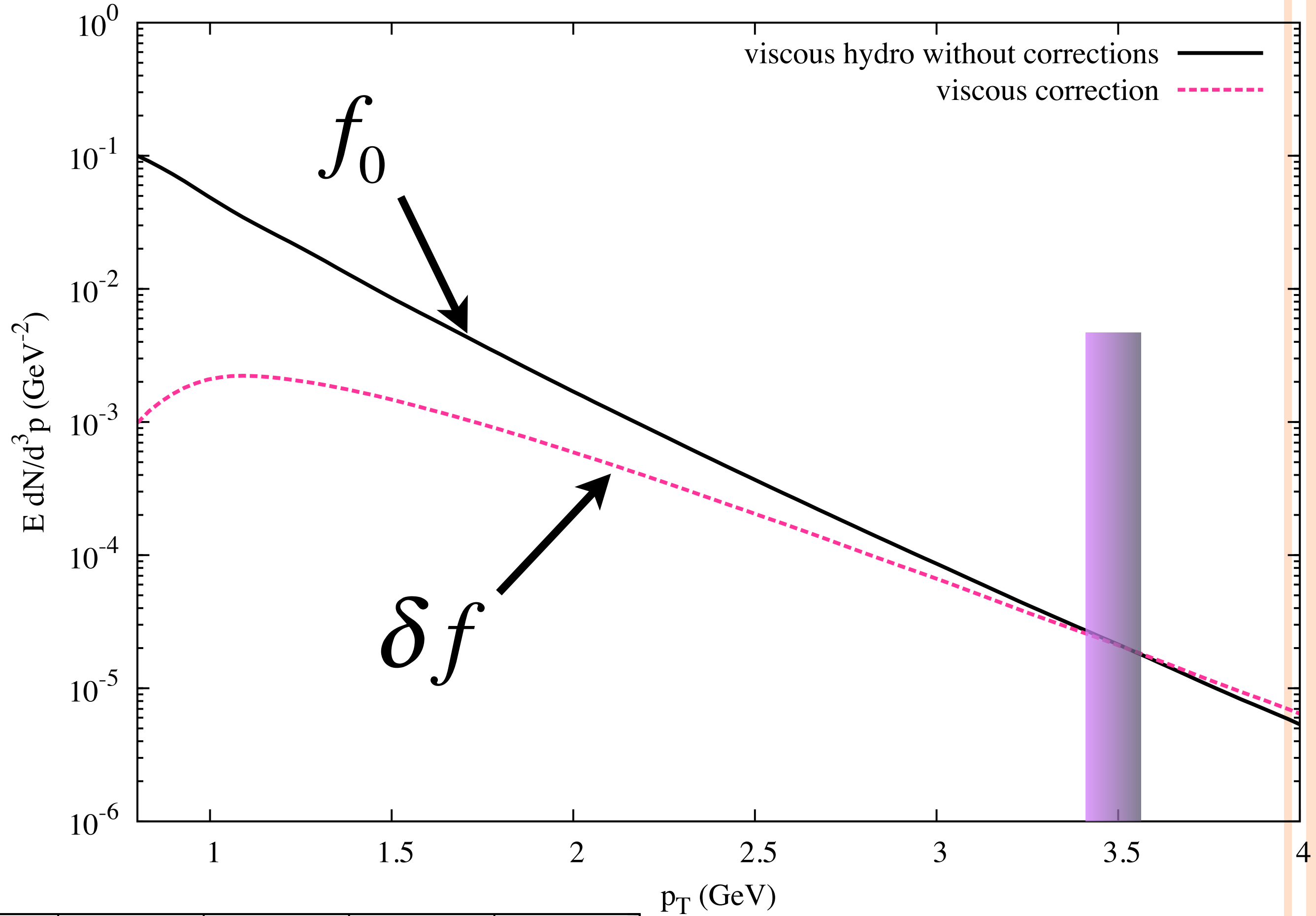
One considers all the reaction and radiative decay channels of external state combinations of:

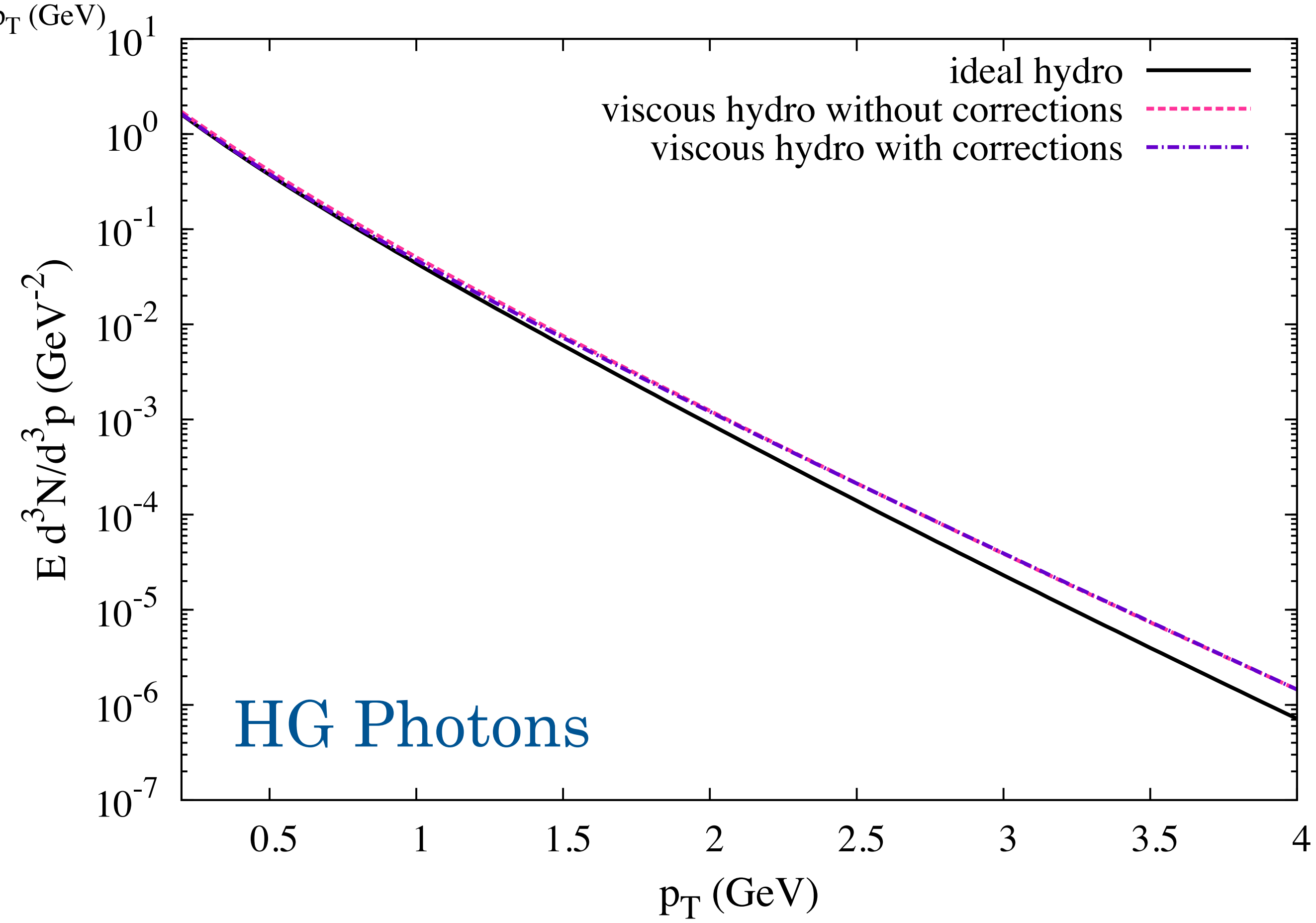
$\{\pi, K, \rho, K^*, a_1\}$ With hadronic form factors

