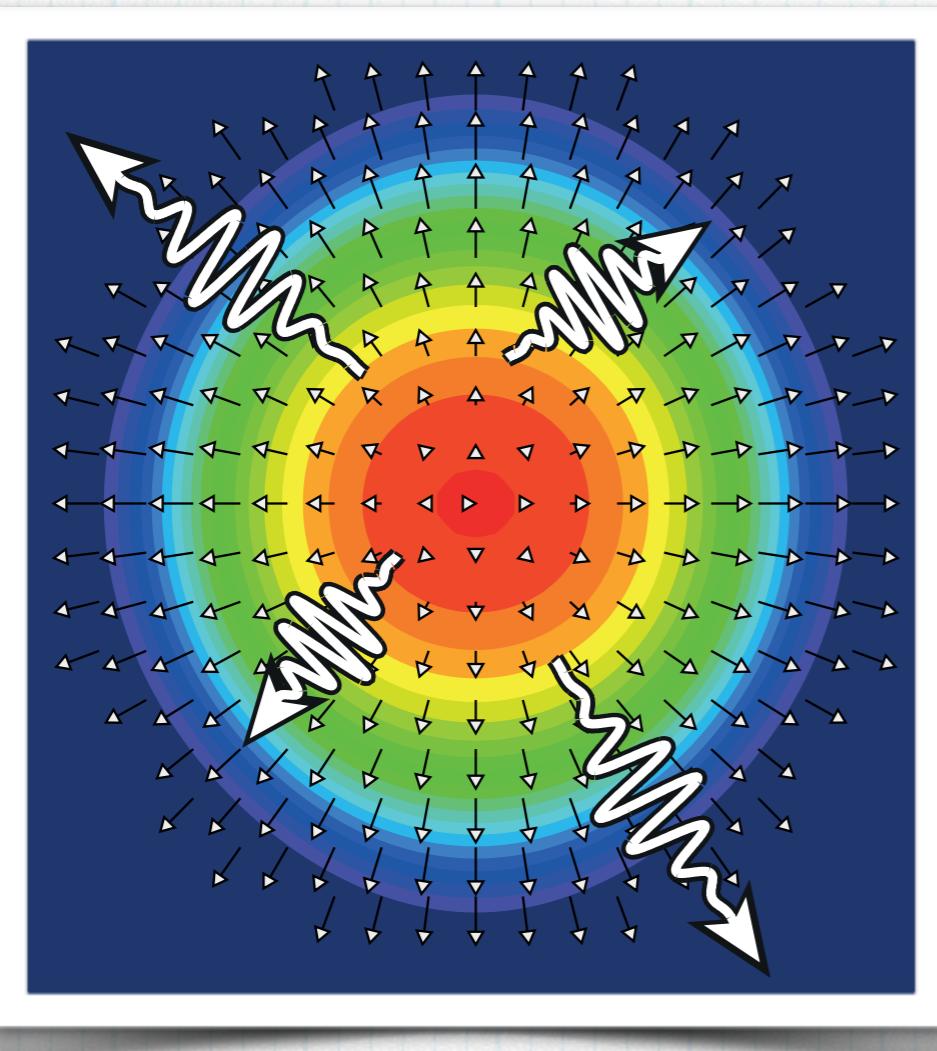


The Direct Photon Flow Puzzle: An Overview



Charles Gale
McGill University
FIAS



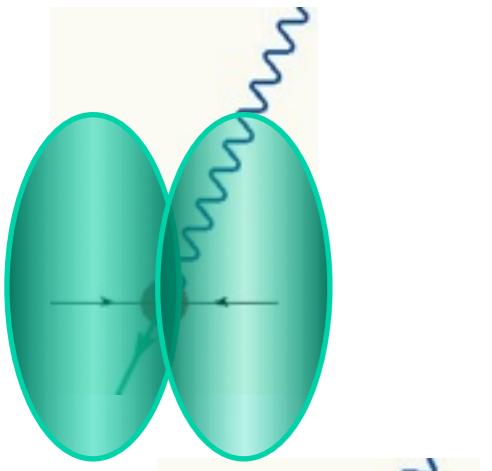
- Sources & EM emissivity: Rates
- Modelling the evolving system:
 - 3D viscous hydro
 - Fluctuating initial states
- How are the photon yields dependent on the dynamics?
- Photons as a characterization tool
- Status of our interpretation of the data

Why study photons and dileptons in relativistic nuclear collisions?

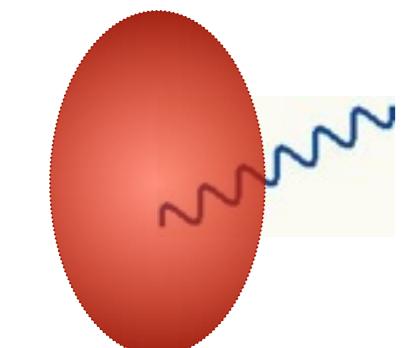
- Penetrating probes: negligible final state effects (α)
- Real and virtual photons are complementary, and they supplement hadronic observables
- Thermal photon emission rate favours hotter zones of the colliding system
- Emitted throughout the collision history
- Low emission rates
- Procedure: Calculate thermal emission rates & use hydrodynamics to model the evolution. Integrate rates over whole history

Sources of photons in a relativistic nuclear collision:

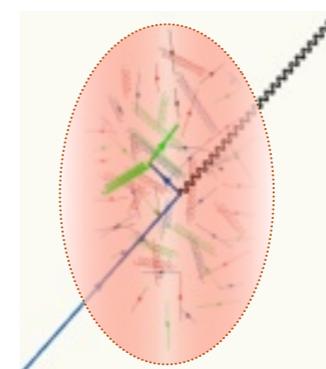
Hard direct photons. pQCD with shadowing
Non-thermal



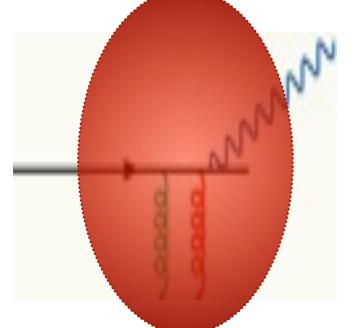
Fragmentation photons. pQCD with shadowing
Non-thermal



Thermal photons
Thermal



Jet-plasma photons
Thermal



Jet in-medium bremsstrahlung
Thermal

Pre-equilibrium?

INFO CARRIED BY THE THERMAL RADIATION

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

Thermal ensemble average of the current-current correlator

Emission rates:

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

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

Feinberg (76), McLerran, Toimela (85)
Weldon (90), Gale, Kapusta (91)

4

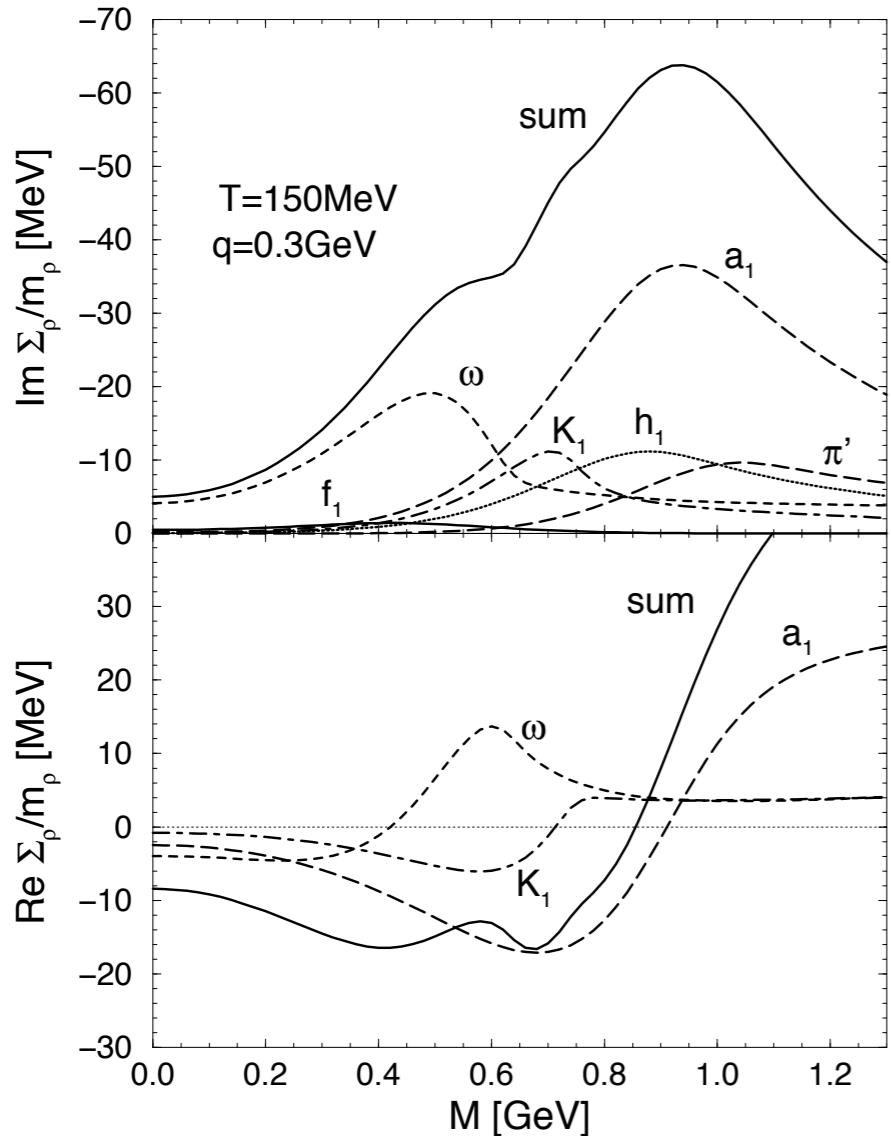
Charles Gale



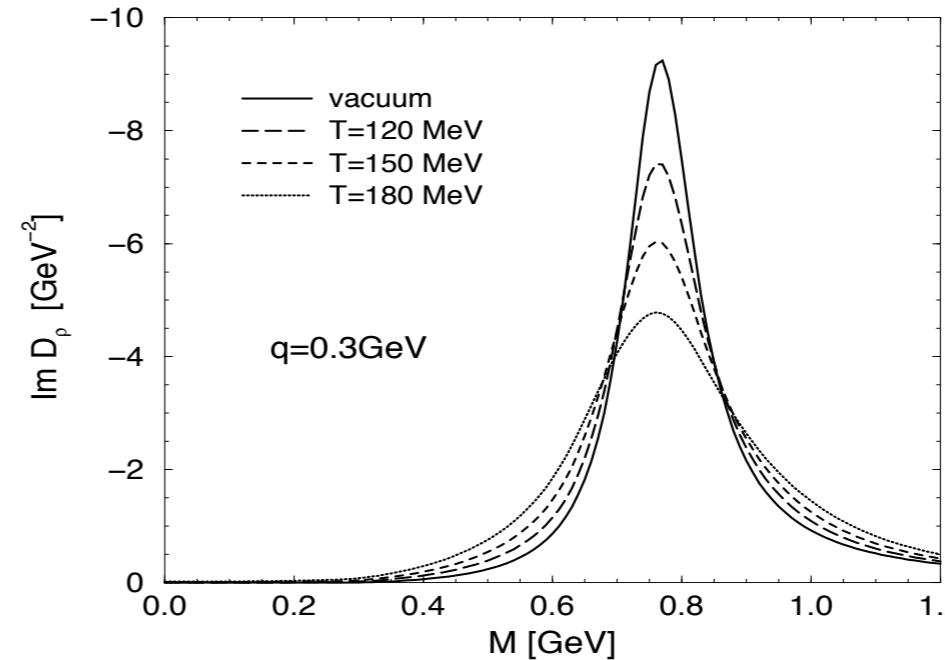
(FOR DILEPTONS:)

VMD

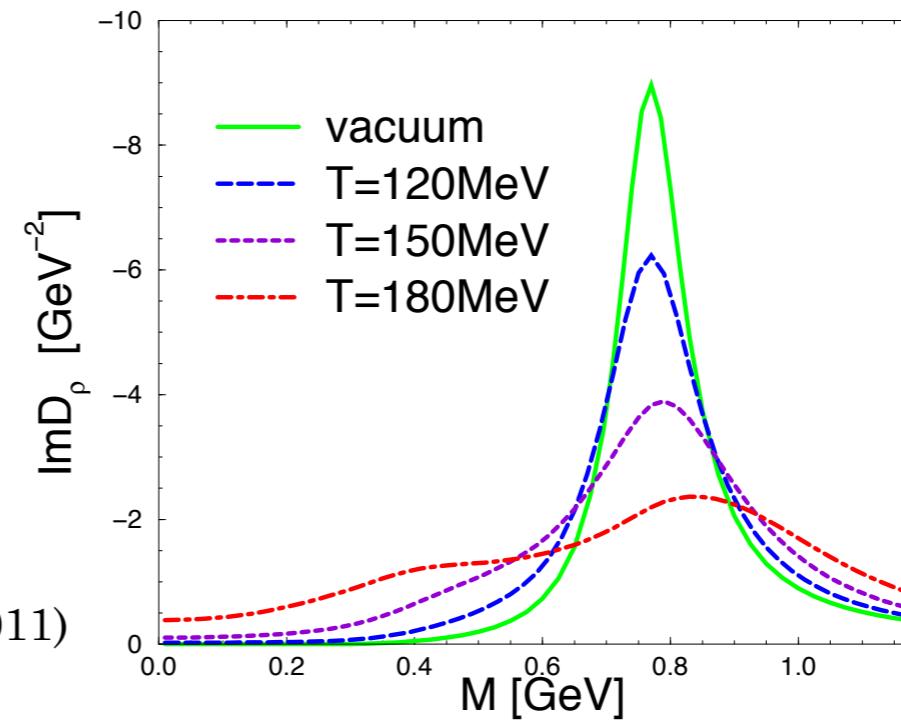
$\text{Im} \langle J_\mu J_\nu \rangle_T \Rightarrow \text{Im} \langle \rho_\mu \rho_\nu \rangle_T \Rightarrow \text{Im} D_{\mu\nu}^T \Rightarrow \text{Vector spectral density}$



R. Rapp, Act. Phys. Pol. (2011)



Rapp and Gale, PRC (1999)

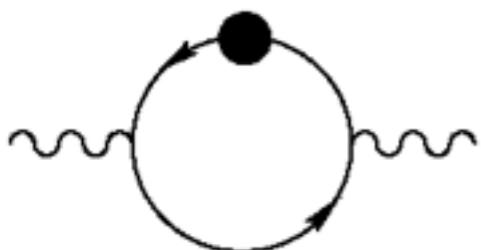


$\rho_B / \rho_0 = 0.1, 0.7, 2.6$

Charles Gale



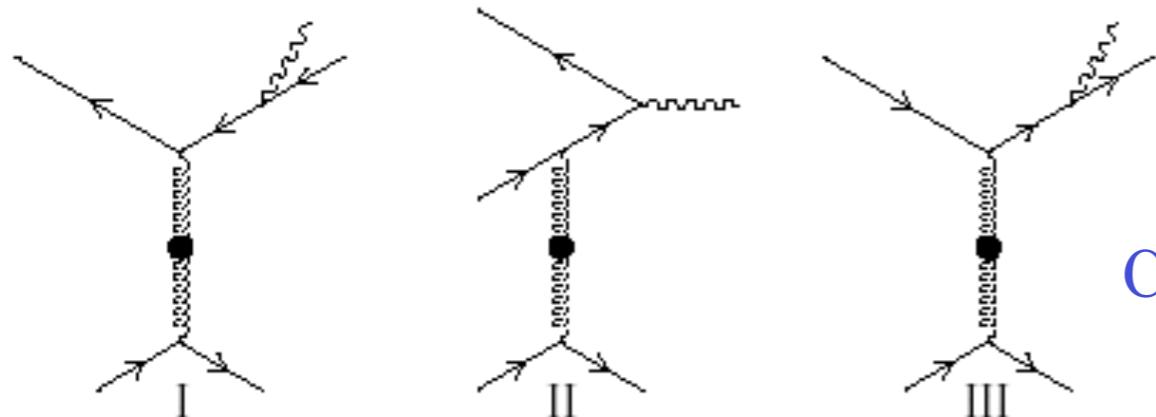
Thermal Photons from hot QCD: HTL program (Klimov (1981), Weldon (1982), Braaten & Pisarski (1990); Frenkel & Taylor (1990))



$$\text{Im } \Pi_{R\mu}^\mu \sim \ln \left(\frac{\pi T}{(m_{th}(\sim gT))^2} \right)$$

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

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



Co-linear singularities:

$$\alpha_s^2 \left(\frac{T^2}{m_{th}^2} \right) \sim \alpha_s$$

2001: Results complete at $\mathcal{O}(\alpha_s)$

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



Going beyond LO AMY rates?