+ QGP Photons

The effects of shear viscosity on the photon distribution

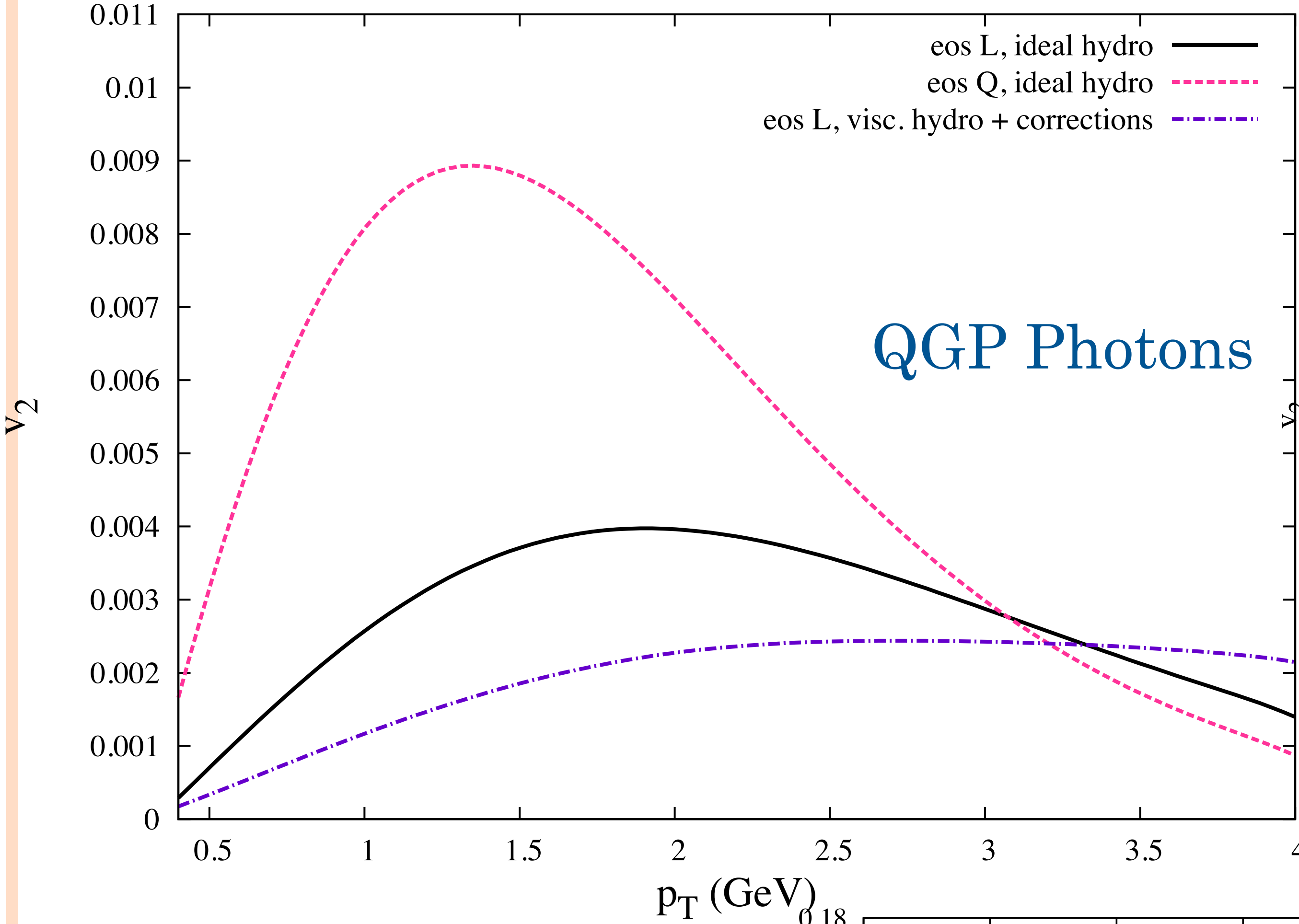


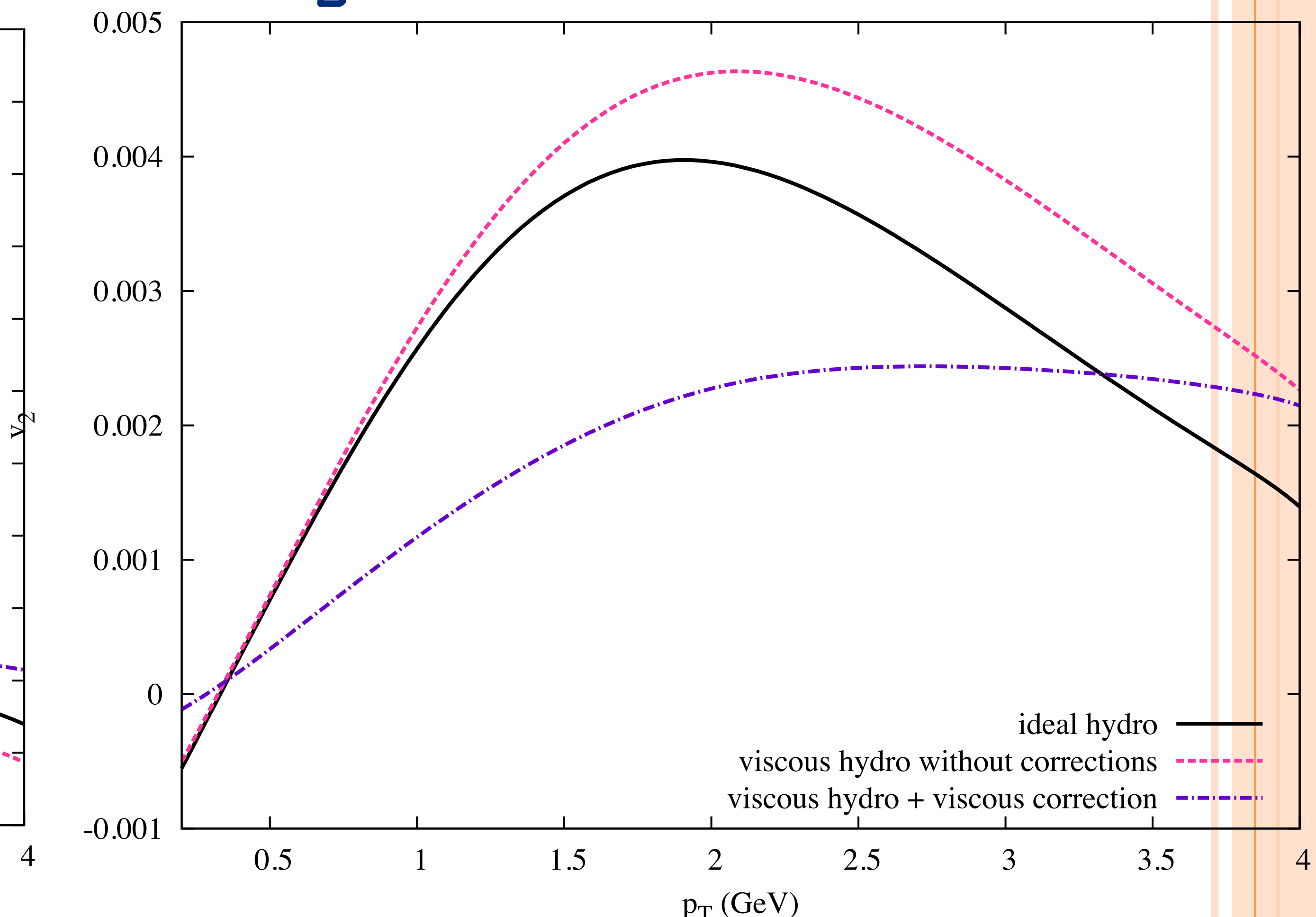


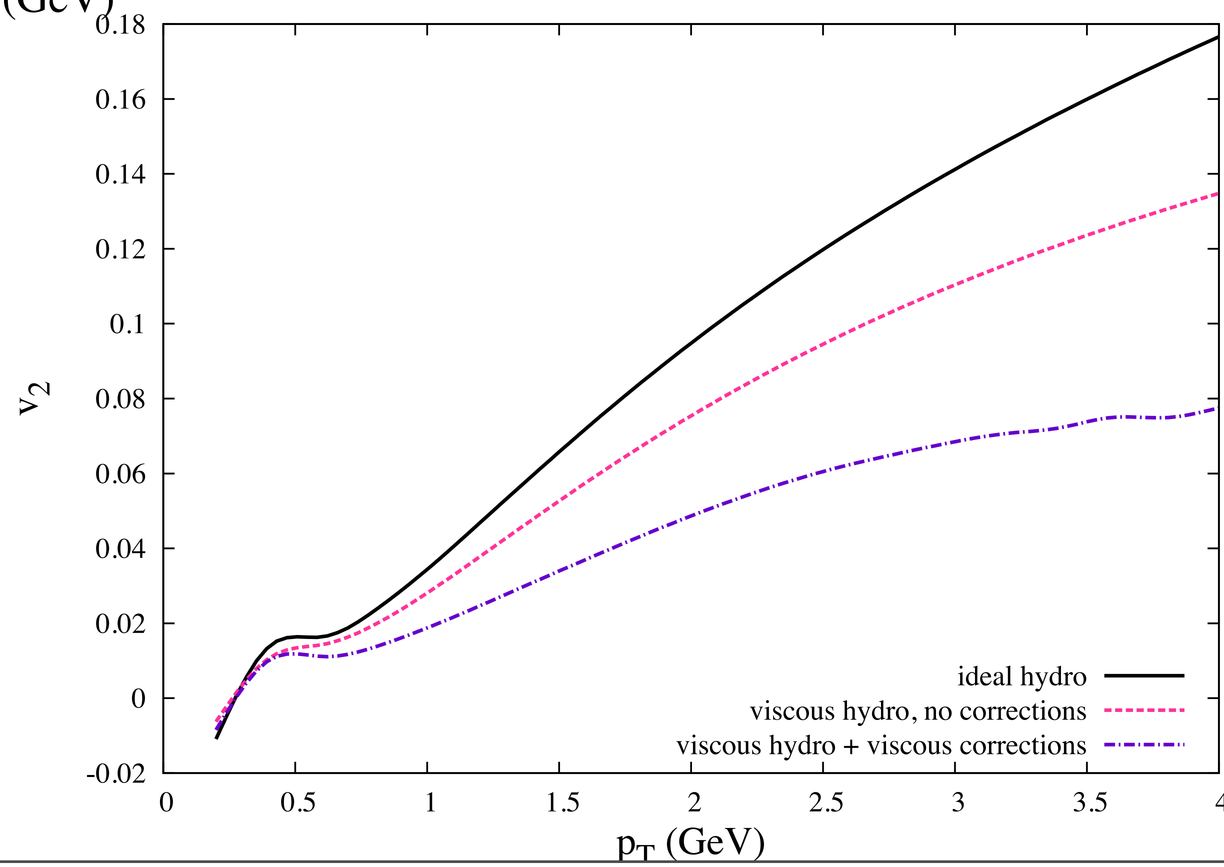


Charles Gale

The effects of the EOS and of shear viscosity on (QGP) photon v_2



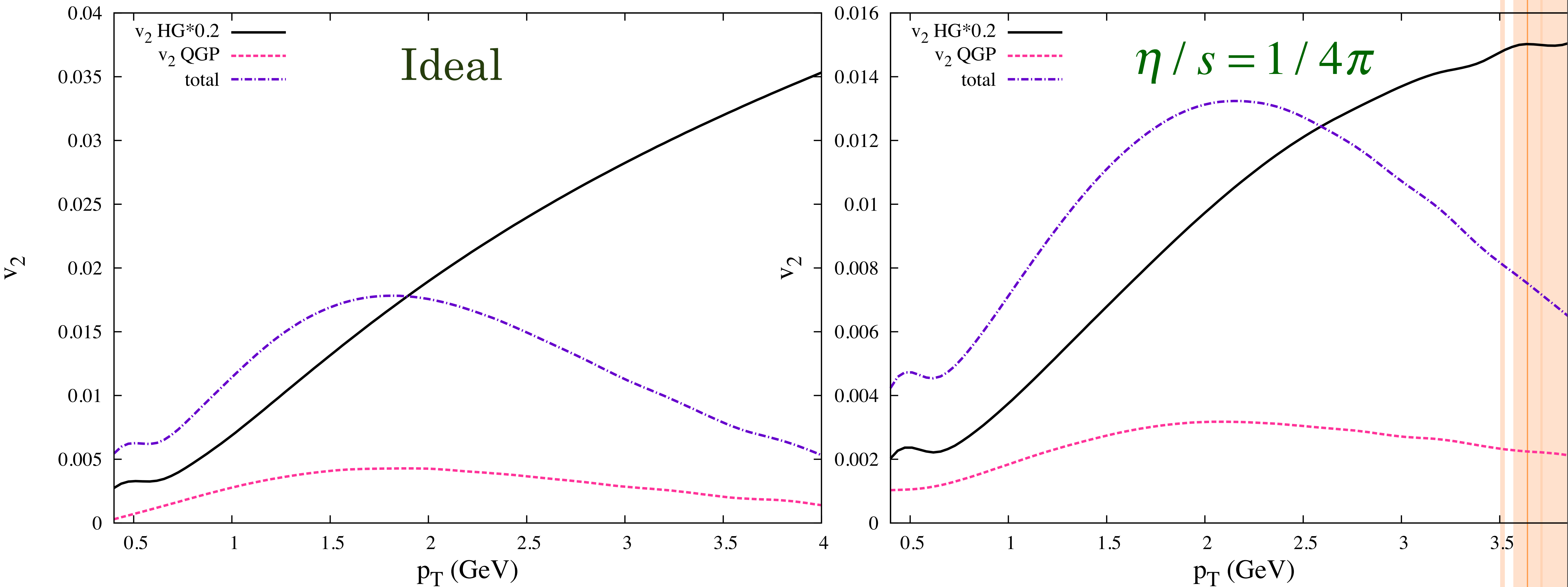




HG Photons