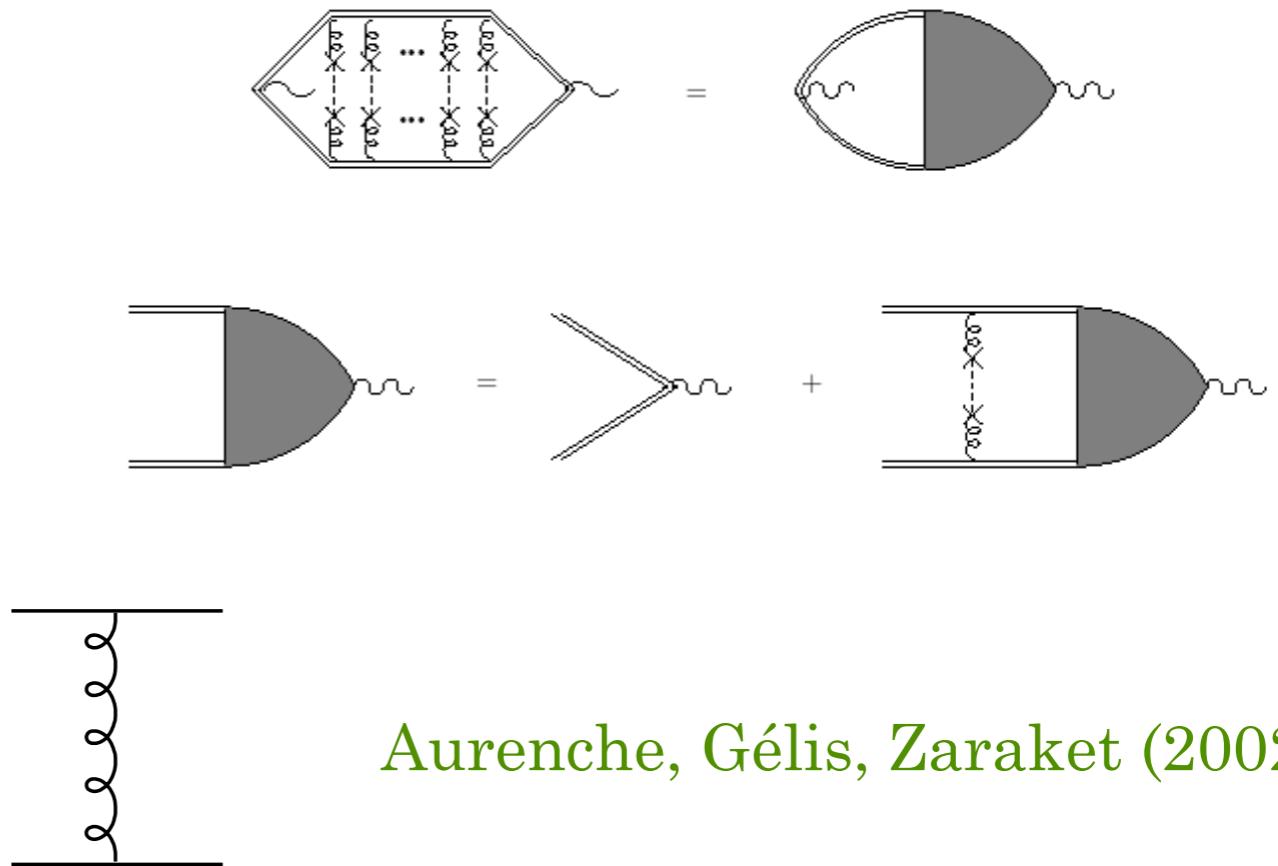
- Approach is LO, but

$$\alpha_s \sim 0.2 - 0.3$$

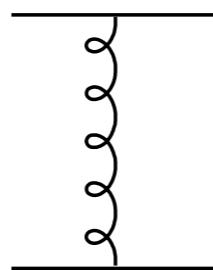
- Integral equation can be written in terms of a Dyson-Schwinger type iteration...

which contains a scattering kernel:

$$C(q_\perp)|_{\text{LO}} = g^2 C_R T \frac{m_D^2}{q_\perp^2 (q_\perp^2 + m_D^2)}$$



Aurenche, Gélis, Zaraket (2002)



The techniques used to derive this - and all results in perturbative, finite-temperature field theory - rely on the scale separation:

$$gT \ll T$$

$$\text{soft} \ll \text{hard}$$

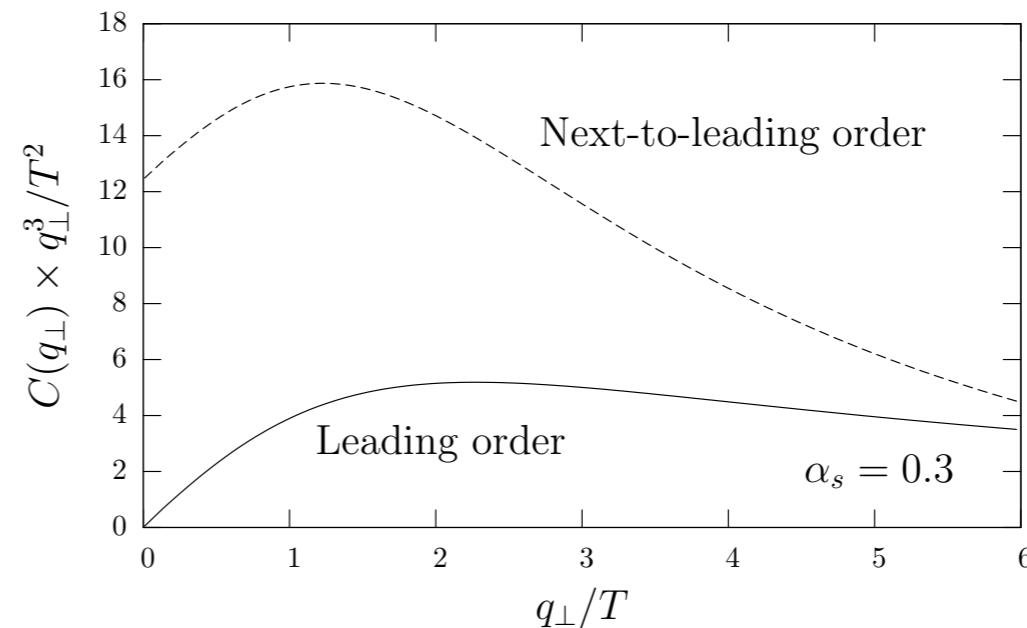
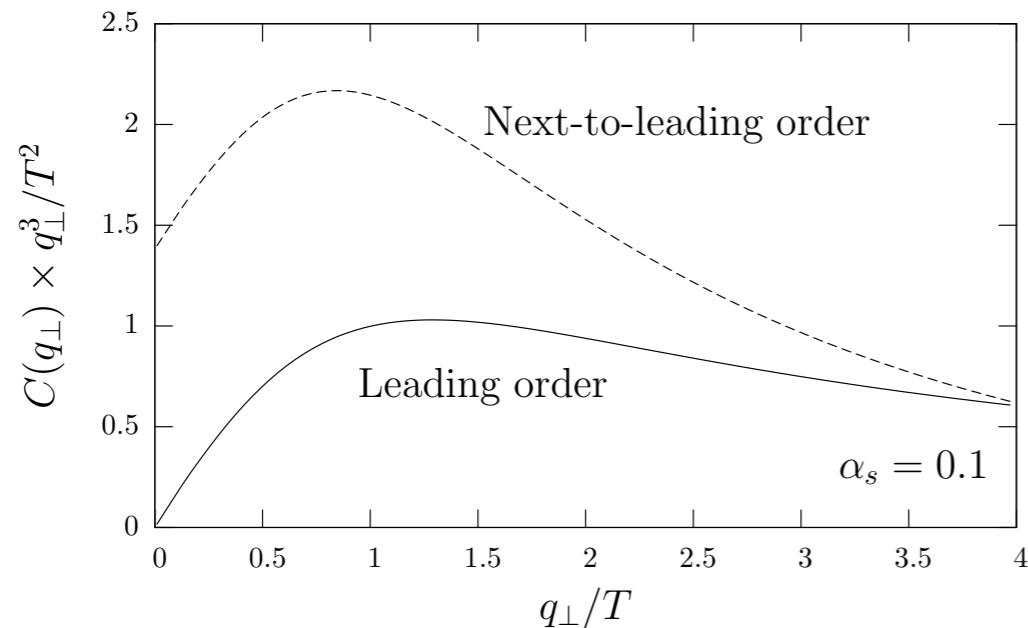
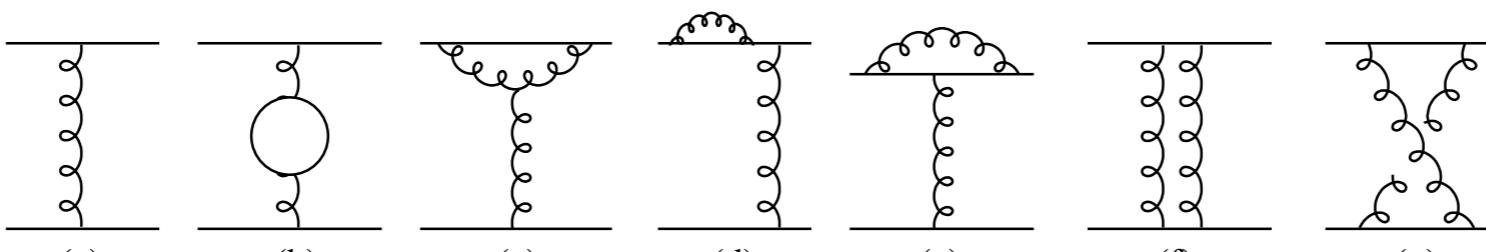
7

The LO-NLO scattering kernel(s)

Clue that NLO effects might be important: Heavy quark diffusion

$$C(q_\perp) \Big|_{\text{LO}} \rightarrow C(q_\perp) \Big|_{\text{NLO}}$$

Simon Caron-Huot PRD (2009)

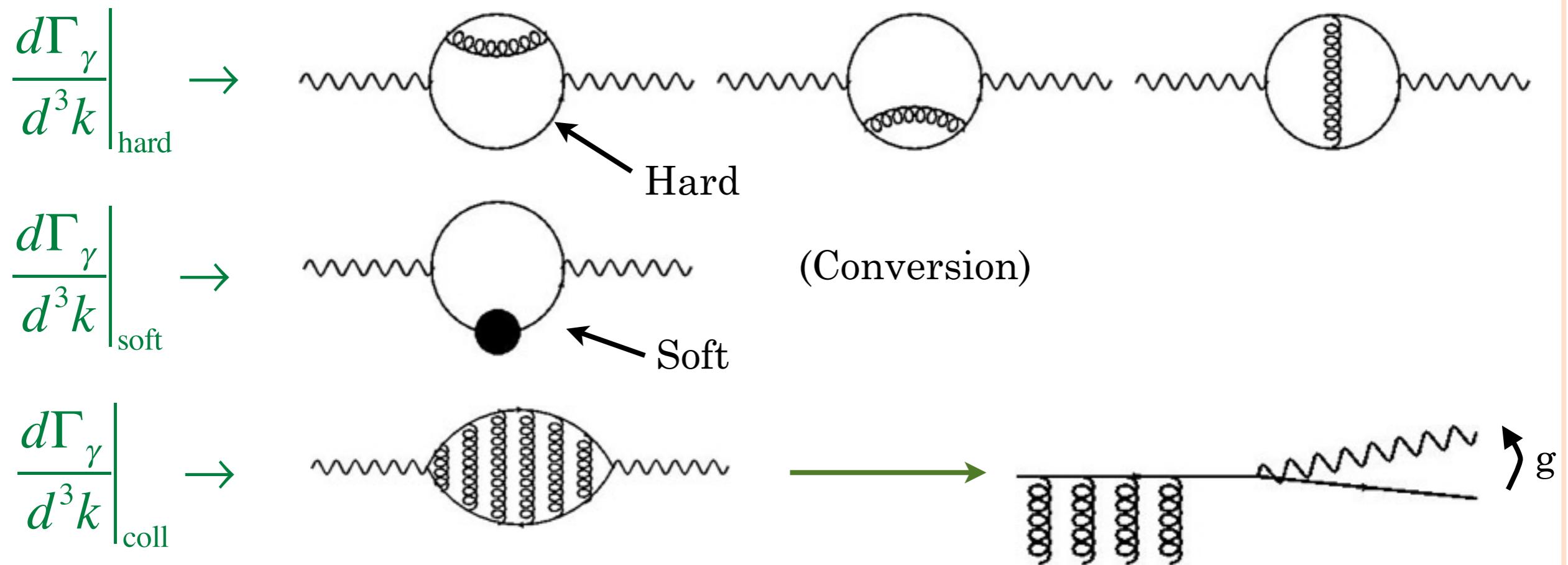


Possible large effects on photon production!?



Photon emission at LO

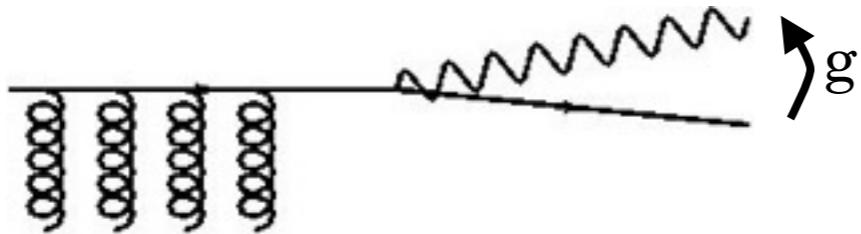
$$\left. \frac{d\Gamma_\gamma}{d^3k} \right|_{\text{LO}} = \left. \frac{d\Gamma_\gamma}{d^3k} \right|_{\text{hard}} + \left. \frac{d\Gamma_\gamma}{d^3k} \right|_{\text{soft}} + \left. \frac{d\Gamma_\gamma}{d^3k} \right|_{\text{coll}}$$



The LO-NLO scattering kernels

Ghiglieri, Hong, Kurkela, Lu, Moore,
Teaney, JHEP (2013)

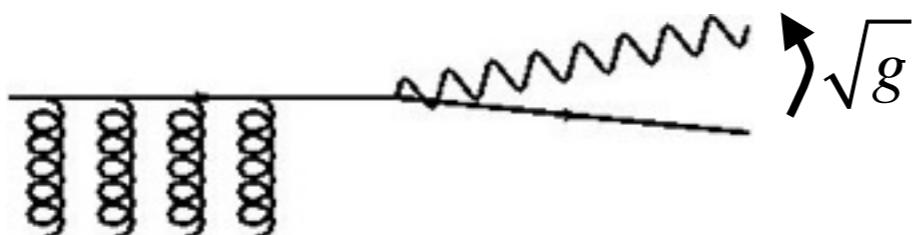
The two main contributions:



$$C(q_T)_{\text{LO}} = \frac{T g^2 m_D}{q_T (q_T + m_D)} \Rightarrow \text{NLO}$$

Simon Caron-Huot PRD (2009)

Enhanced at NLO



Larger angle bremmstrahlung

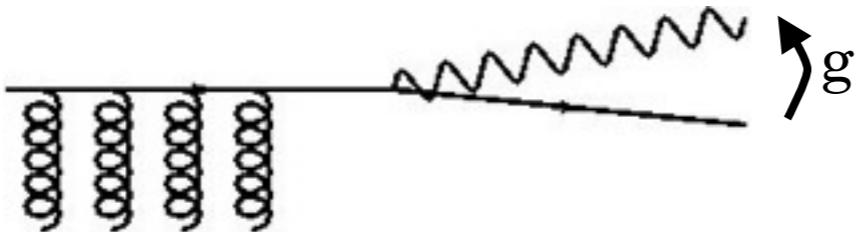
Suppressed at NLO



The LO-NLO scattering kernels

Ghiglieri, Hong, Kurkela, Lu, Moore,
Teaney, JHEP (2013)

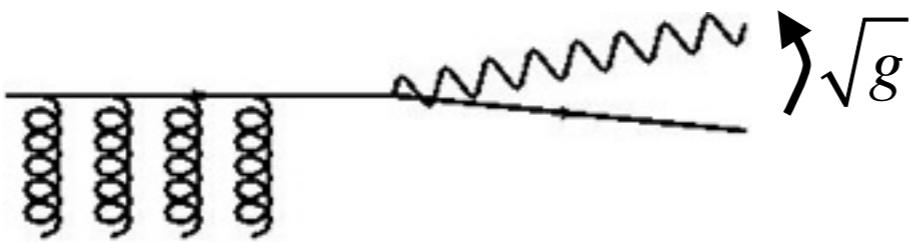
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$$C(q_T)_{\text{LO}} = \frac{T g^2 m_D}{q_T(q_T + m_D)} \Rightarrow \text{NLO}$$

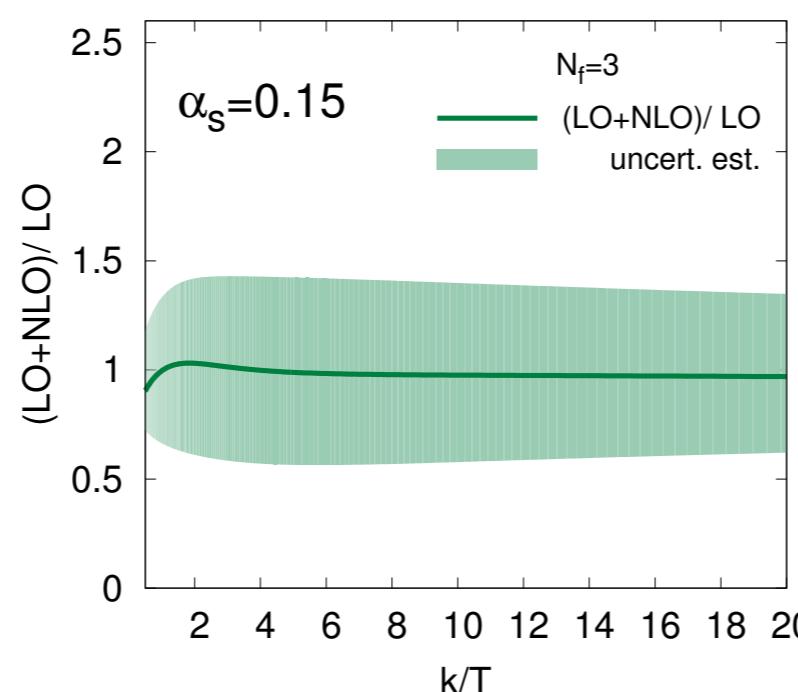
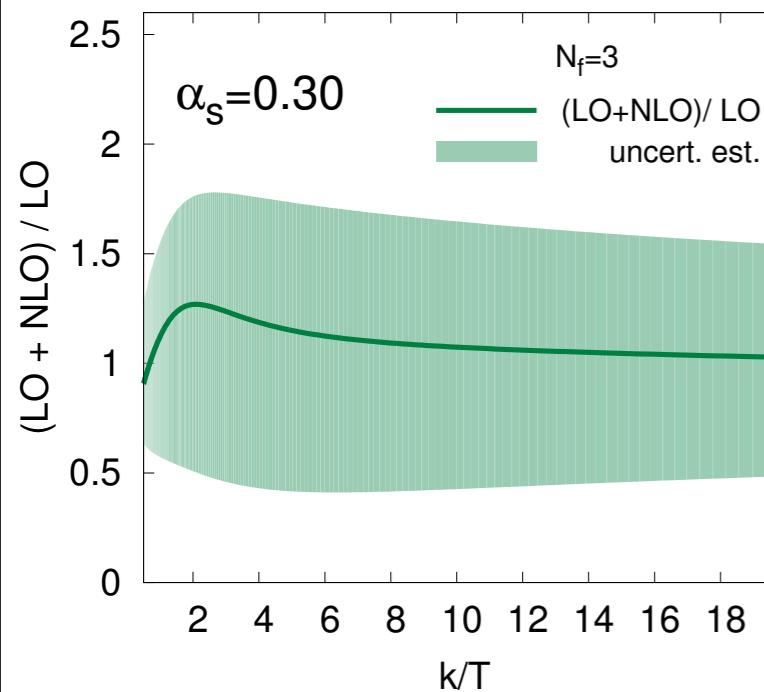
Simon Caron-Huot PRD (2009)