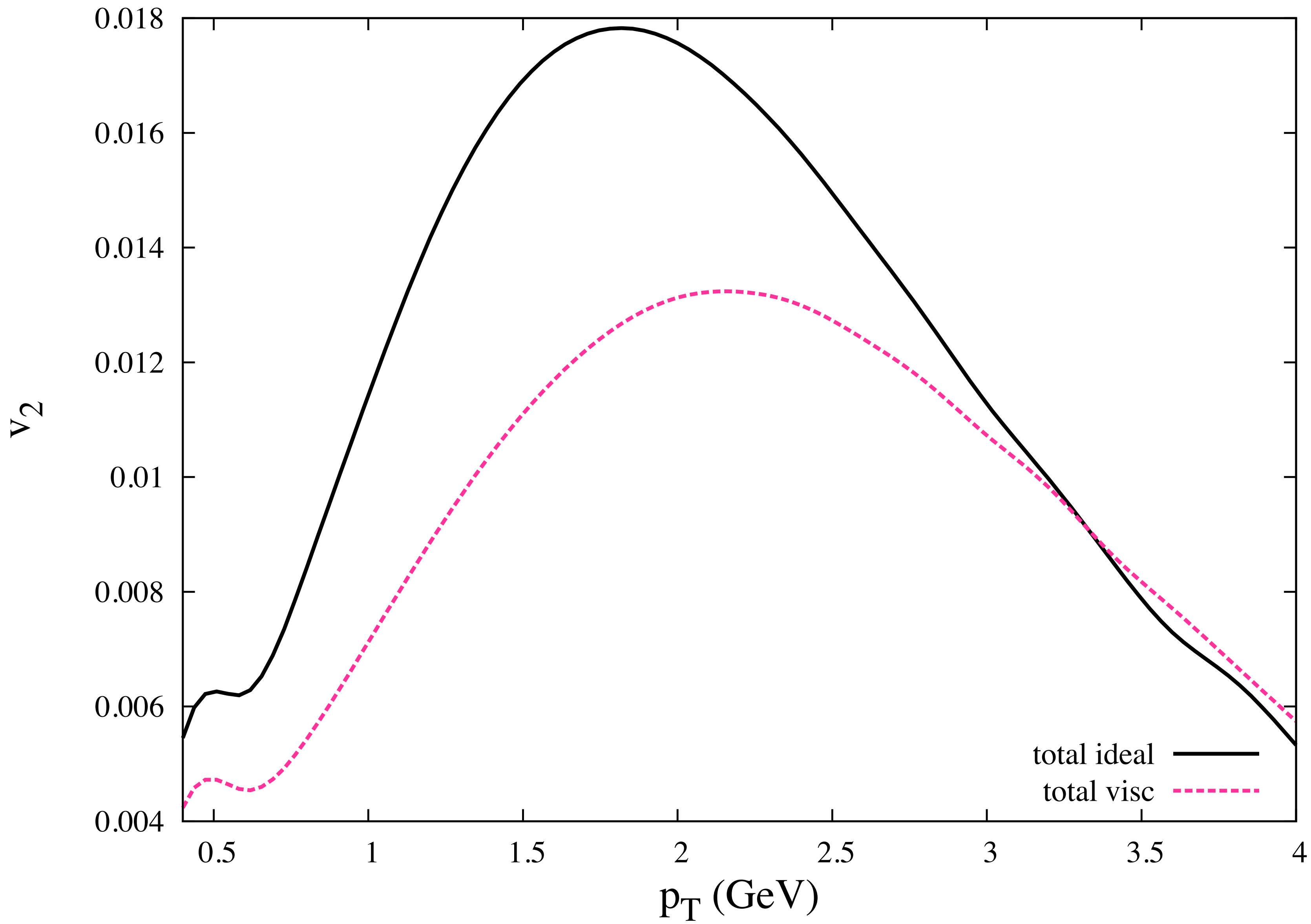
Charles Gale

Photons from the QGP + those from the hadronic gas: net v_2



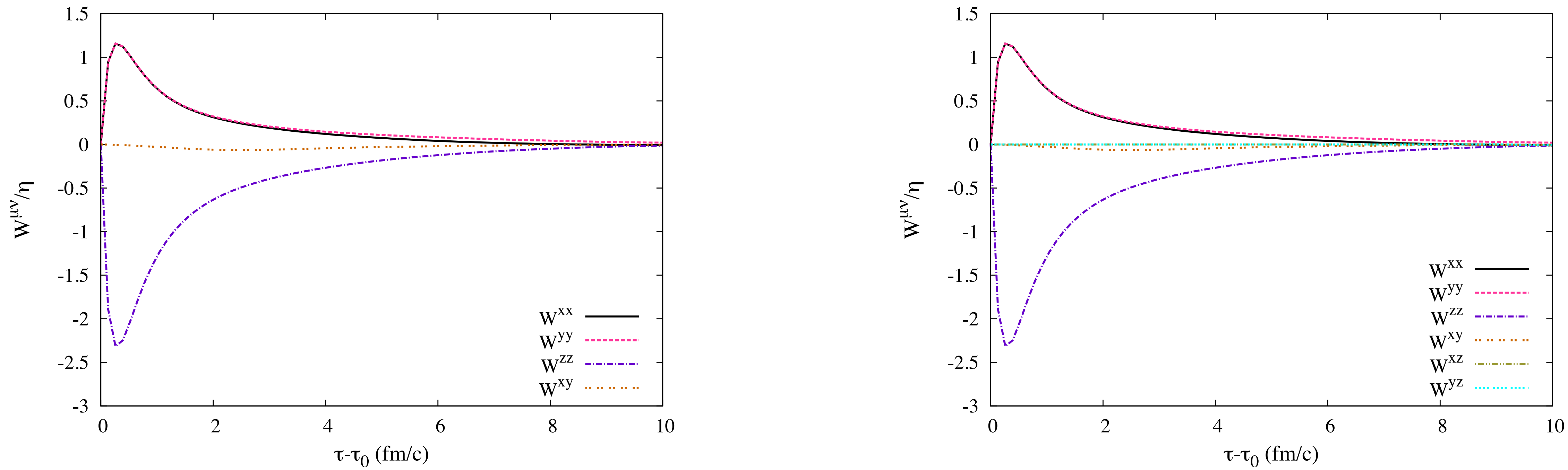
Charles Gale

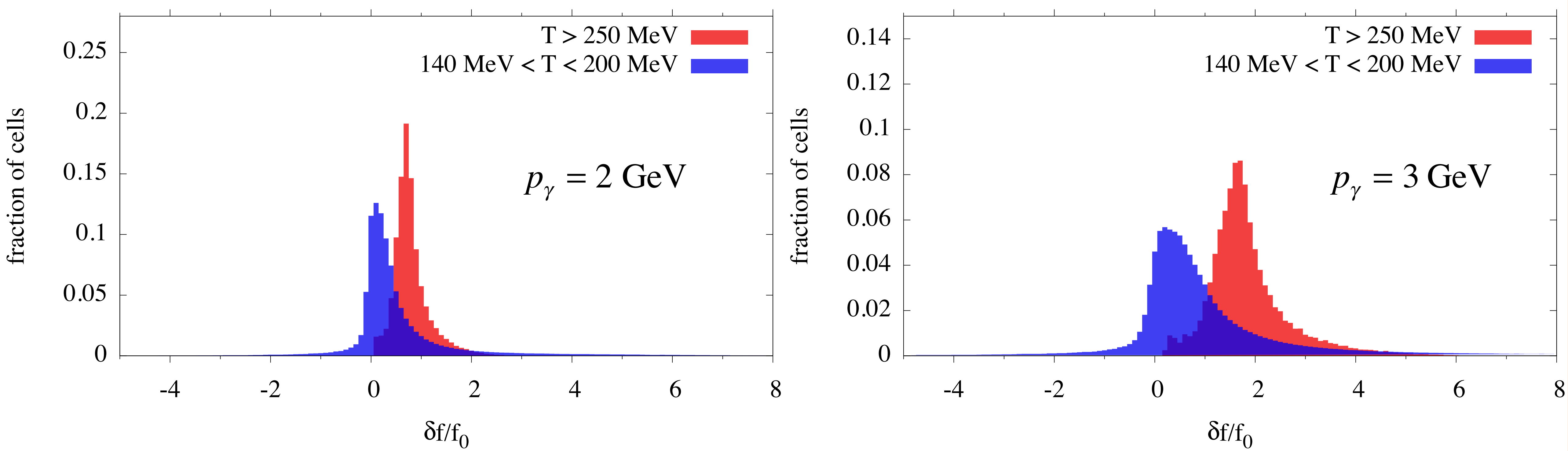
Photons from the QGP + those from the hadronic gas: net v_2



- Viscous corrections reduce v_2 (as for hadrons). At ~2 GeV ~40% reduction.