Enhanced at NLO



Larger angle bremmstrahlung

Suppressed at NLO



- Net correction to photon production rate is modest up to high k/T
- Techniques developed here have many more applications in FTFT
- Perturbative

ELECTROMAGNETIC RADIATION FROM HADRONS

Chiral, Massive Yang-Mills:

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

$$\begin{aligned} \mathcal{L} = & \frac{1}{8} F_\pi^2 \text{Tr } D_\mu U D^\mu U^\dagger + \frac{1}{8} F_\pi^2 \text{Tr } M (U + U^\dagger) \\ & - \frac{1}{2} \text{Tr} \left(F_{\mu\nu}^L F^{L\mu\nu} + F_{\mu\nu}^R F^{R\mu\nu} \right) + m_0^2 \text{Tr} \left(A_\mu^L A^{L\mu} + A_\mu^R A^{R\mu} \right) \\ & + \text{non-minimal terms} \end{aligned}$$

Parameters and form factors are constrained by hadronic phenomenology:

- Masses & strong decay widths
- Electromagnetic decay widths
- Other hadronic observables:

- e.g. $a_1 \rightarrow \pi\rho \quad D/S$ (See also, Lichard and Vojik, Nucl. Phys. (2010); Lichard and Juran, PRD (2008))

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

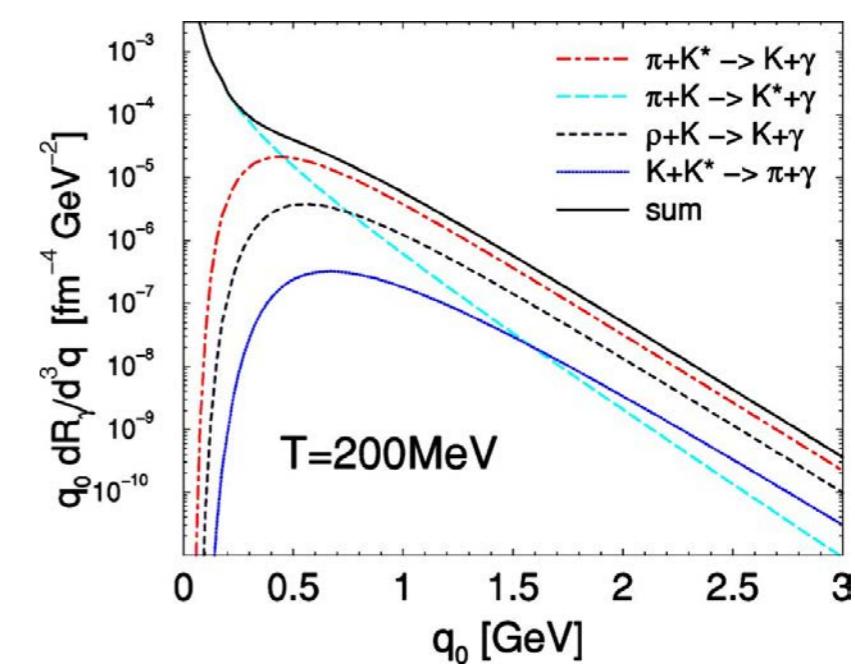
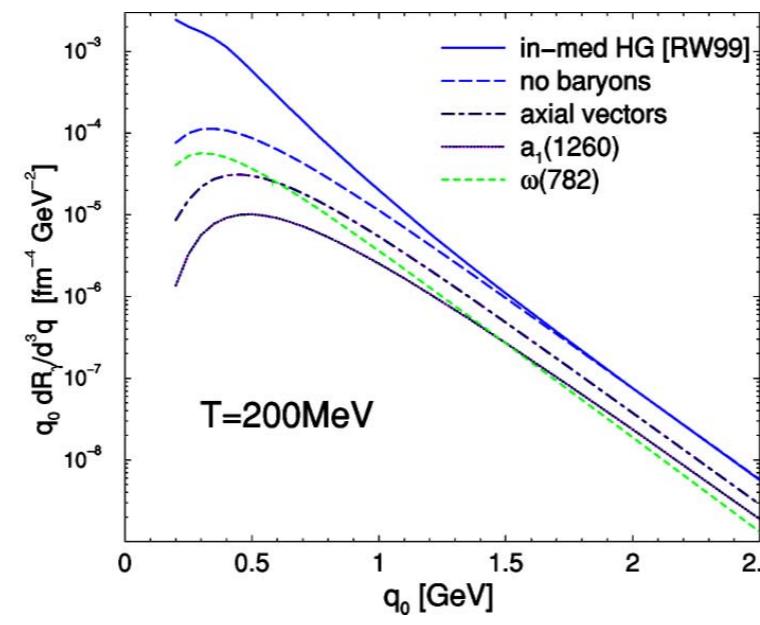
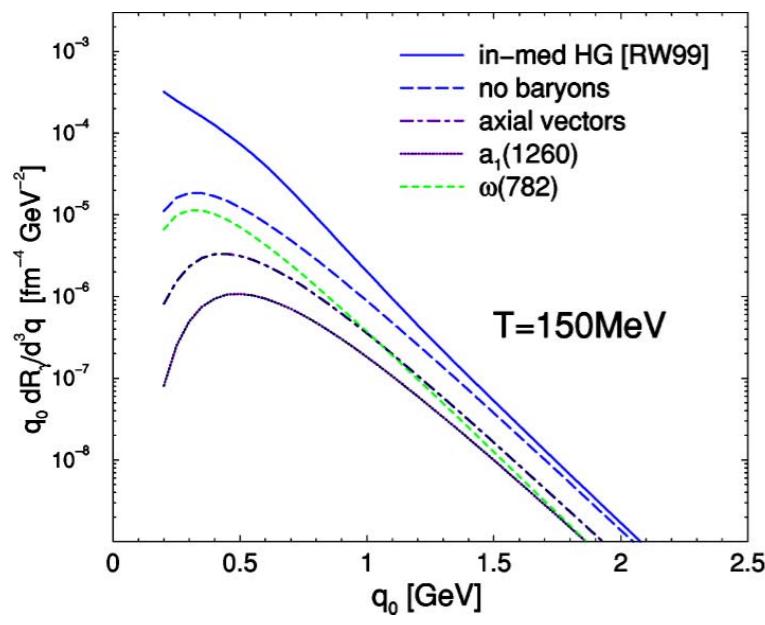
Charles Gale



ELECTROMAGNETIC RADIATION FROM HADRONS

All possible s-, t-, and u- Born graphs of the reactions:

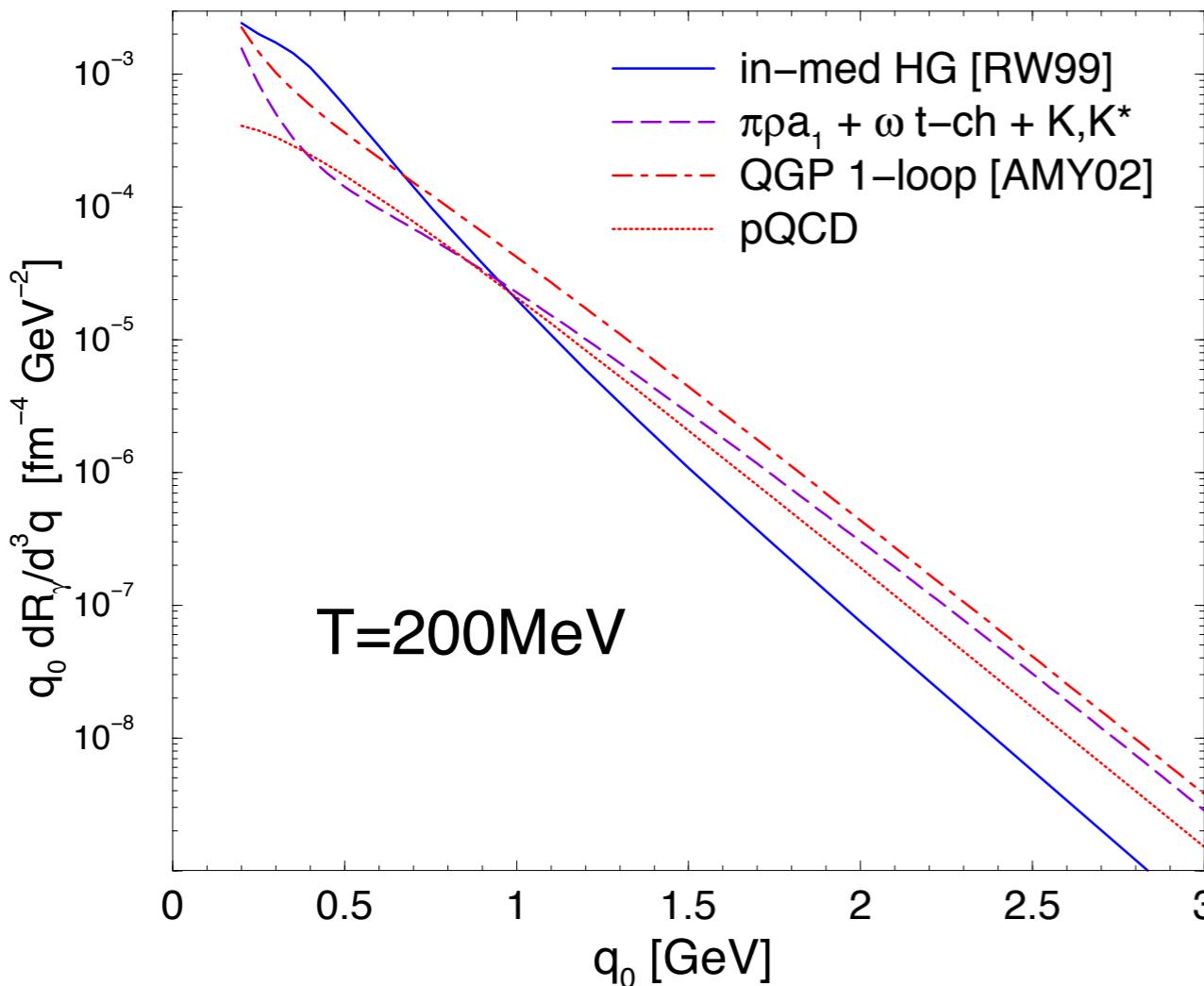
$$\left. \begin{array}{l} X + Y \rightarrow Z + \gamma \\ \rho \rightarrow Y + Z + \gamma \\ K^* \rightarrow Y + Z + \gamma \end{array} \right\} X, Y, Z \in \{\rho, \pi, K^*, K\}$$



Turbide, Rapp, and Gale, PRC (2004)



COMPARING RATES

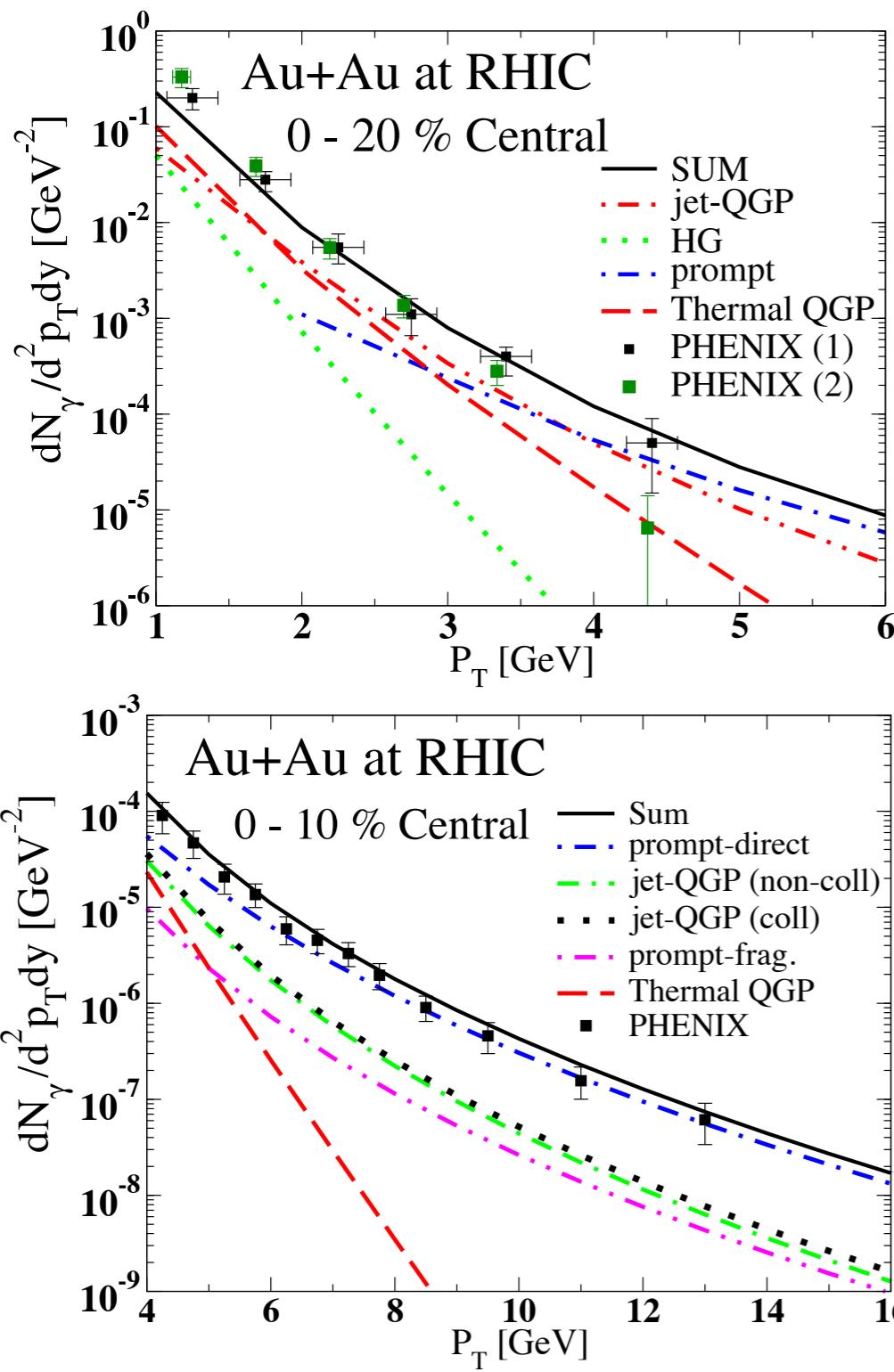


Integrate rates with
hydro evolution

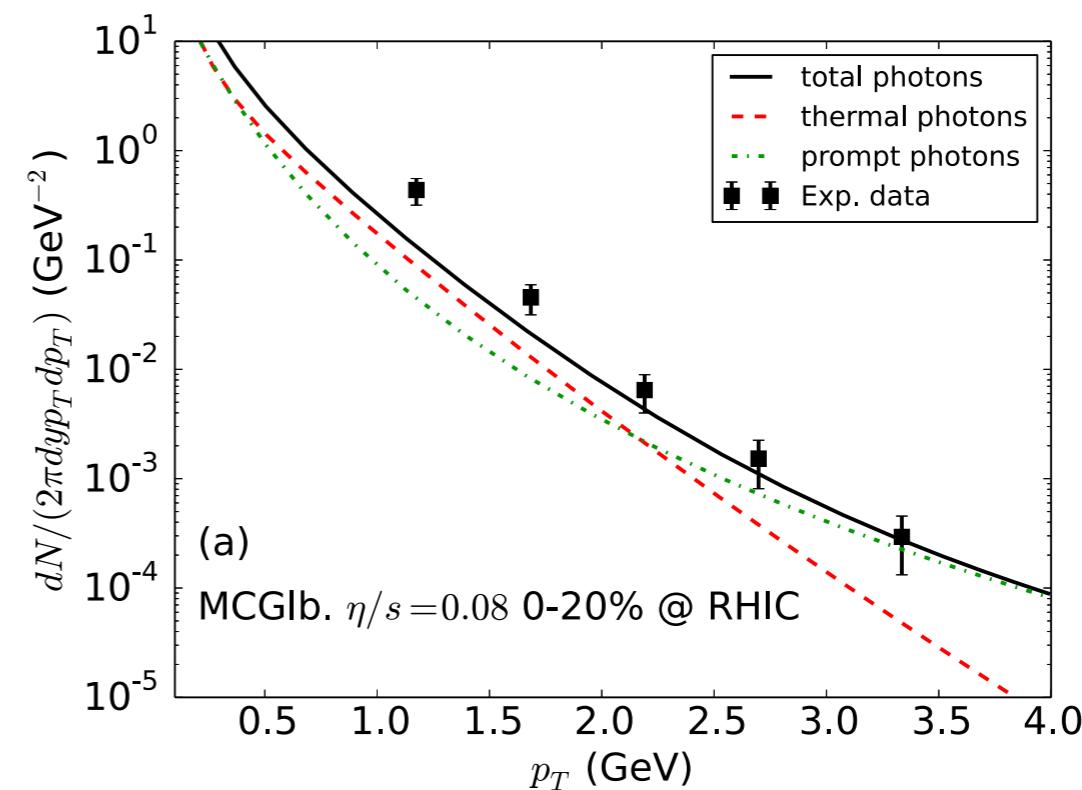
Turbide, Rapp, and Gale, PRC (2004)