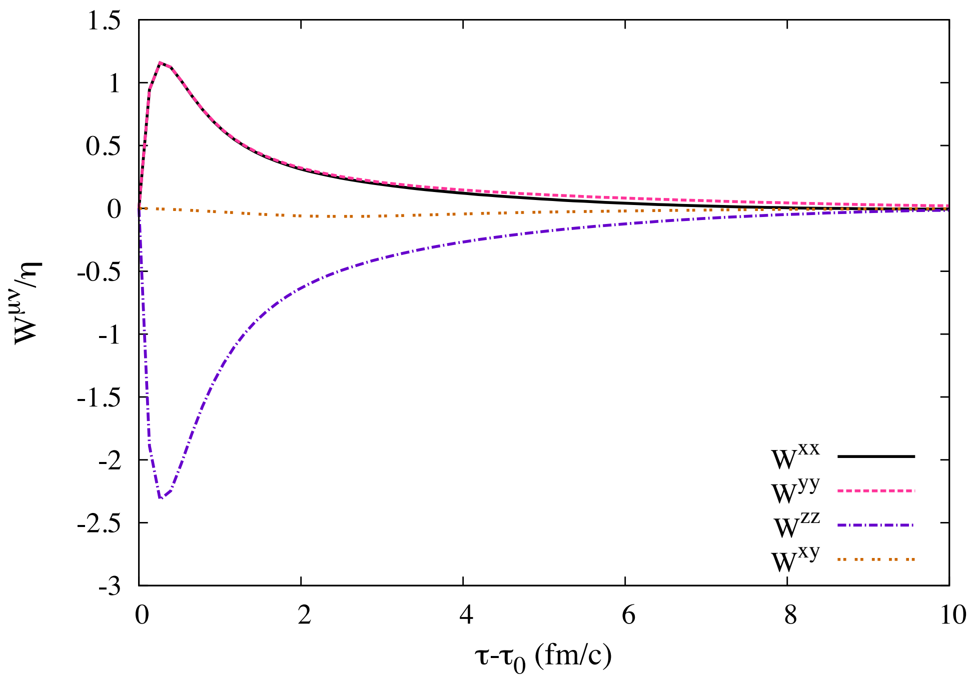
NON-EQUILIBRIUM EFFECTS

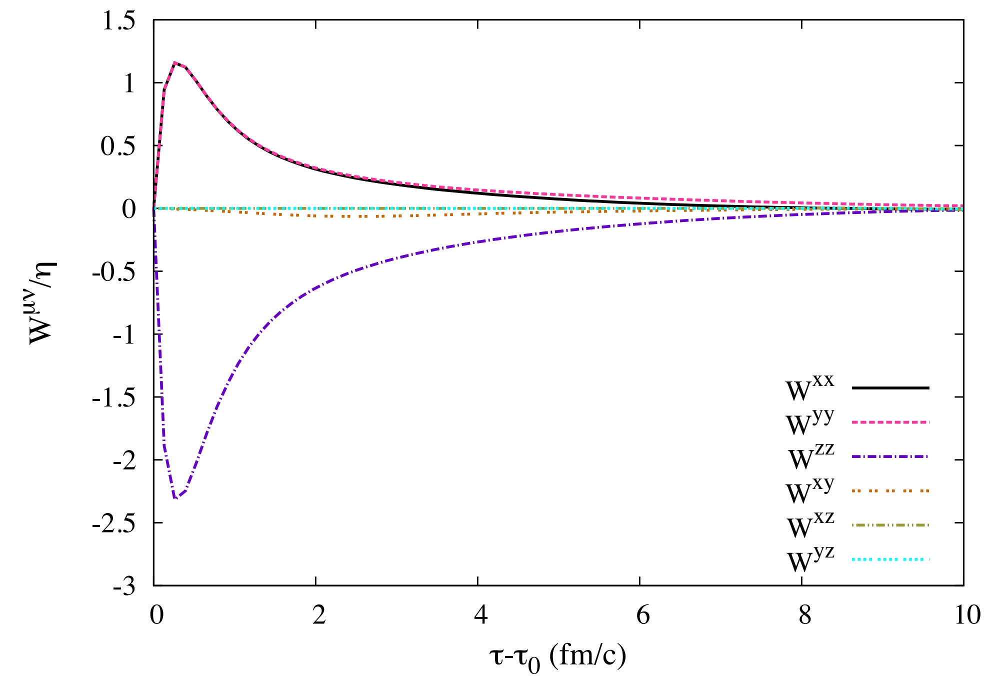


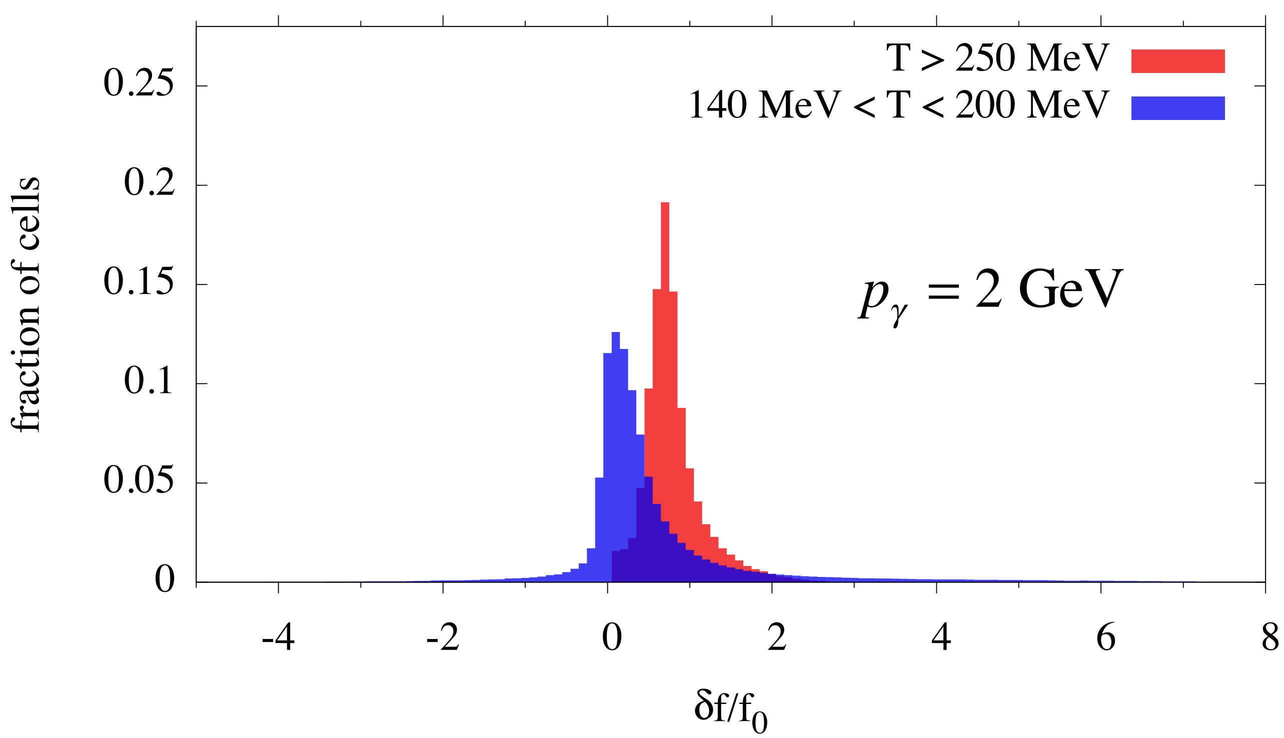


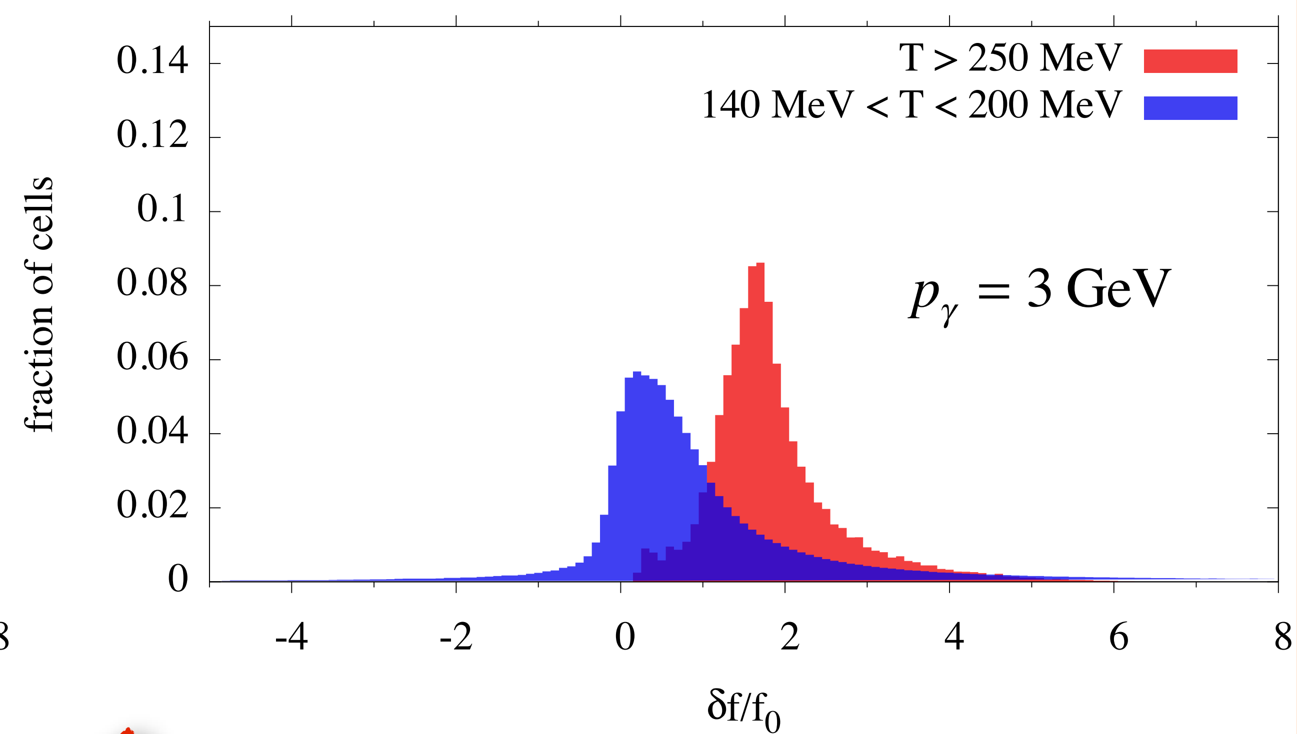
Photons probe the dynamics of the entire time-evolution

Non-equilibrium effects









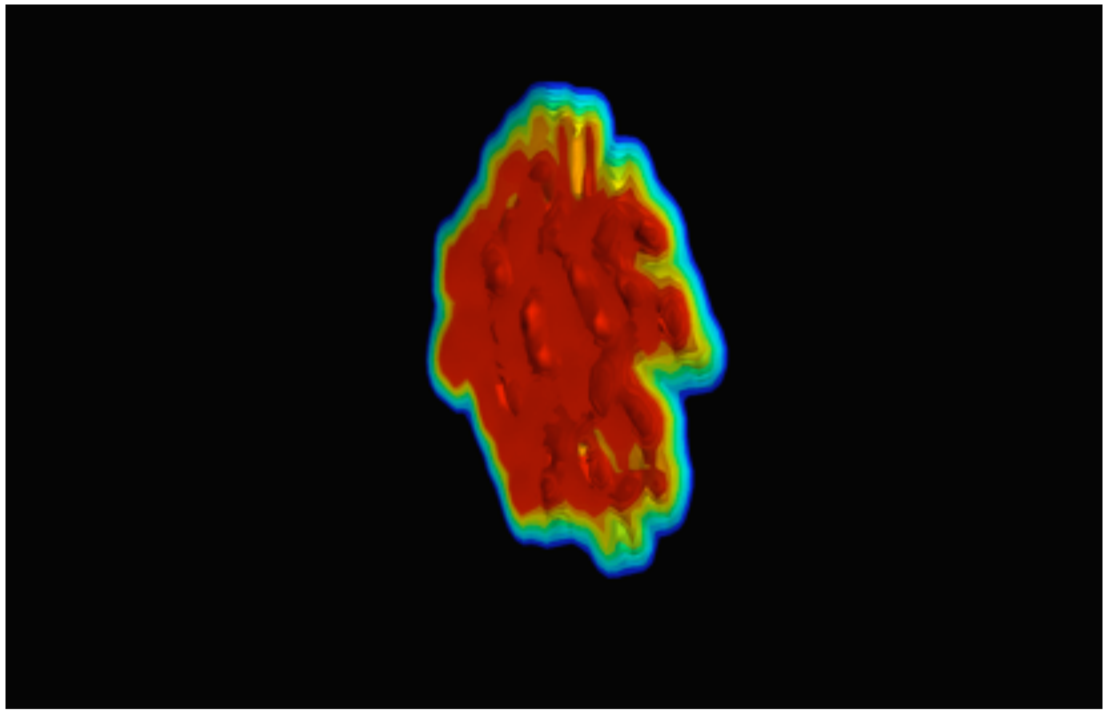
Photons probe the dynamic[illegible]he entire time-evolution

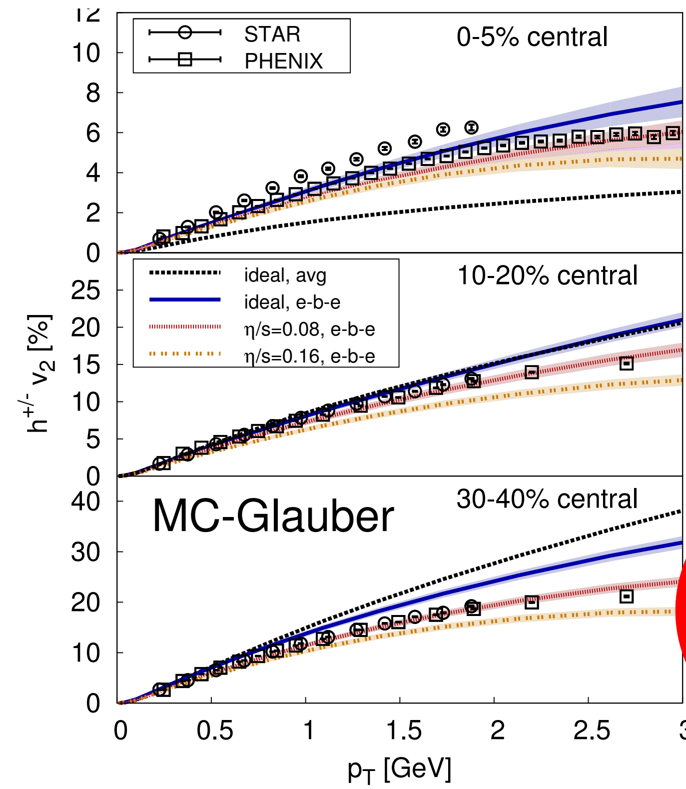
Caution

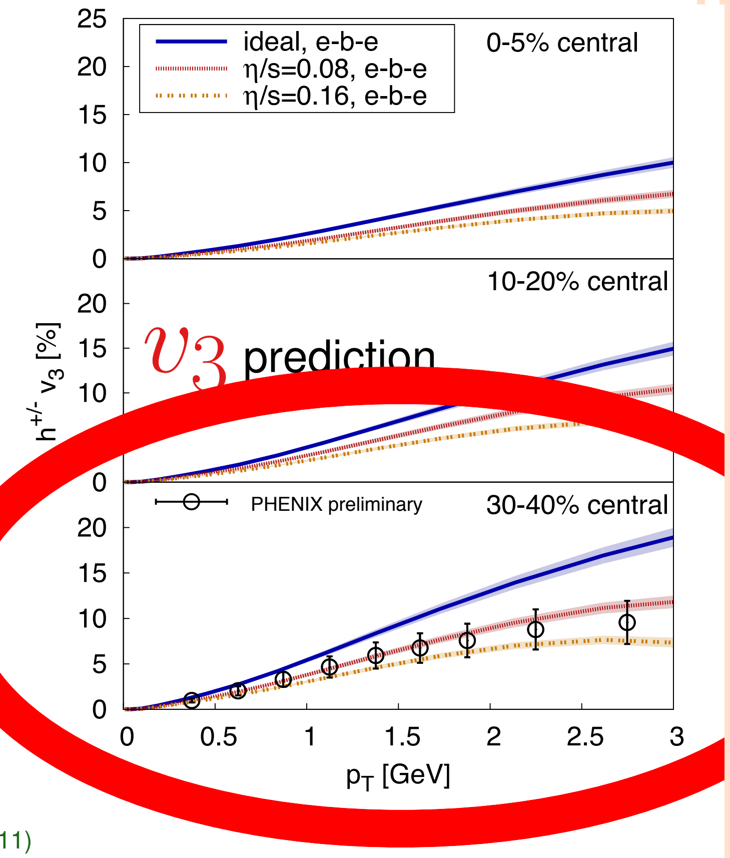
Charles Gale

INITIAL STATE FLUCTUATIONS: A PARADIGM SHIFT IN HEAVY ION ANALYSES

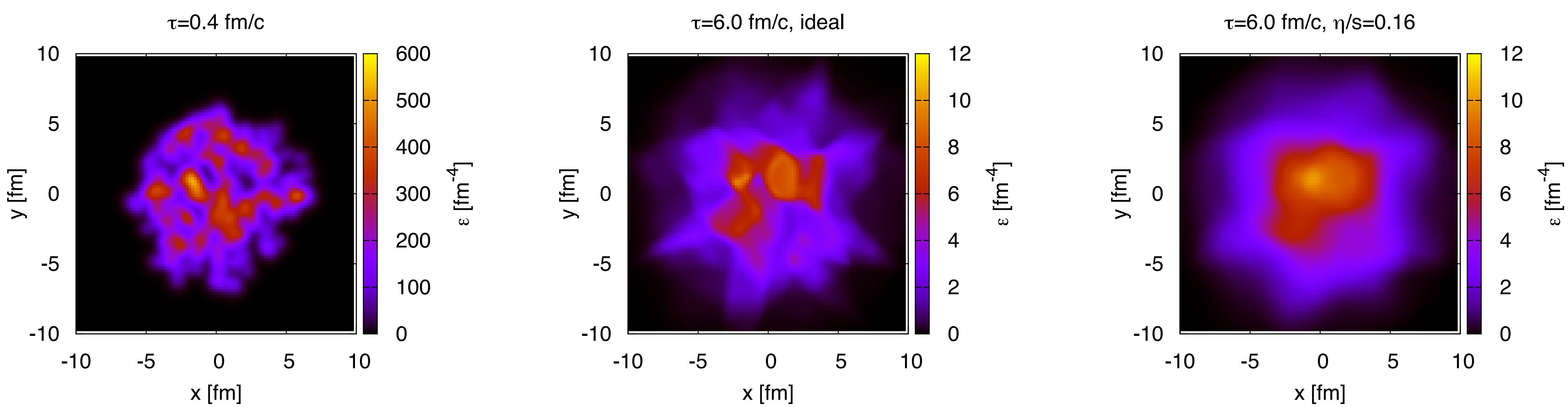