PHOTONS @ RHIC: RATES ARE INTEGRATED USING RELATIVISTIC HYDRODYNAMIC MODELLING



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



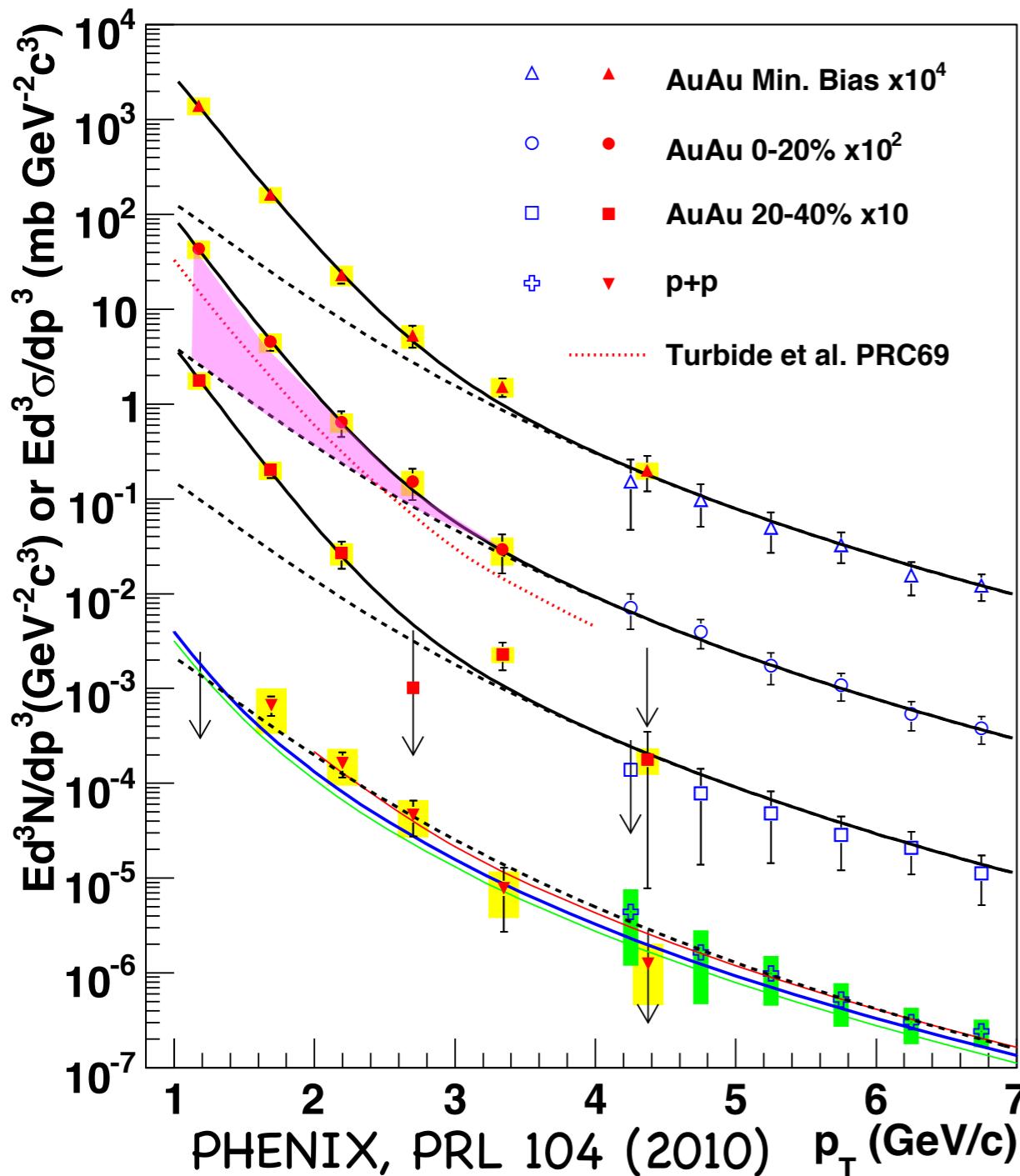
Turbide, Gale, Frodermann, Heinz, PRC (2008);
Higher p_T : G. Qin et al., PRC (2009)

Shen, Heinz, Paquet, Gale, arXiv:1308.2440¹⁴

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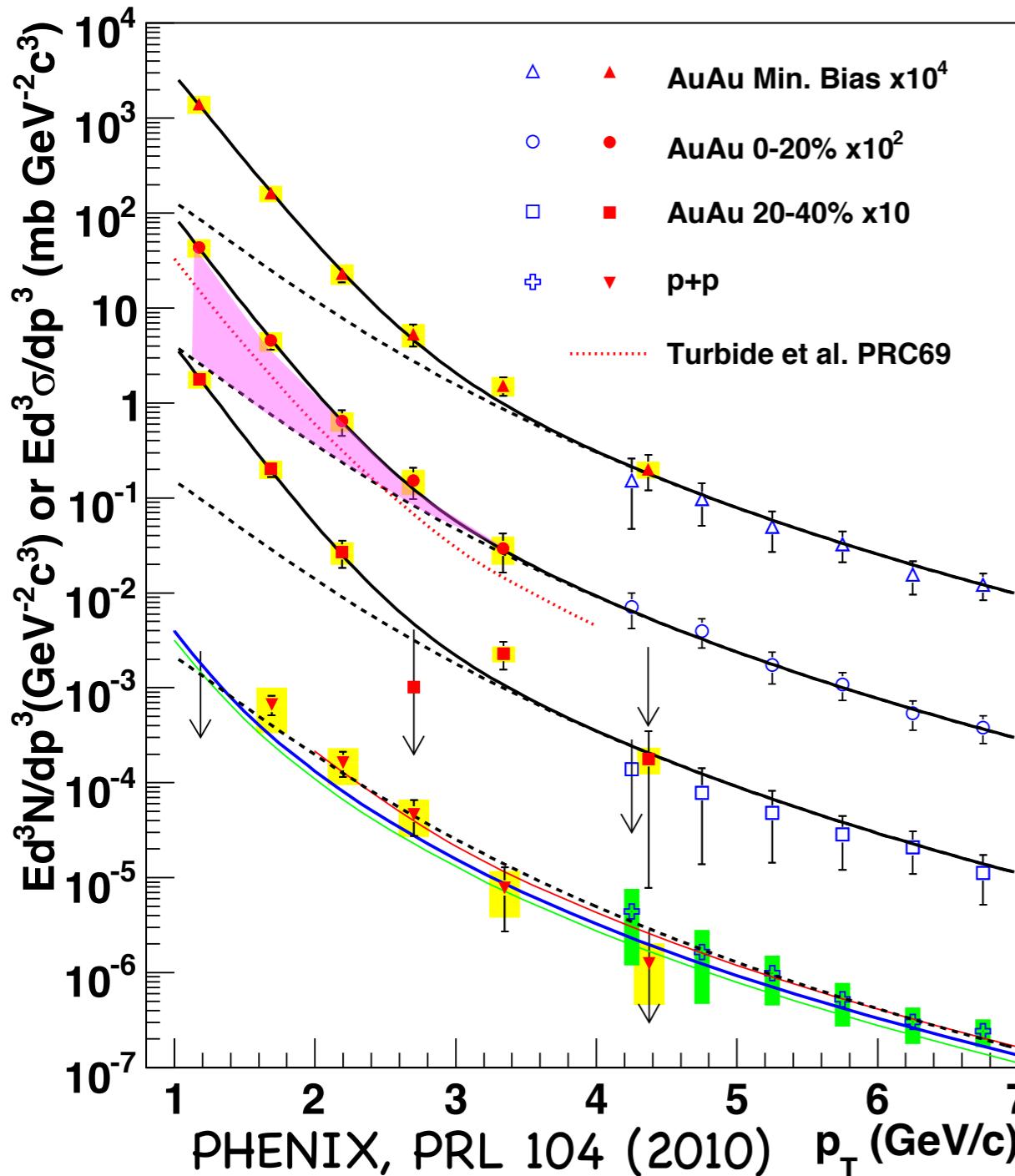
ONE OF THE USES OF PHOTONS: CHARACTERIZING THE HOT MATTER CREATED AT RHIC



$$T_{\text{excess}} = 221 \pm 19 \pm 19 \text{ MeV}$$



ONE OF THE USES OF PHOTONS: CHARACTERIZING THE HOT MATTER CREATED AT RHIC



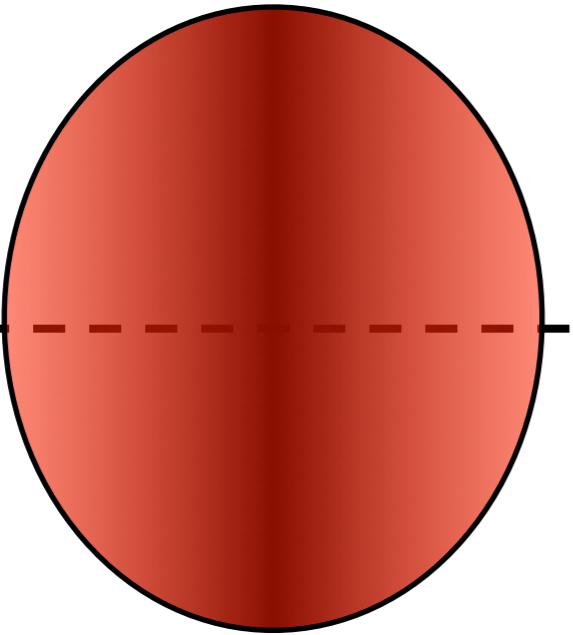
$$T_{\text{excess}} = 221 \pm 19 \pm 19 \text{ MeV}$$



Flow effects will be important

- van Hees, Gale Rapp, PRC (2011)
- Shen, Heinz, Paquet, Gale, arXiv:1308.2440

BEYOND SIMPLE SPECTRA: FLOW AND CORRELATIONS

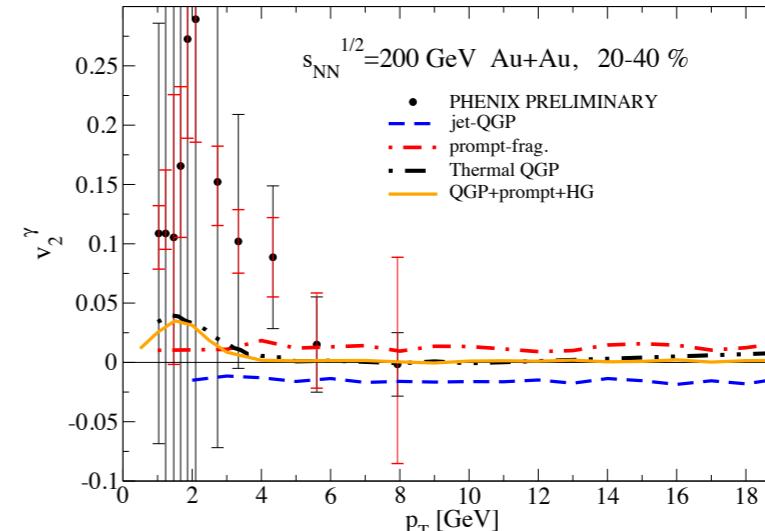


$$\frac{dN}{p_T dp_T d\phi} = \frac{dN}{2\pi p_T dp_T} \left[1 + \sum_n 2v_n \cos(n\phi) \right]$$

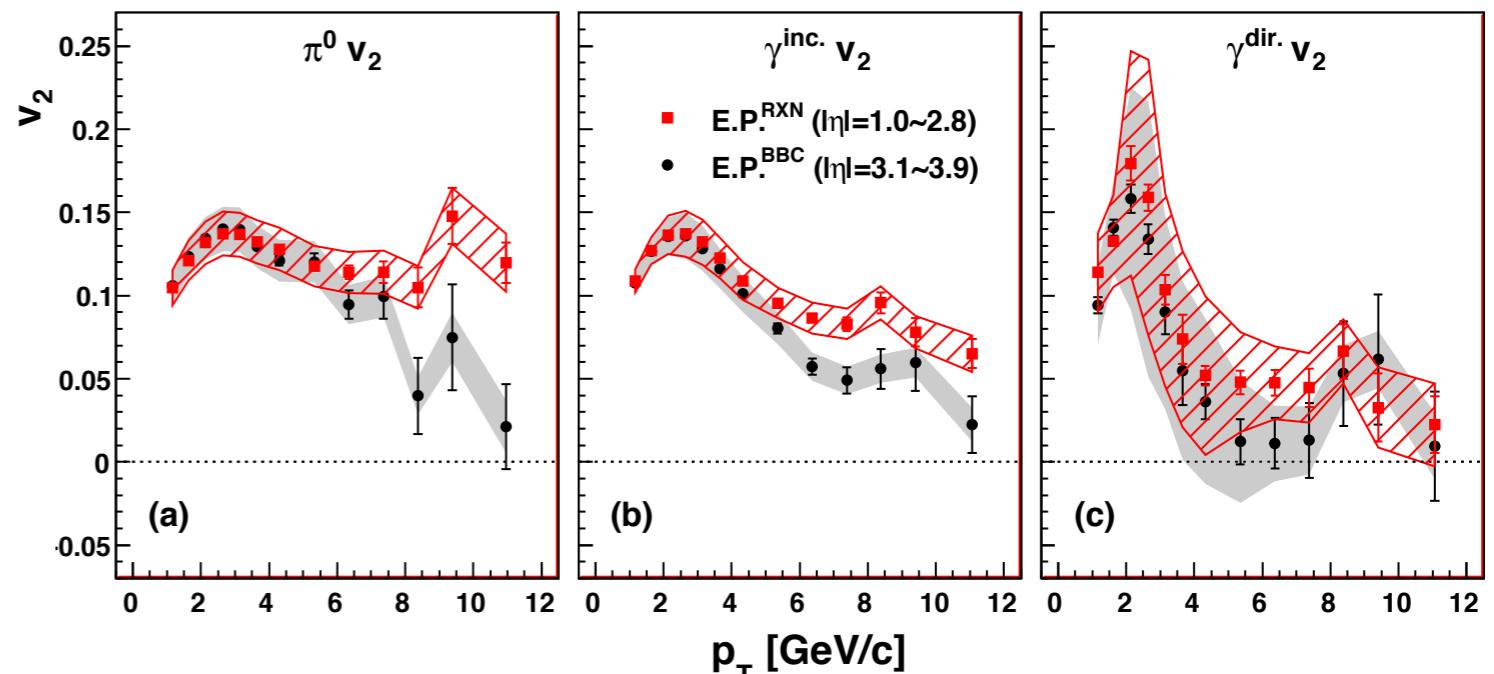
- Soft photons will go with the flow
- Jet-plasma photons: a negative v_2
- Details will matter: flow, $T(t)$. . .

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

(2008)

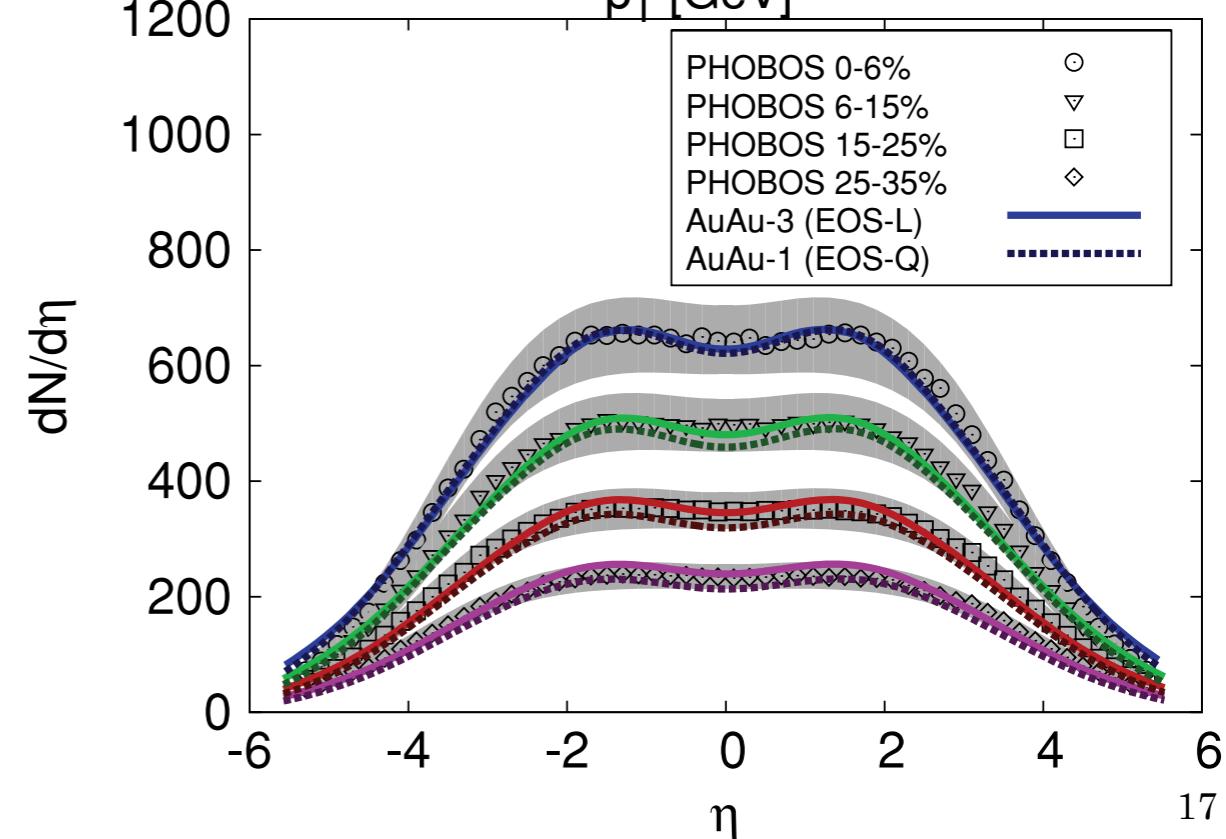
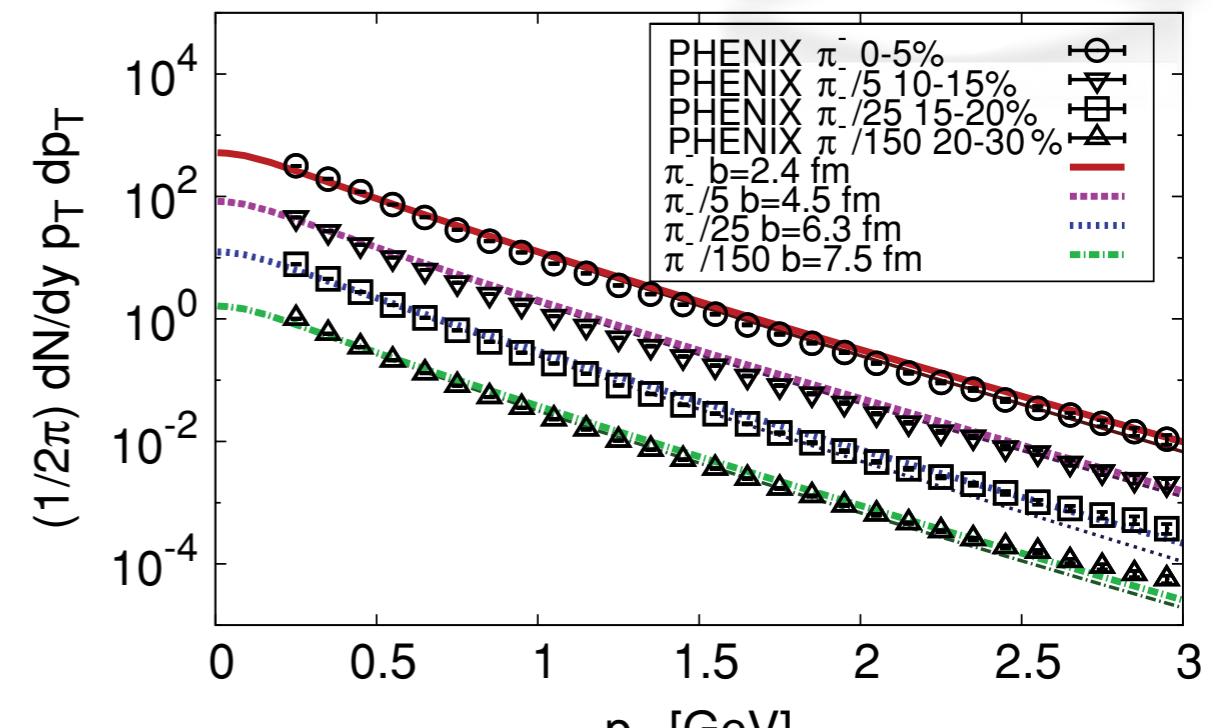
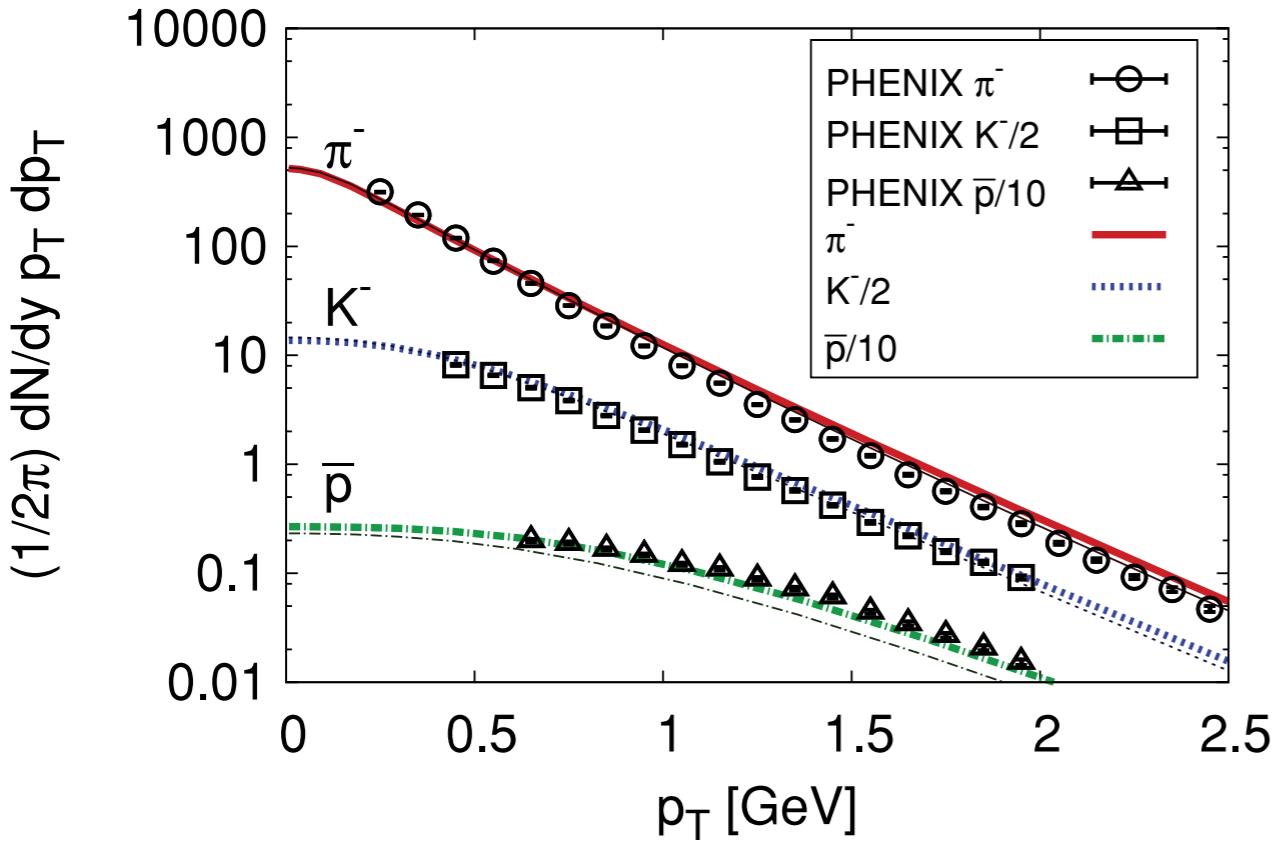


(2011)



PROGRESS IN CHARACTERIZATION TOOL: 3D VISCOUS RELATIVISTIC HYDRODYNAMICS

MUSIC:



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

Viscosity & FIC effects on EM observables?

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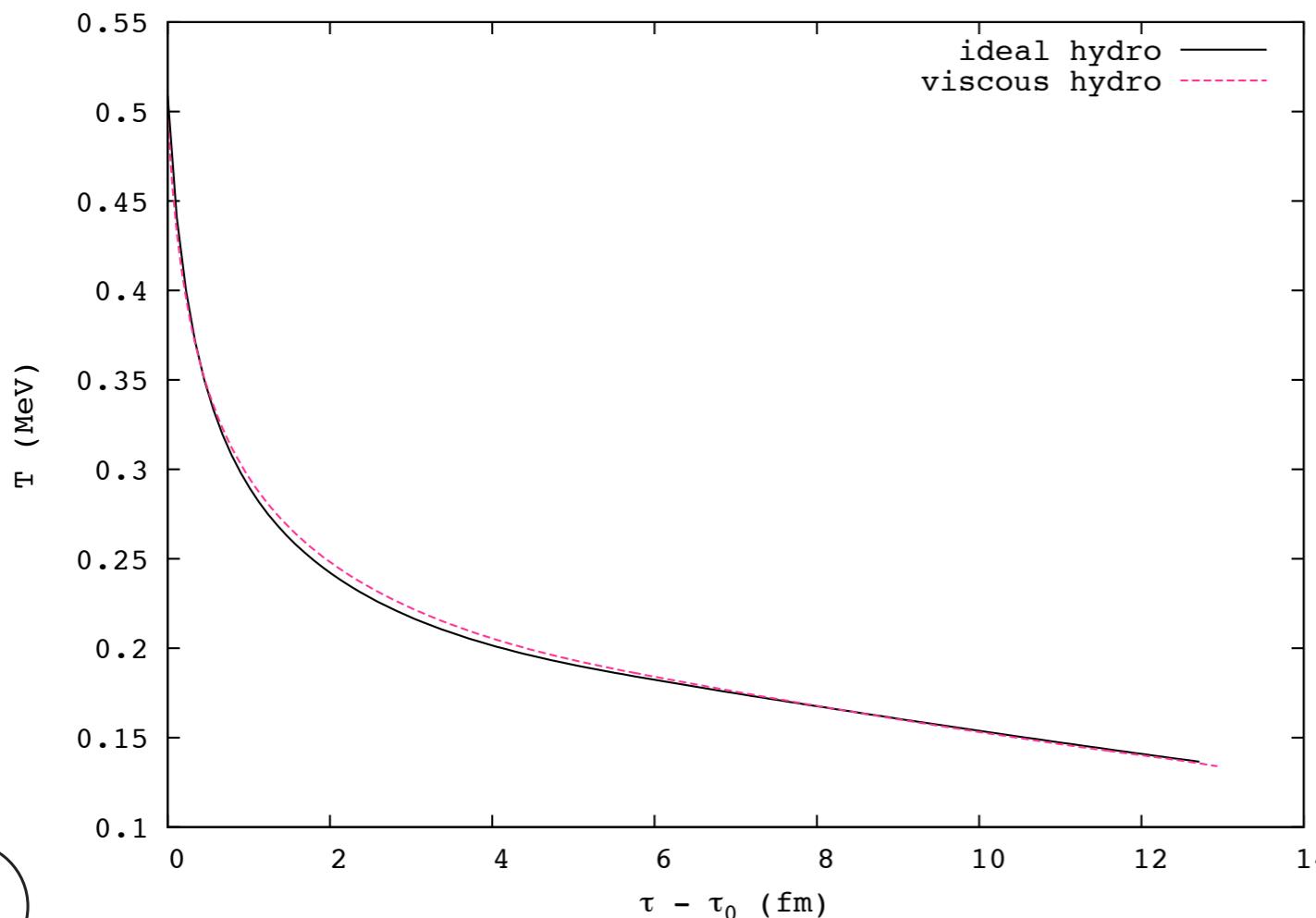
THE EFFECTS OF SHEAR VISCOSITY ON BULK DYNAMICS

$$T_{\text{ideal}}^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - Pg^{\mu\nu}$$

$$T^{\mu\nu} = T_{\text{ideal}}^{\mu\nu} + \pi^{\mu\nu}$$

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

$$\partial_\mu(su^\mu) \propto \eta$$



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



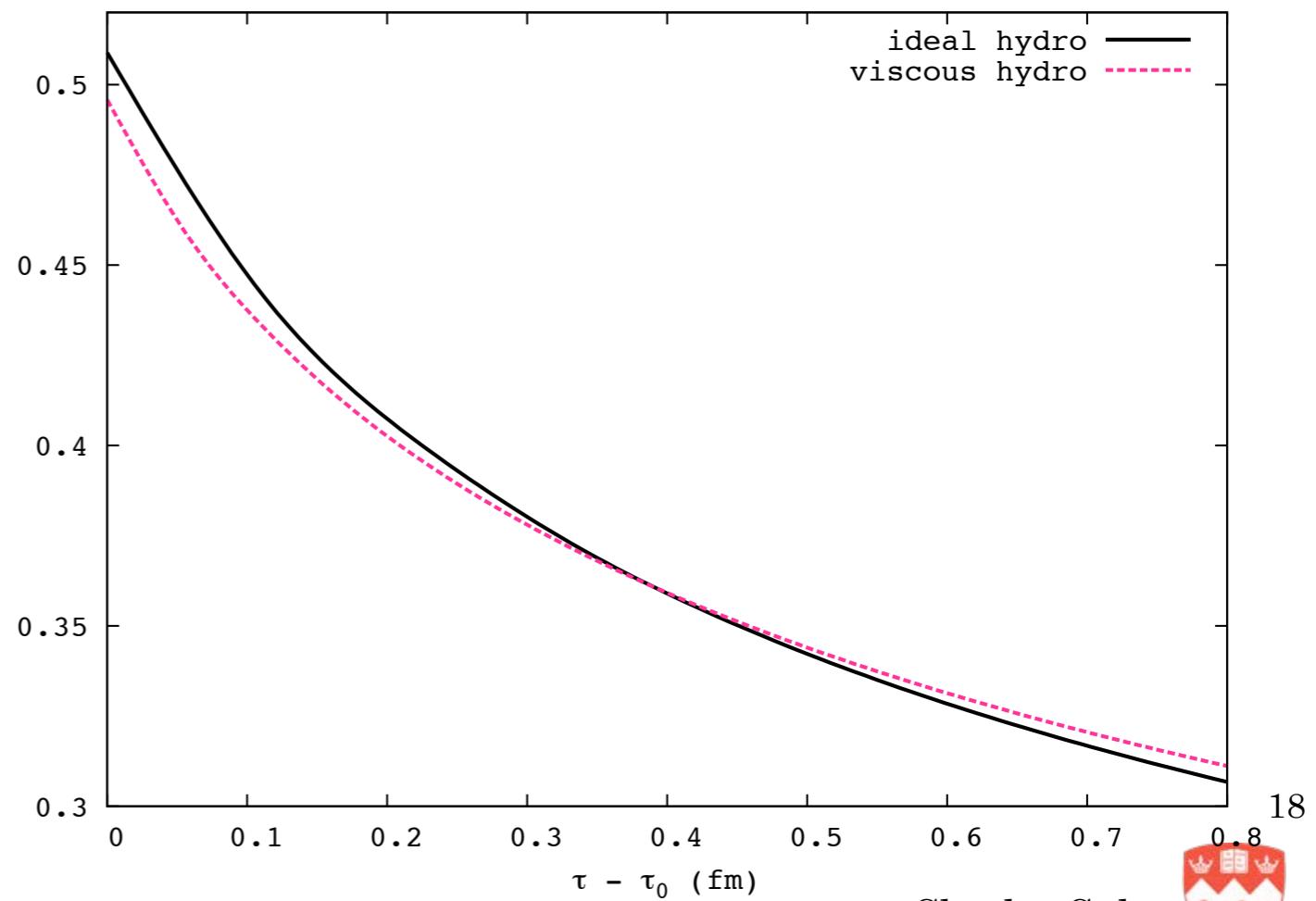
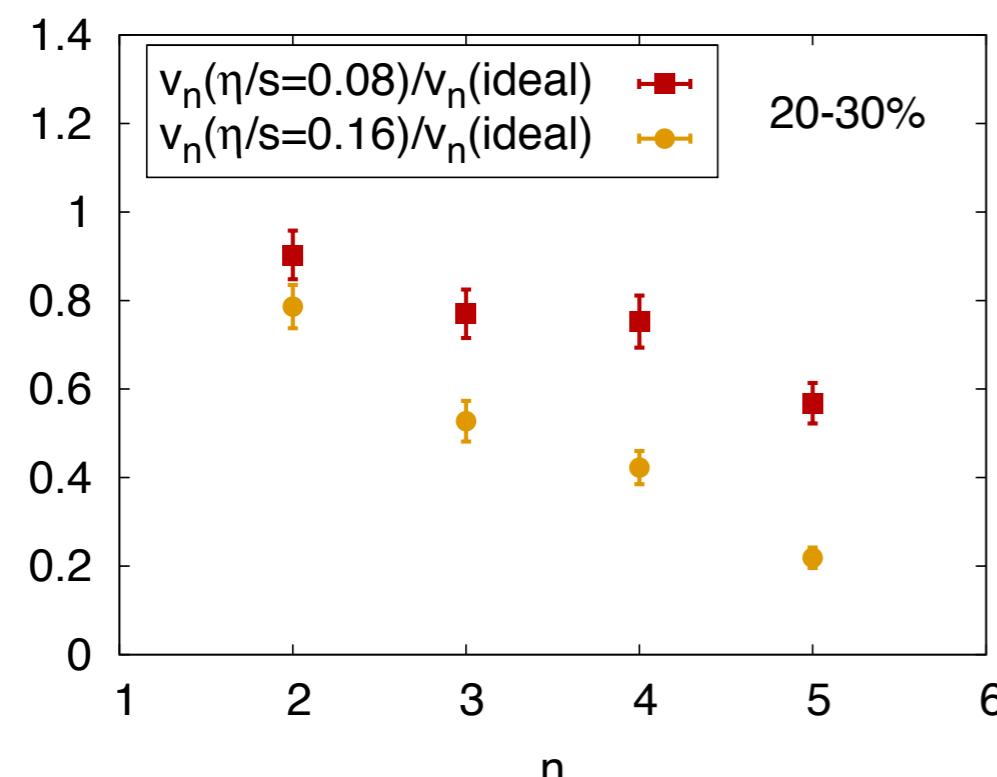
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Israël & Stewart, Ann. Phys. (1979), Baier et al., JHEP (2008), Luzum and Romatschke, PRC (2008)



THE EFFECTS OF SHEAR VISCOSITY ON THE PHOTON DISTRIBUTION

In-medium hadrons:

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

$$f \rightarrow f_0 + \delta f, \quad \delta f = f_0(1 \pm (2\pi)^3 f_0) p^\alpha p^\beta \pi_{\alpha\beta} \frac{1}{2(\varepsilon + P)T^2}$$