Lumpy MUSIC





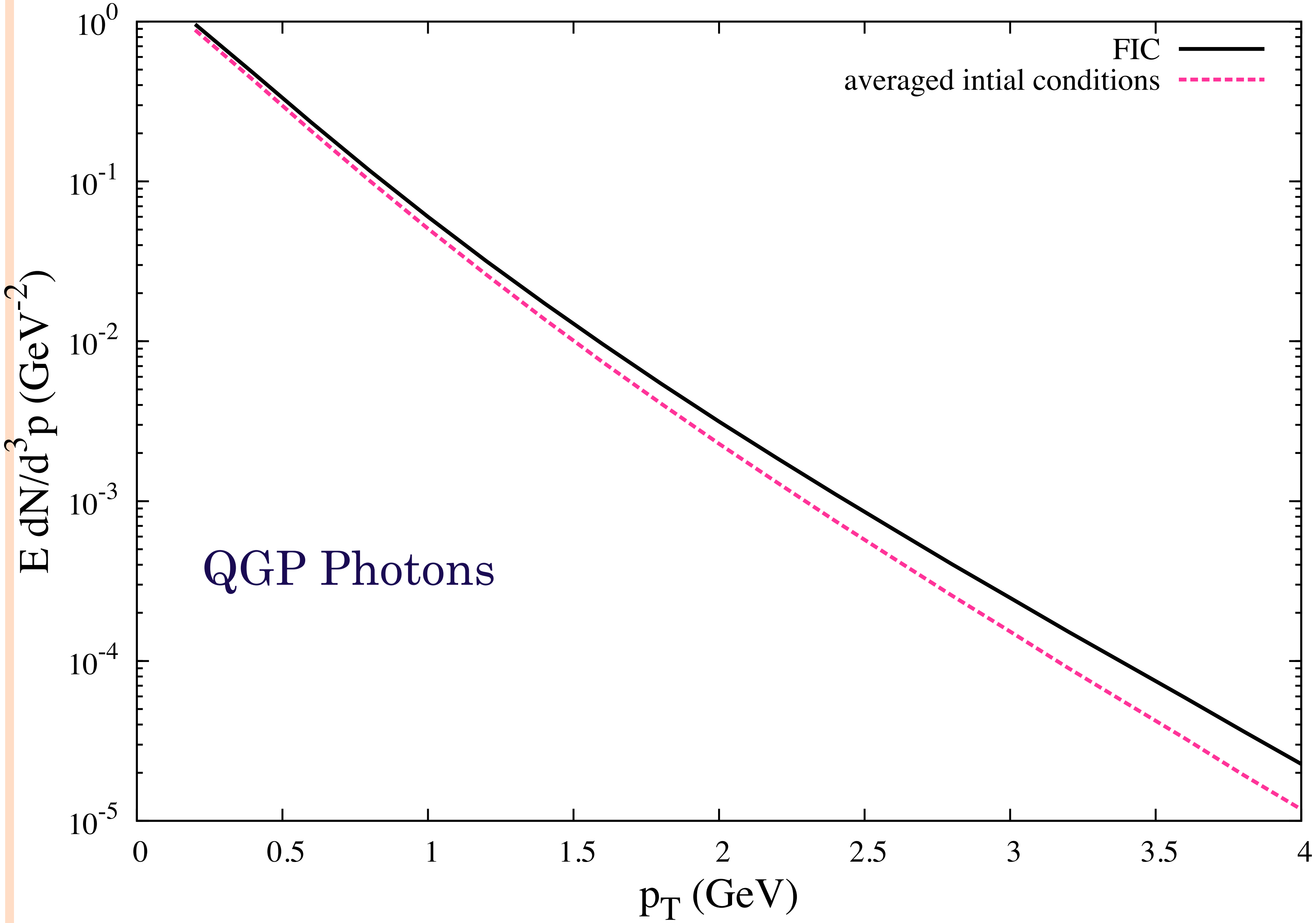


B. Schenke, S. Jeon, and C. Gale, Phys.Rev.Lett.106, 042301 (2011)



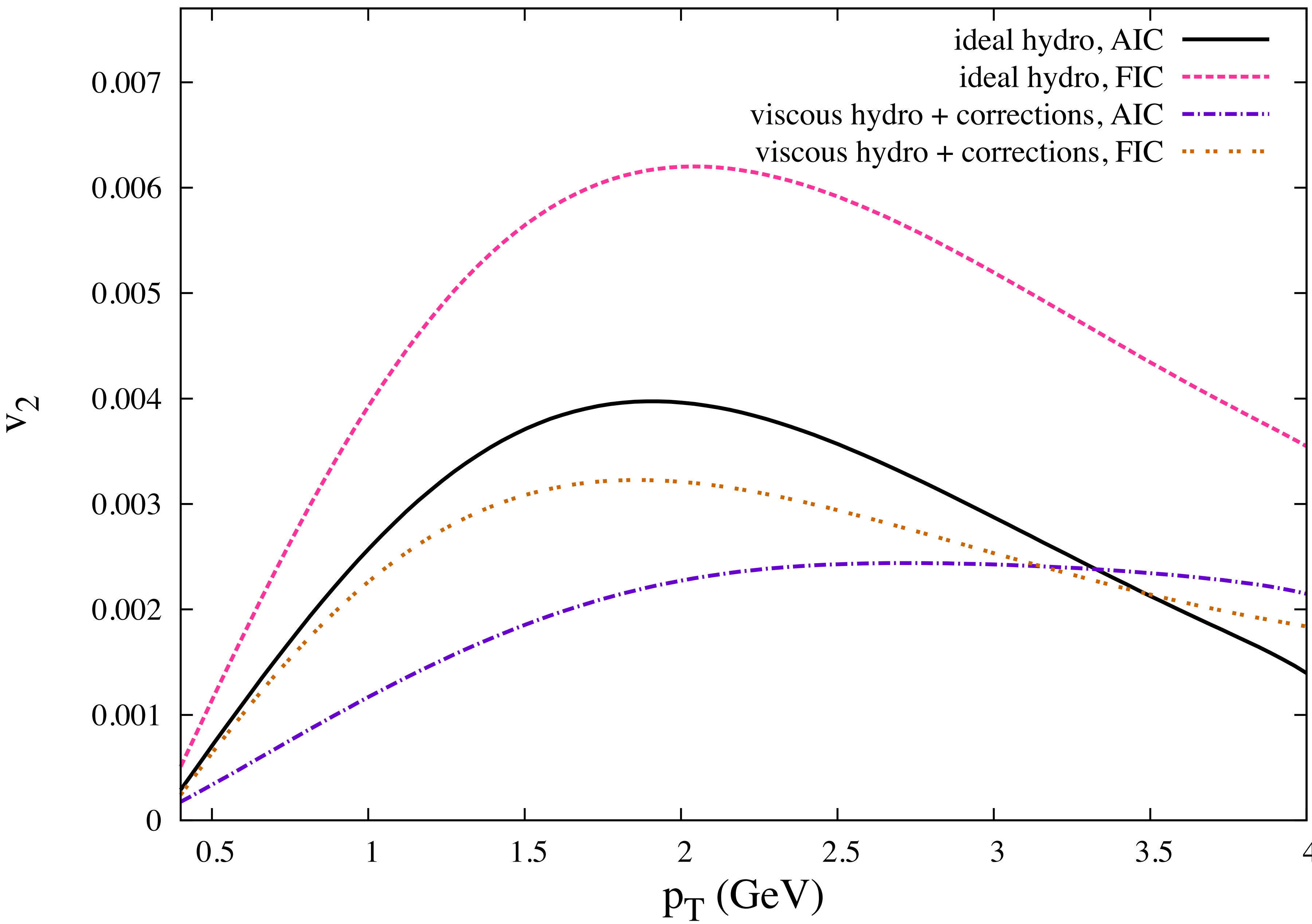
Schenke, Jeon, Gale, PRL (2011)