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

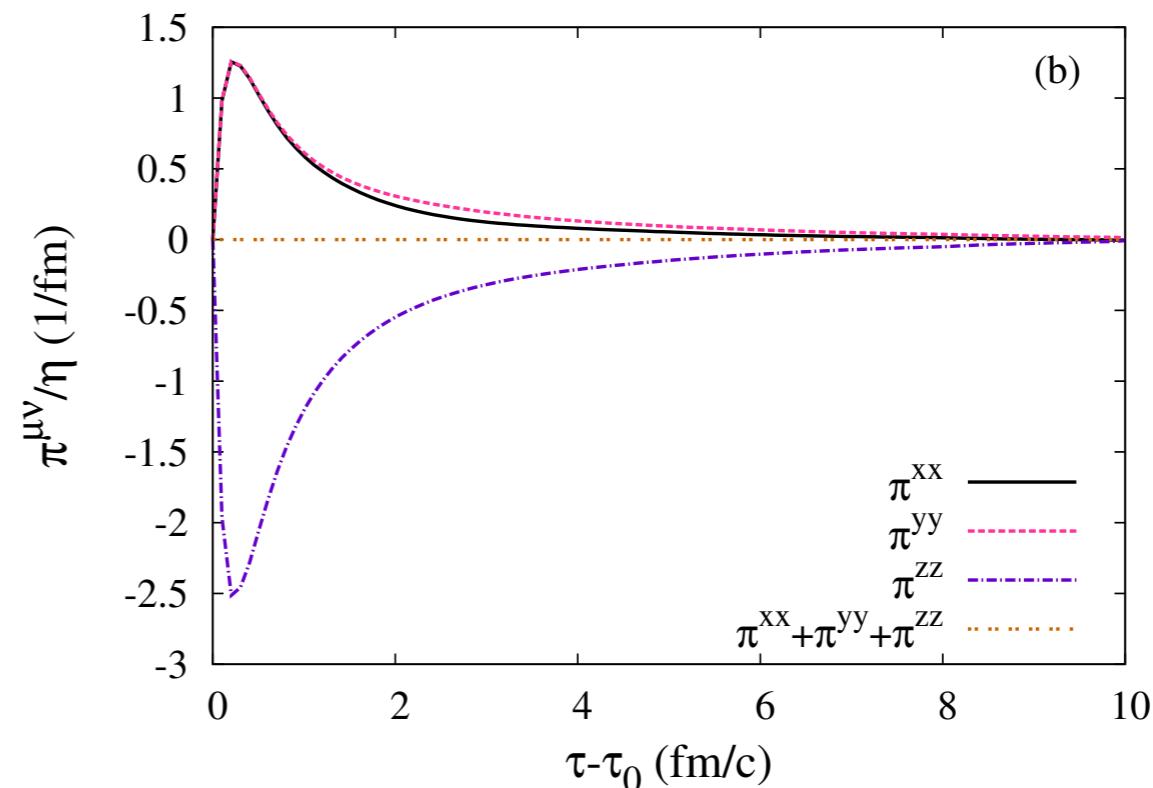
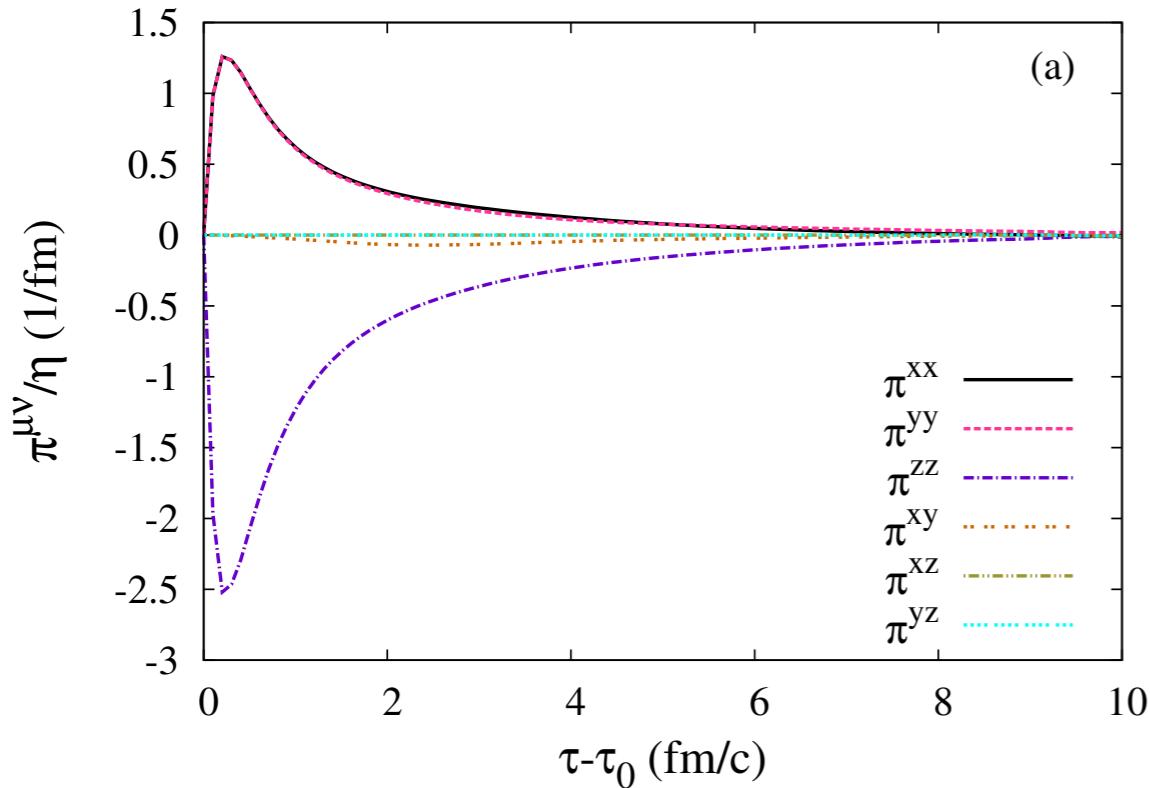
One considers all the reaction and radiative decay channels of external state combinations of:

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

+ QGP Photons

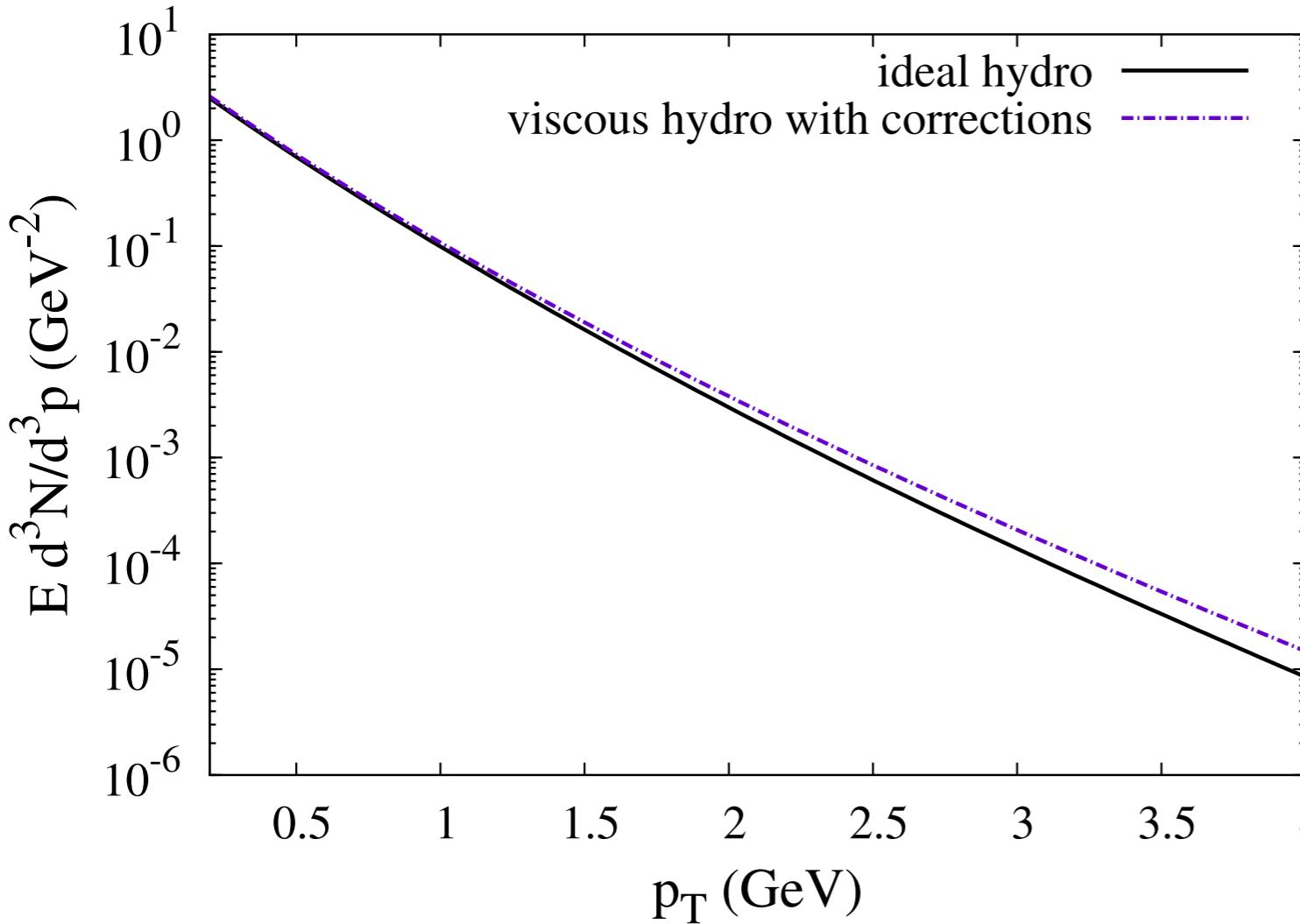


THE EFFECTS OF SHEAR VISCOSITY ON THE BULK DYNAMICS



- Large at early times
- Small at later times: viscosity corrections to the distribution functions will also vanish

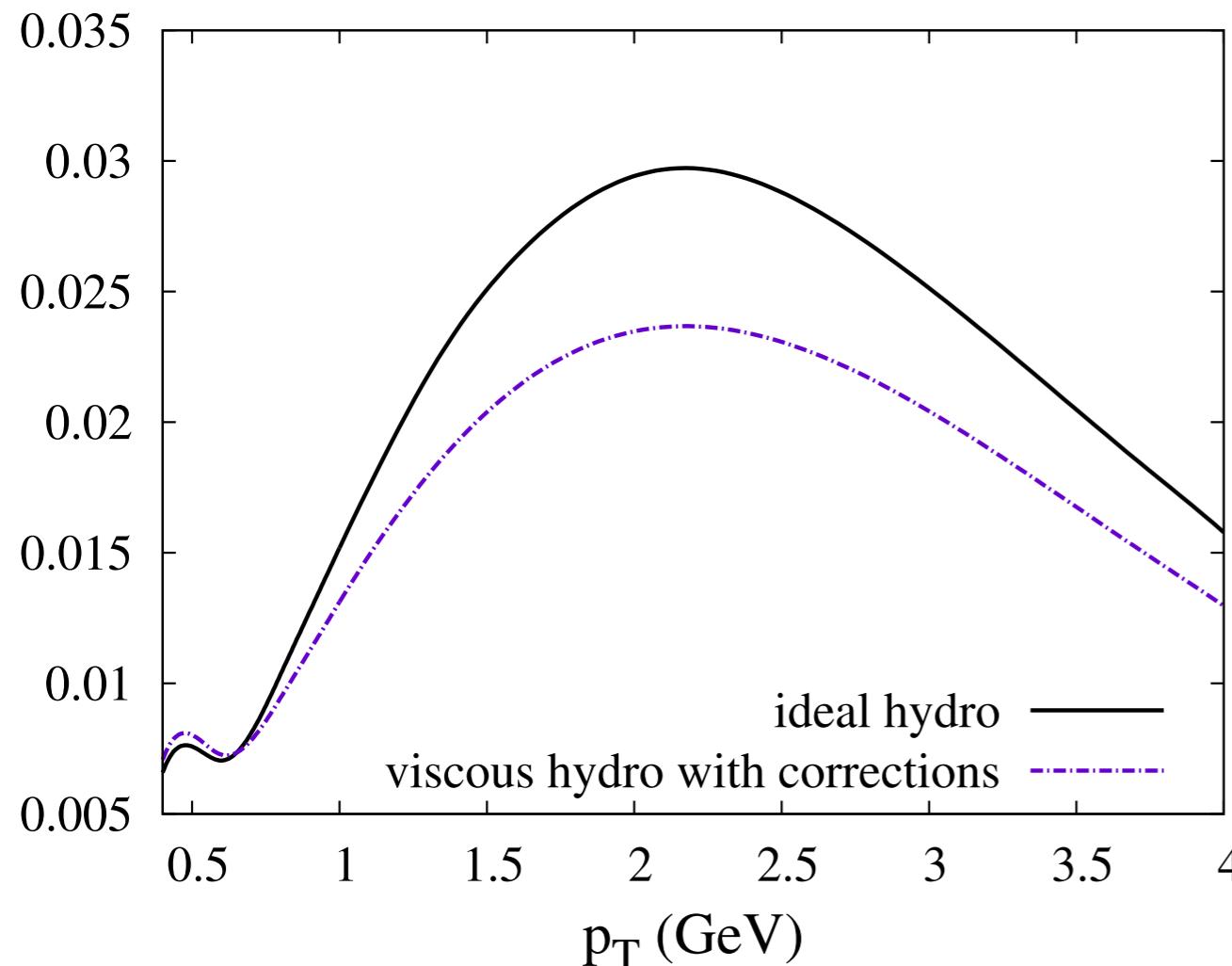
THE NET THERMAL PHOTON YIELD



- Viscous corrections make the spectrum harder, $\approx 100\%$ at $p_T = 4 \text{ GeV}$.
- Increase in the slope of $\approx 15\%$ at $p_T = 2 \text{ GeV}$.
- Extracting the viscosity from the photon spectra will be challenging.
- Once pQCD photons are included: a few % effect from viscosity
- More work is still needed to properly include all photon sources in a consistent way



SHEAR VISCOSITY AND PHOTON v_2

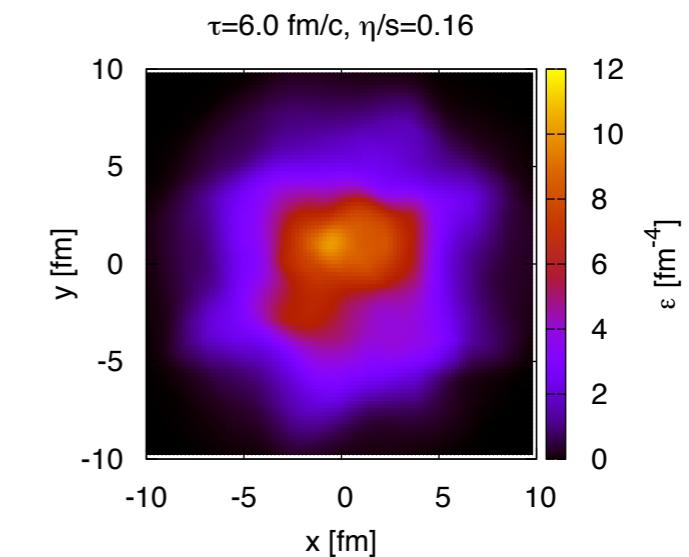
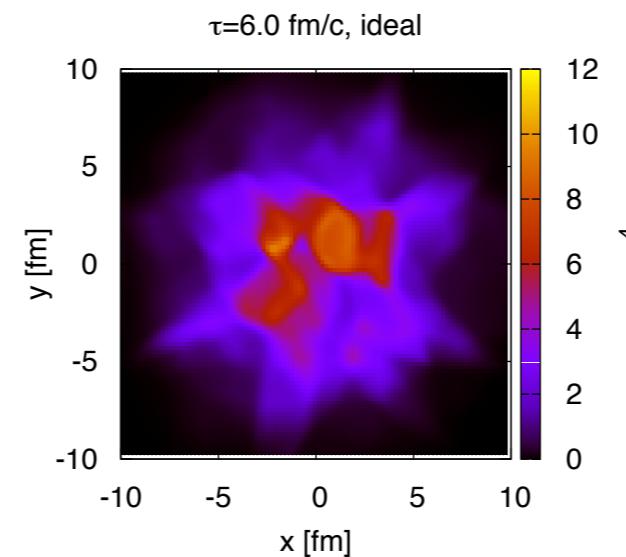
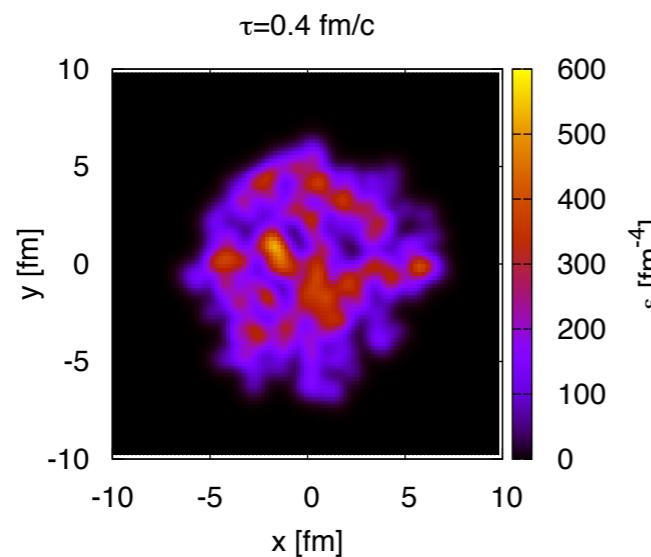
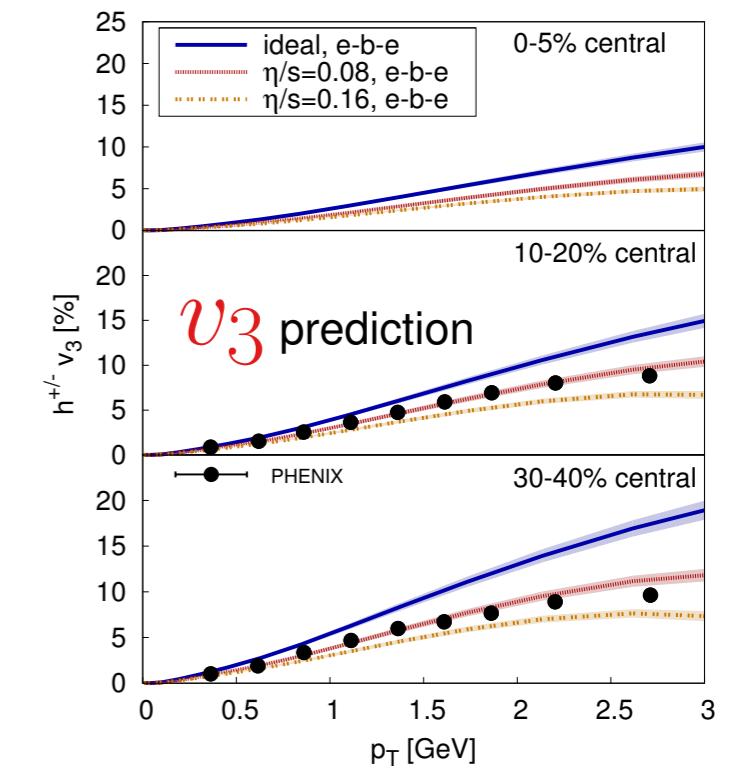
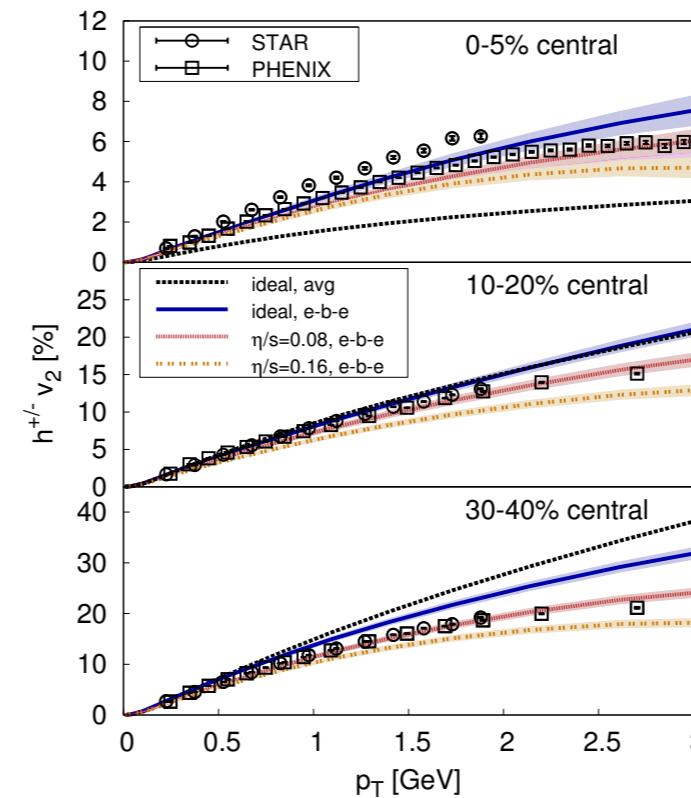
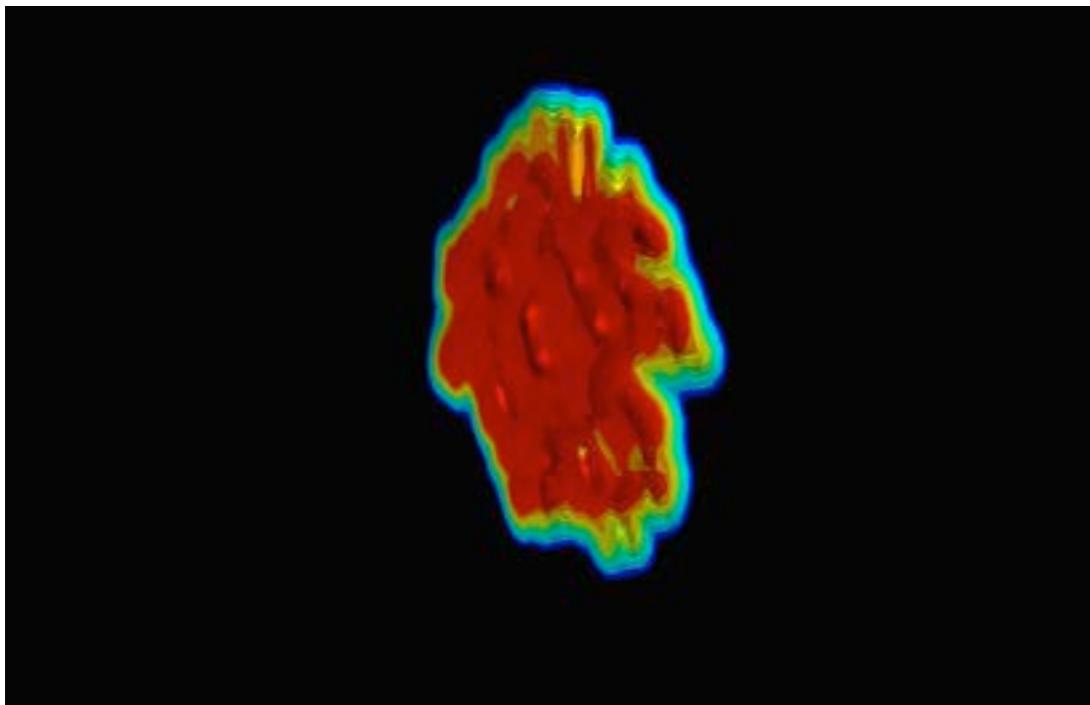


- The net elliptic flow is a *weighted average*. A larger QGP yield will yield a smaller v_2 . Same story - *mutatis mutandis* -for the HG
- The turnover at $p_T \approx 2$ GeV could be QGP-driven and/or pQCD-driven
- The net effect of viscous corrections makes the photon elliptic flow *smaller*, as it does for hadrons

M. Dion *et al.*, PRC 2011

INITIAL STATE FLUCTUATIONS: A PARADIGM SHIFT IN HEAVY ION ANALYSES

Lumpy
MUSIC

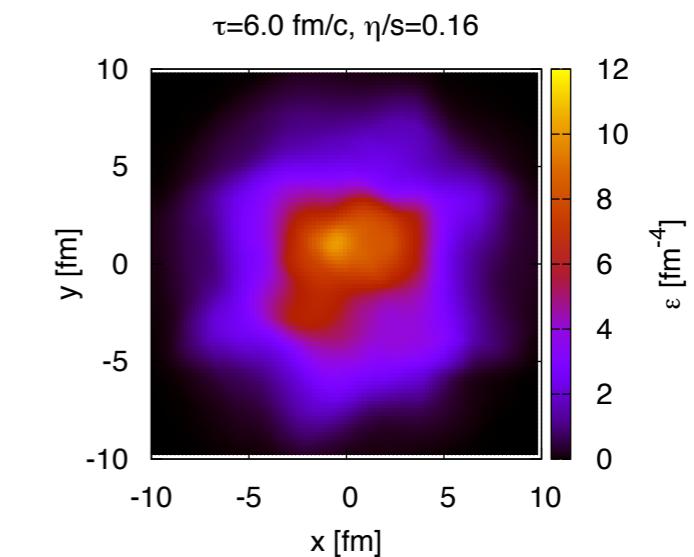
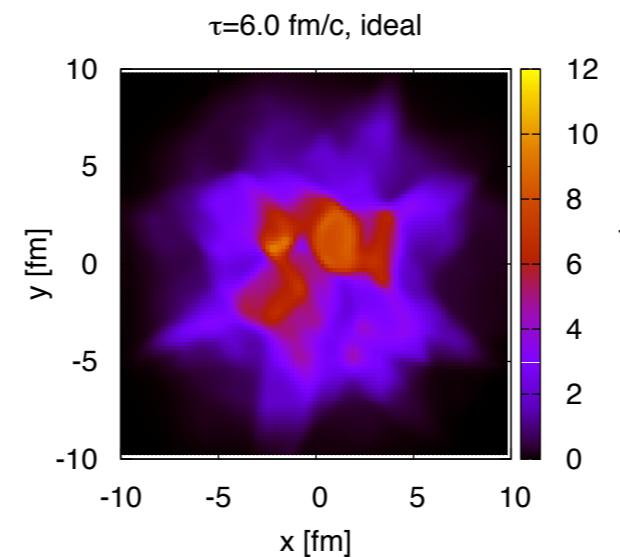
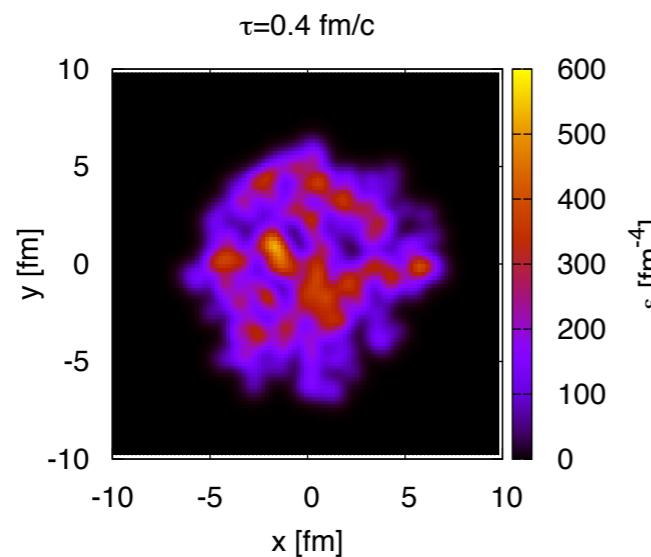
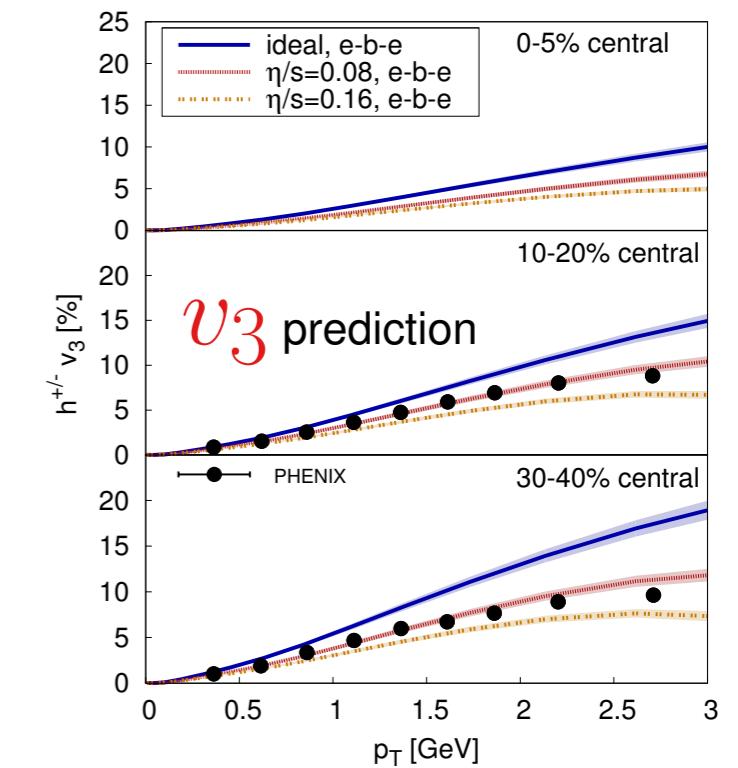
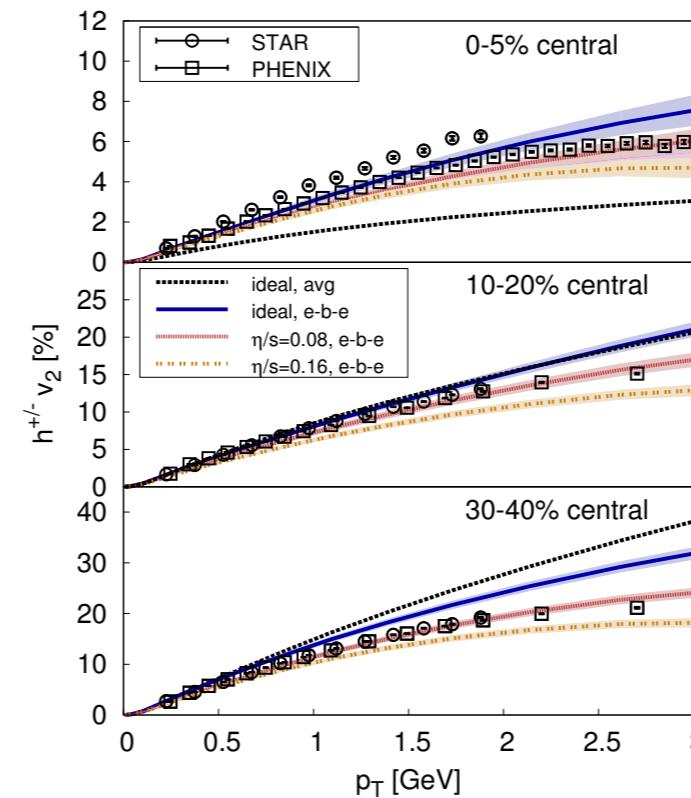
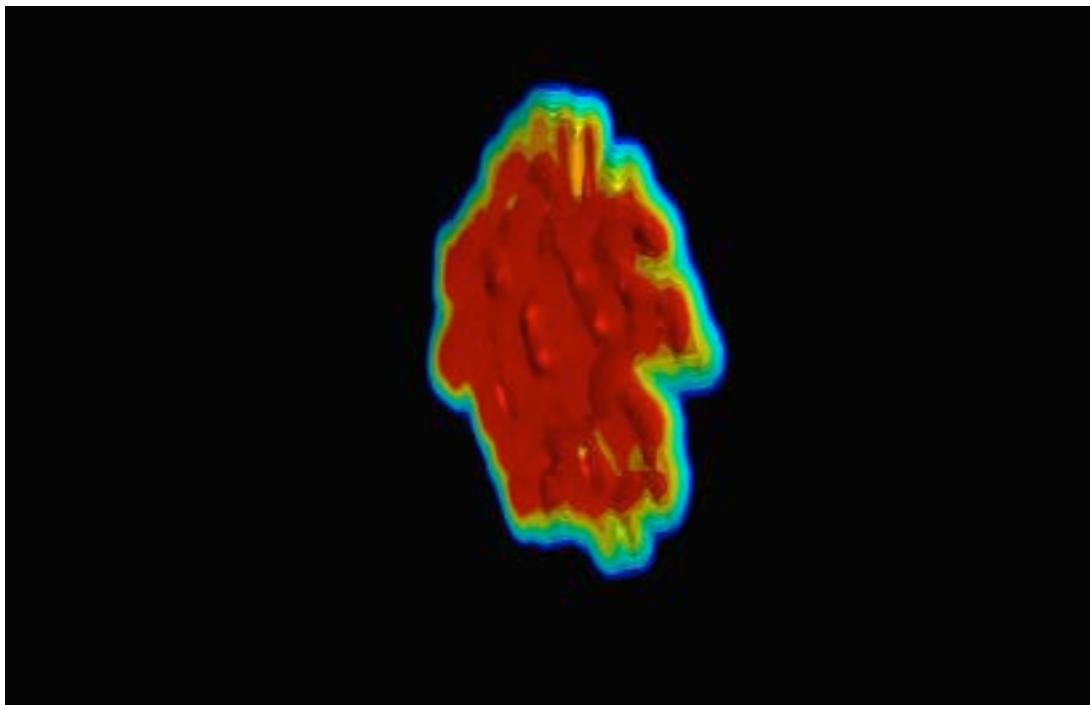


Schenke, Jeon, Gale, PRL (2011)