The effect on the thermal photon spectrum



- FIC produces higher initial T (hot spots), and higher initial gradients
- FIC conditions are demanded by hadronic data (v_{odd})
- These lead to a harder spectrum, *as for hadrons*
- In this centrality class, v_2 goes up

The effect on the thermal photon spectrum

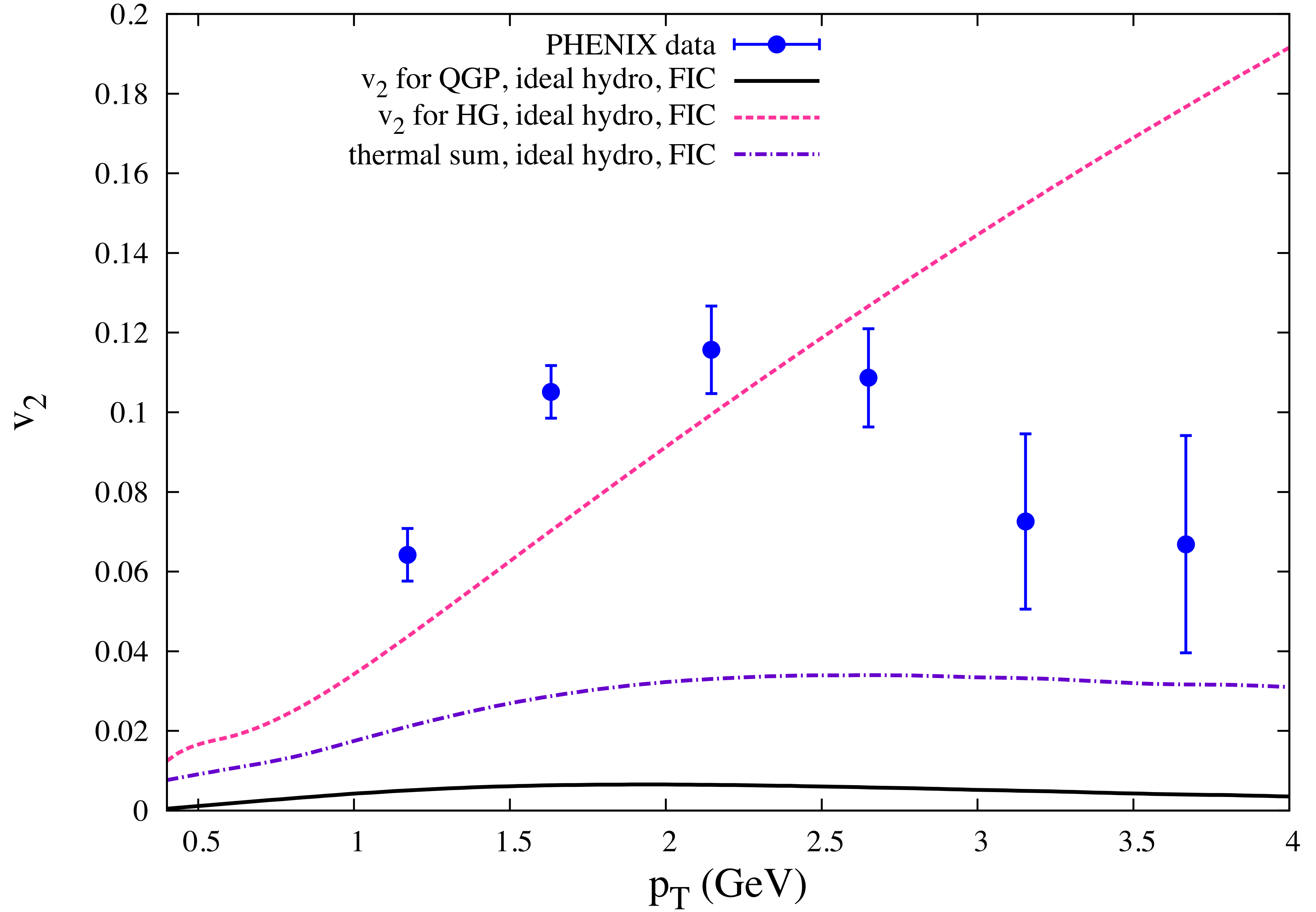


- FIC produces higher initial T (hot spots), and higher initial gradients
- FIC conditions are demanded by hadronic data (v_{odd})
- These lead to a harder spectrum, *as for hadrons*
- In this centrality class, v_2 goes up

QUANTIFYING THE EFFECT ON THE THERMAL PHOTON SPECTRUM

P_T (GeV)	Viscosity	FIC	Viscosity + FIC
1	18%	18%	41%
2	30%	45%	82%
3	30%	77%	126%

v_2 Data?



- New data is higher than calculation, even with e-b-e initial state fluctuations, and ideal hydro

CONCLUSIONS

Work done with:

- Maxime Dion
- Jean-François Paquet
- Björn Schenke
- Clint Young
- Sangyong Jeon

Conclusions

- Bad news: Photon v_2 is very sensitive to the EOS, and to various hydro parameters such as viscosity, and initial state fluctuations

Work done with:

- Maxime Dion
- Jean-François Paquet
- Björn Schenke
- Clint Young
- Sangyong Jeon

CONCLUSIONS

- Bad news: Photon v_2 is very sensitive to the EOS, and to various hydro parameters such as viscosity, and initial state fluctuations
- Good news: Photon v_2 is very sensitive to the EOS, and to various hydro parameters such as viscosity, and initial state fluctuations

Work done with:

- Maxime Dion
- Jean-François Paquet
- Björn Schenke
- Clint Young
- Sangyong Jeon

Conclusions

- Bad news: Photon v_2 is very sensitive to the EOS, and to various hydro parameters such as viscosity, and initial state fluctuations
- Good news: Photon v_2 is very sensitive to the EOS, and to various hydro parameters such as viscosity, and initial state fluctuations
- Photons are penetrating probes: at high p_T, they will reveal jet-medium interactions, at low p_T, they will reveal details of out-of-equilibrium dynamics

Work done with:

- Maxime Dion
- Jean-François Paquet
- Björn Schenke
- Clint Young
- Sangyong Jeon

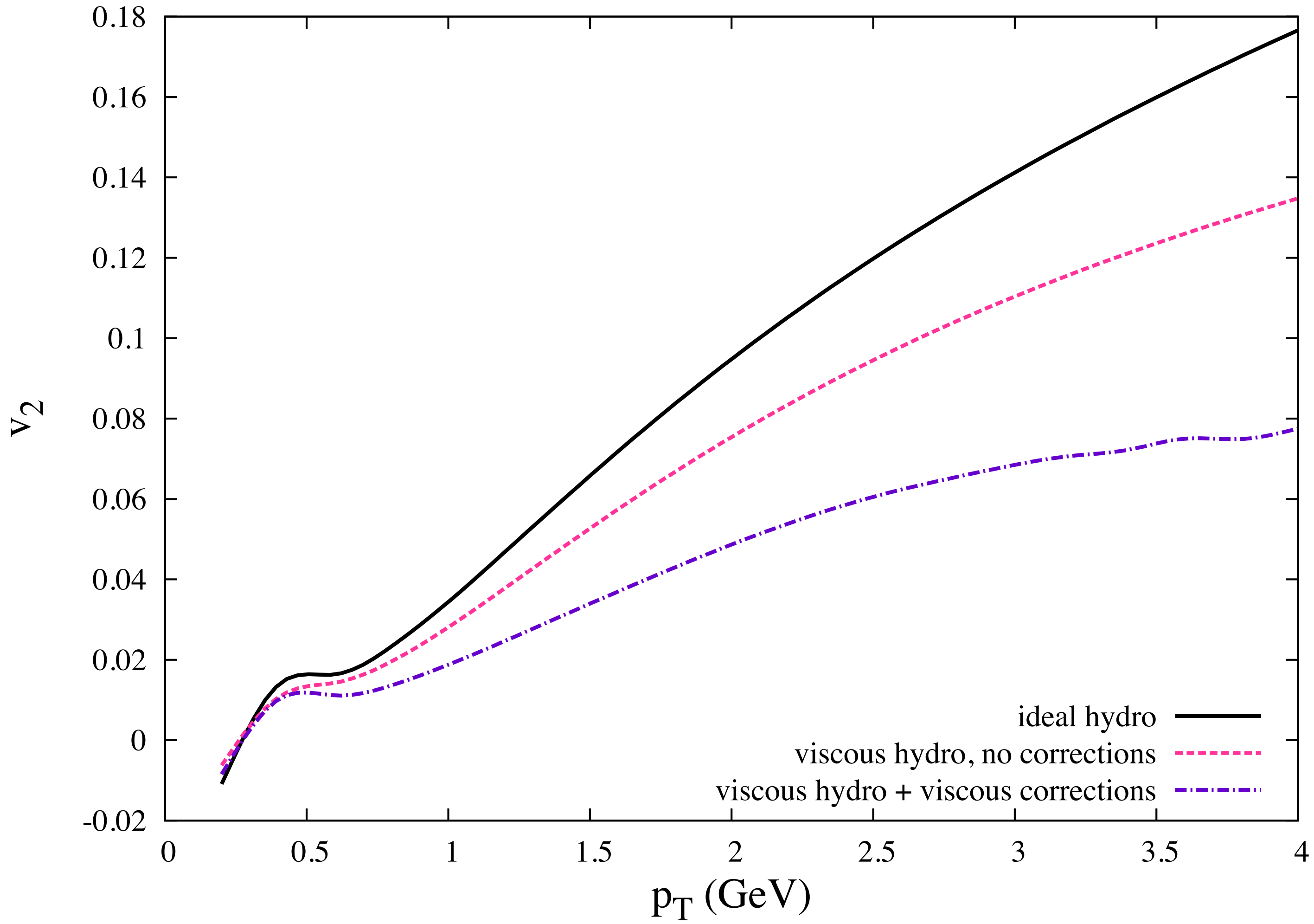
Conclusions

- Bad news: Photon v_2 is very sensitive to the EOS, and to various hydro parameters such as viscosity, and initial state fluctuations
- Good news: Photon v_2 is very sensitive to the EOS, and to various hydro parameters such as viscosity, and initial state fluctuations
- Photons are penetrating probes: at high p_T, they will reveal jet-medium interactions, at low p_T, they will reveal details of out-of-equilibrium dynamics
- New data is intriguing. . .

Work done with:

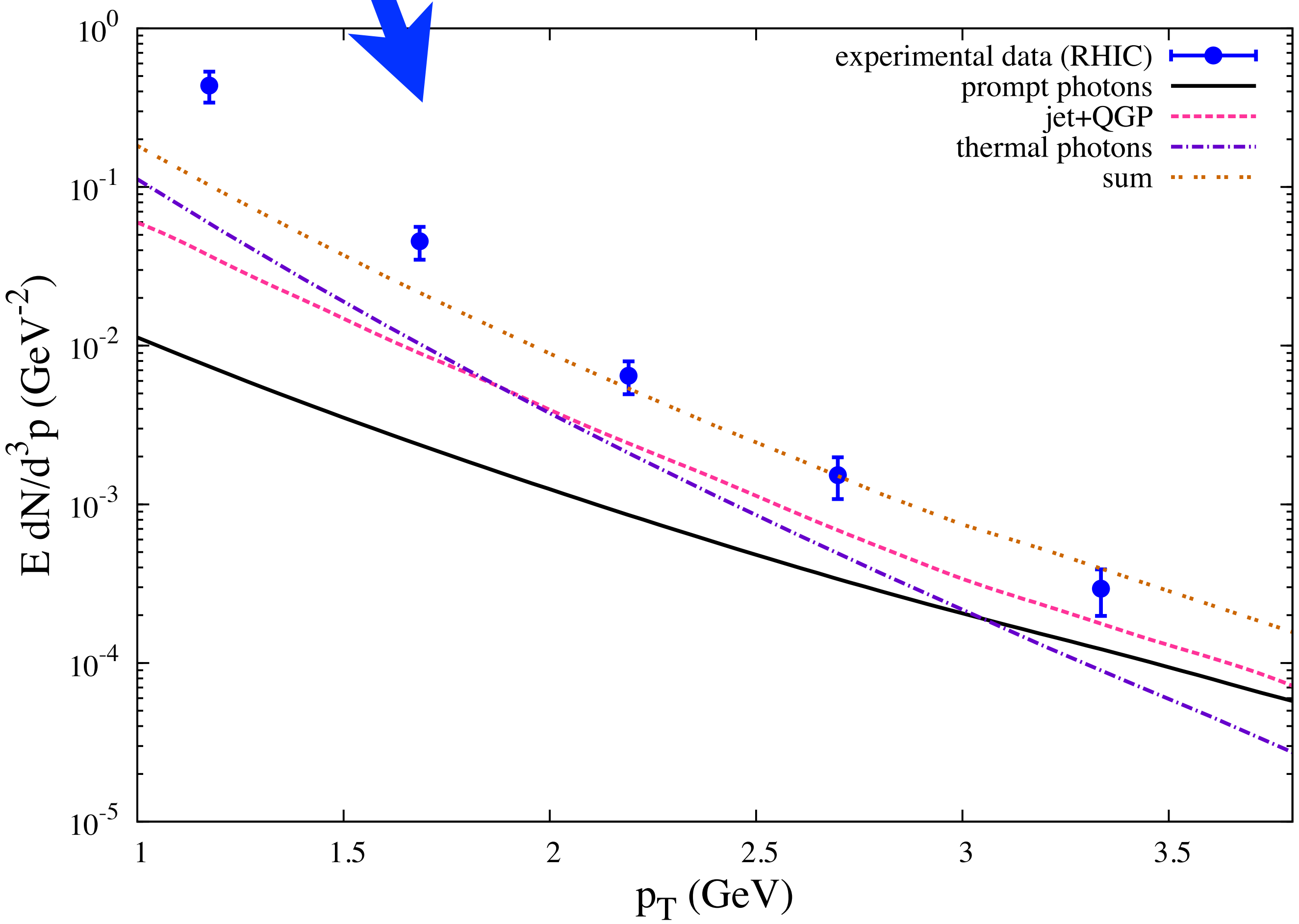
- Maxime Dion
- Jean-François Paquet
- Björn Schenke
- Clint Young
- Sangyong Jeon

Viscous effects on HG anisotropy

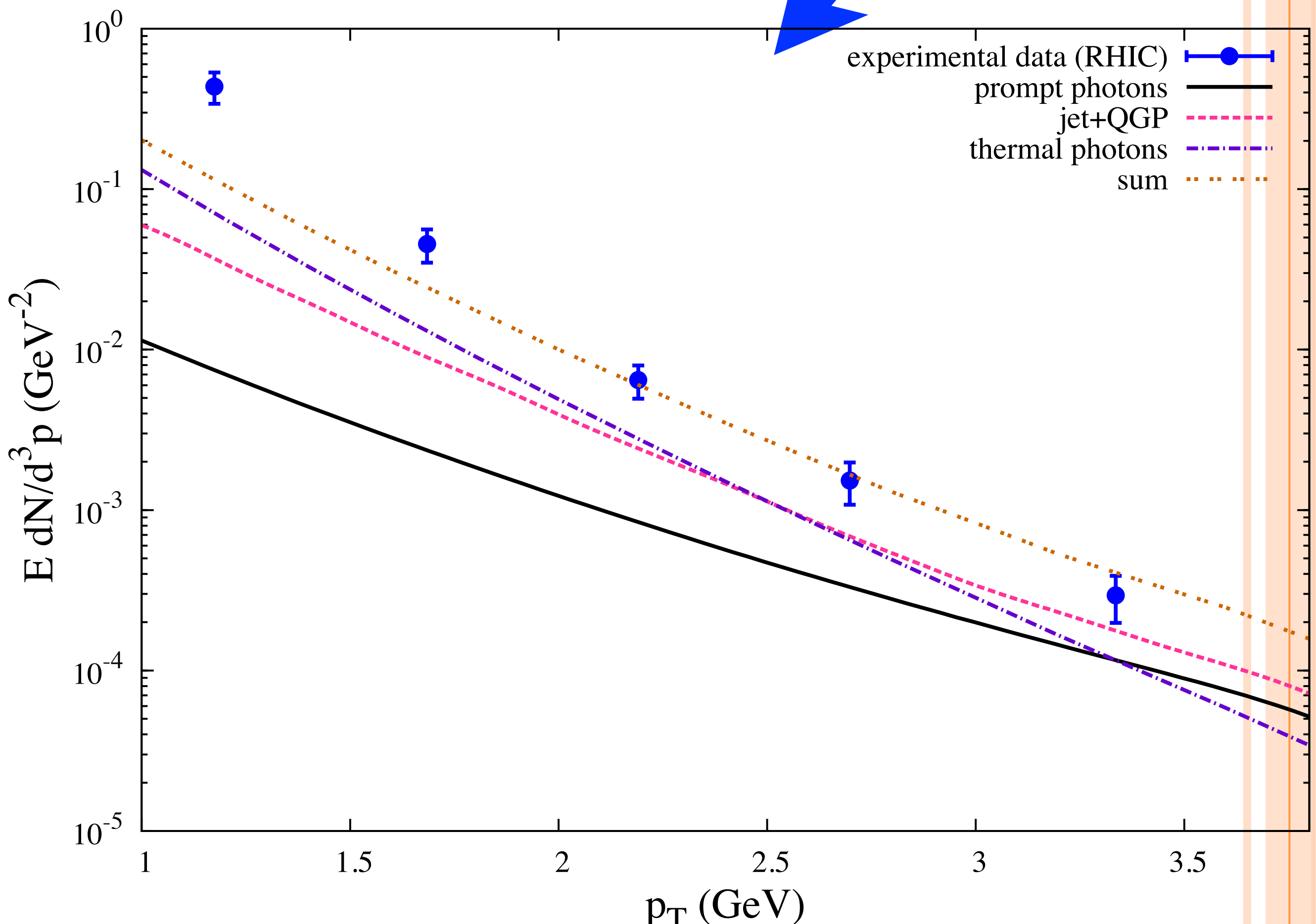


Photons from the QGP + those from the hadronic gas: net spectra

Ideal



$\eta / s = 1/4\pi$



- It is important to compare situations that yield *the same* (hadronic) final state: no contradictions between photon and hadron analyses
- Viscous effects on the net photon yield are small (a few %)