INITIAL STATE FLUCTUATIONS: A PARADIGM SHIFT IN HEAVY ION ANALYSES

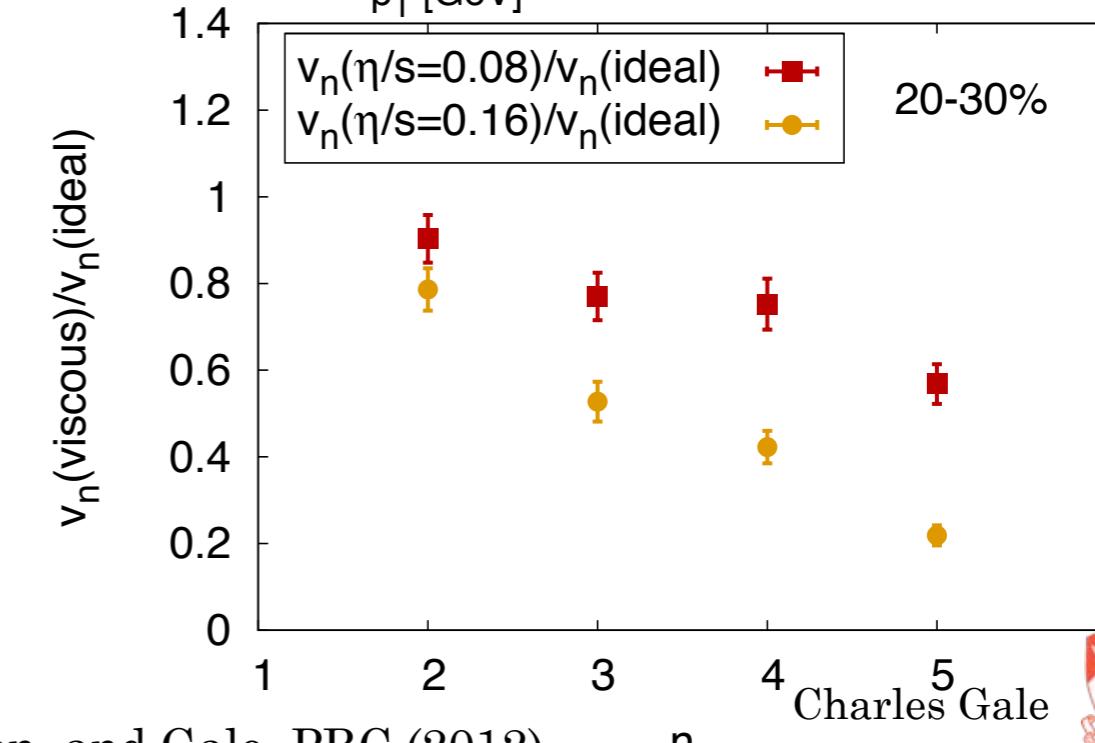
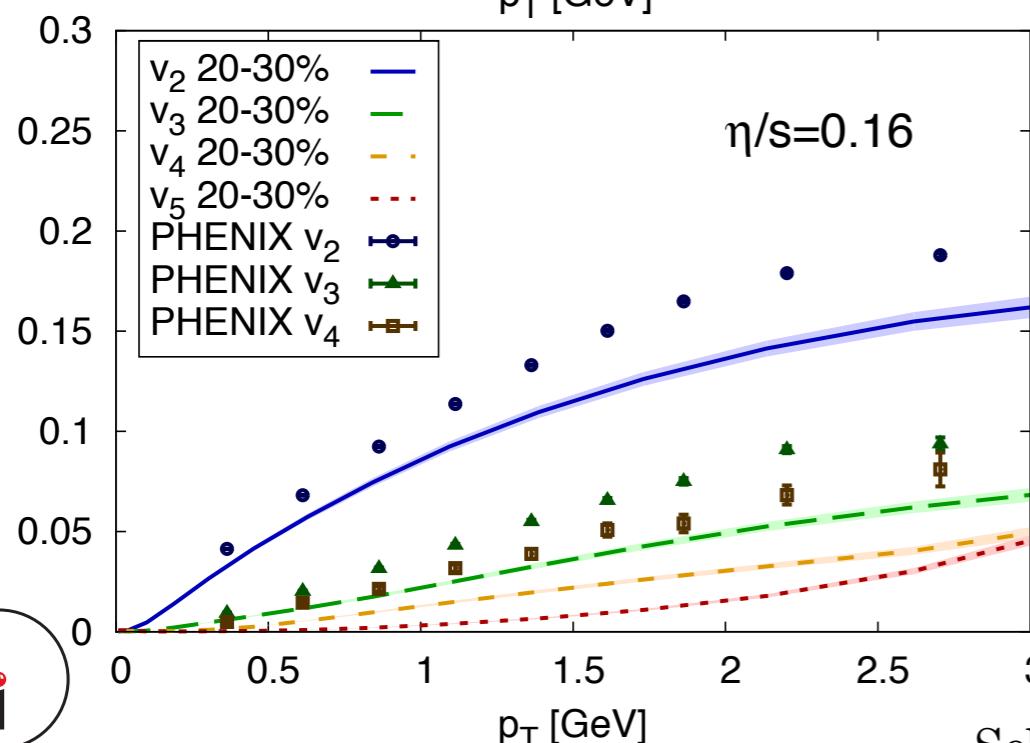
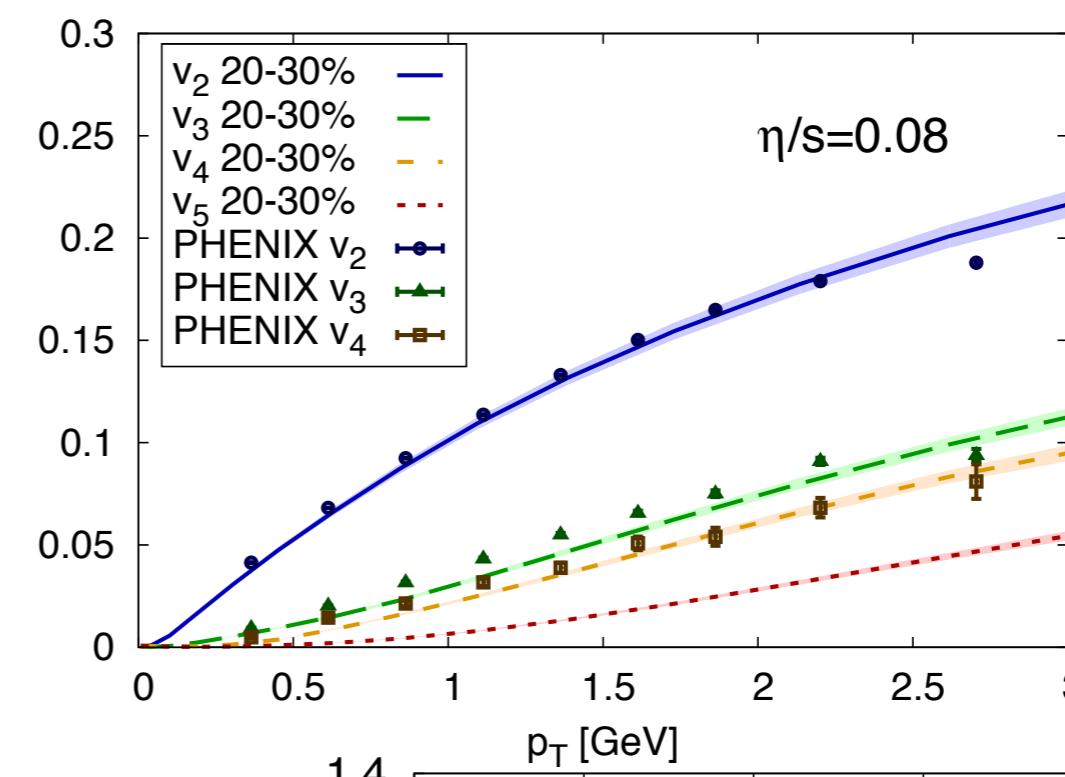
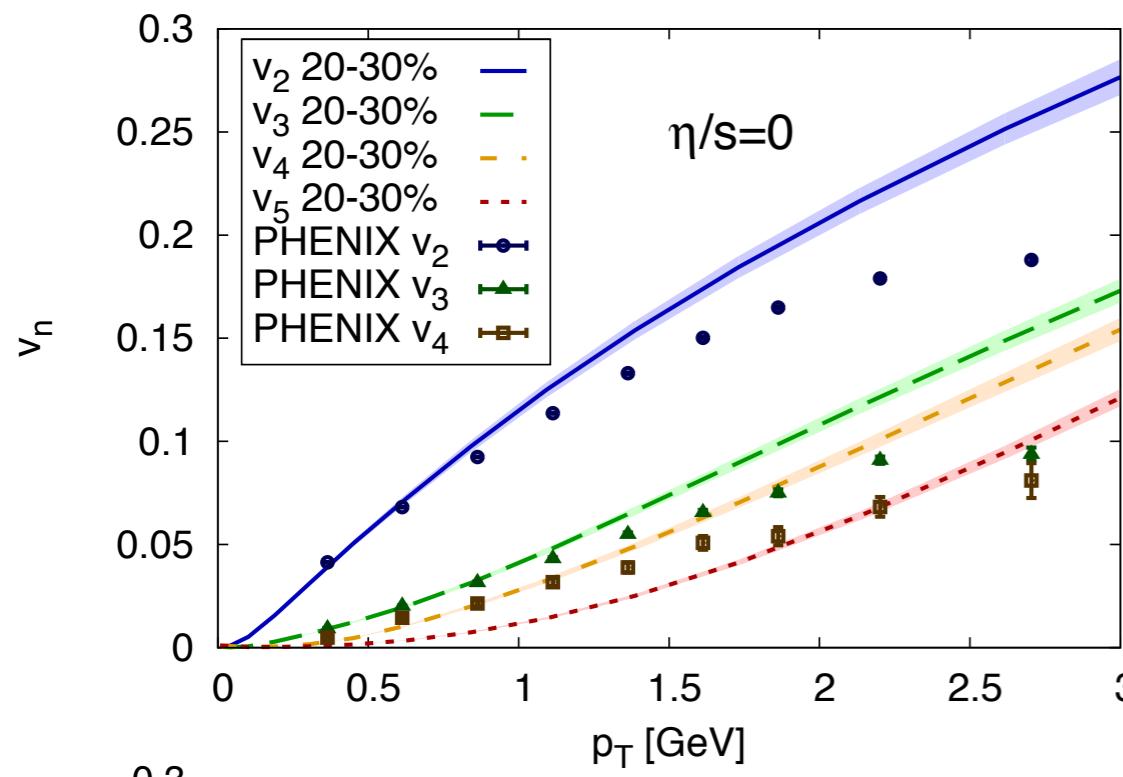
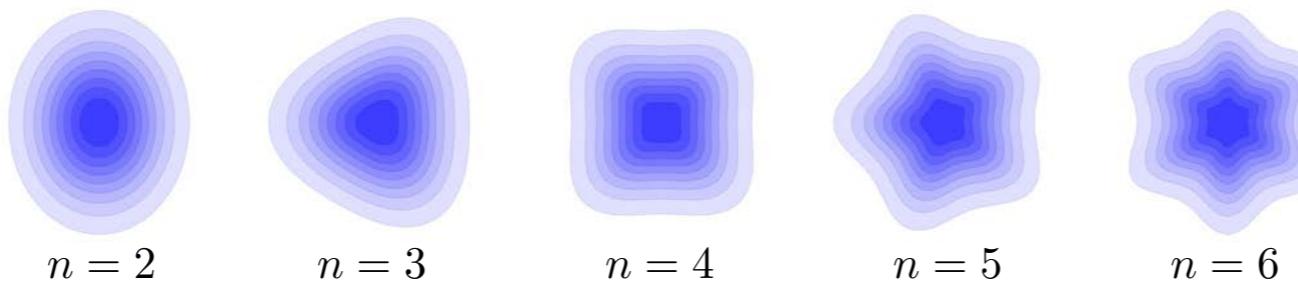
Lumpy
MUSIC



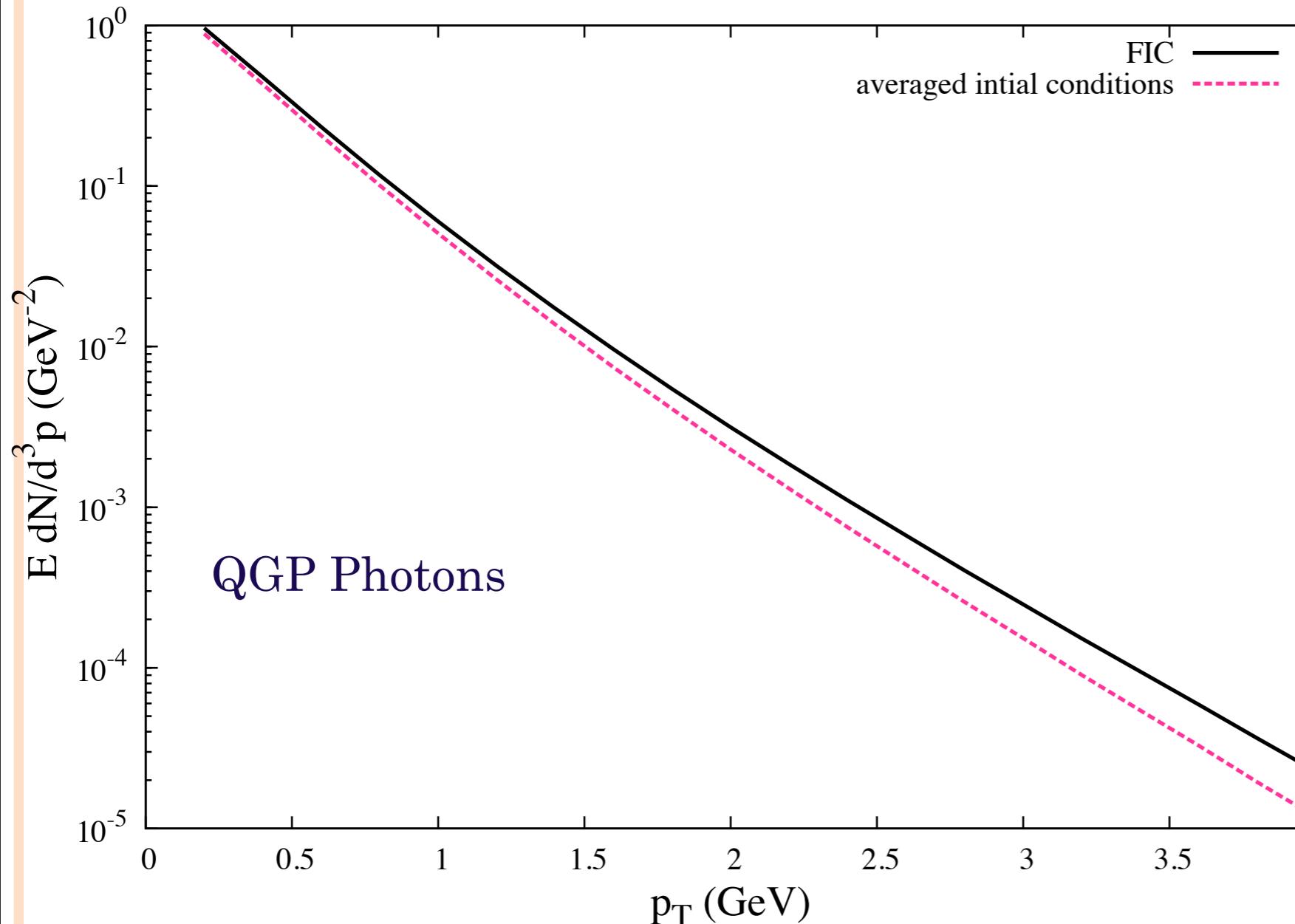
Schenke, Jeon, Gale, PRL (2011)



MOVING INTO THE “CHARACTERIZATION” PHASE...



THE EFFECT OF FIC 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*

Dion et al., PRC (2011)
Chatterjee et al., PRC (2011)

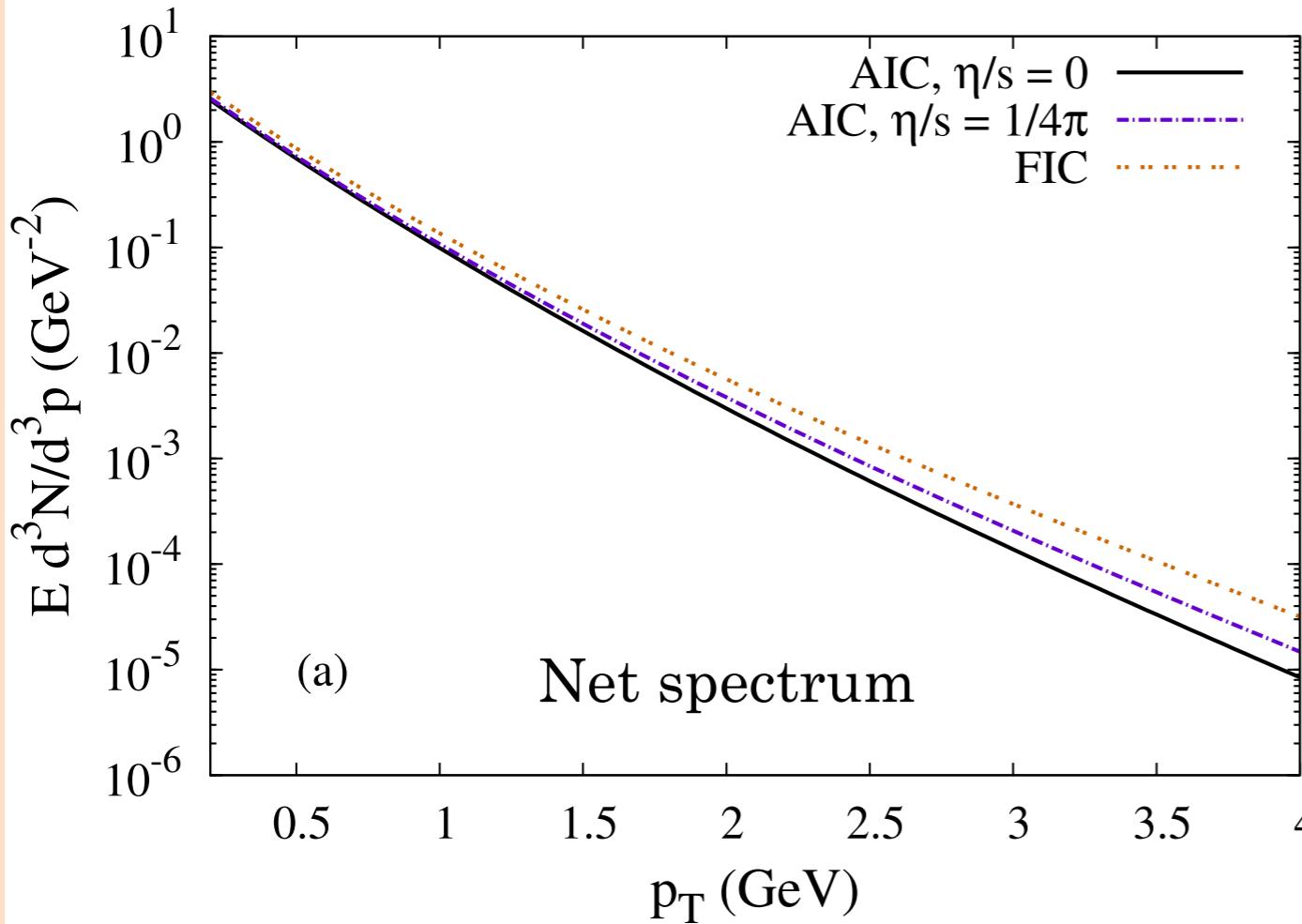


ALL TOGETHER: FICs + VISCOSITY

- Combined with viscous corrections, FIC yield an enhancement by ≈ 5 @ 4 GeV, and ≈ 2 @ 2 GeV
- Temperature estimated by slopes can vary considerably
- A combination of hot spots and blue shift hardens spectra
- Once pQCD photons are included: only modest changes from viscous corrections + FICs



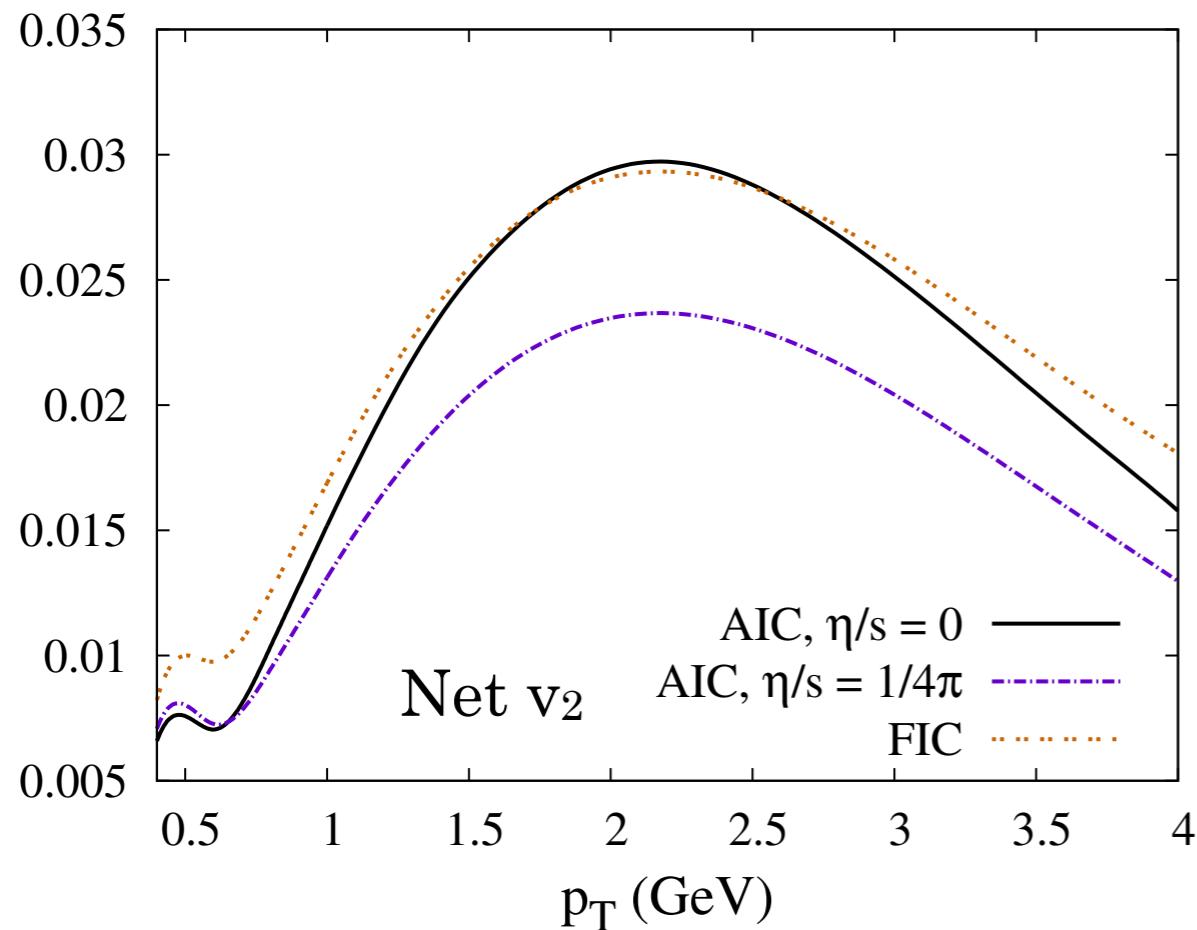
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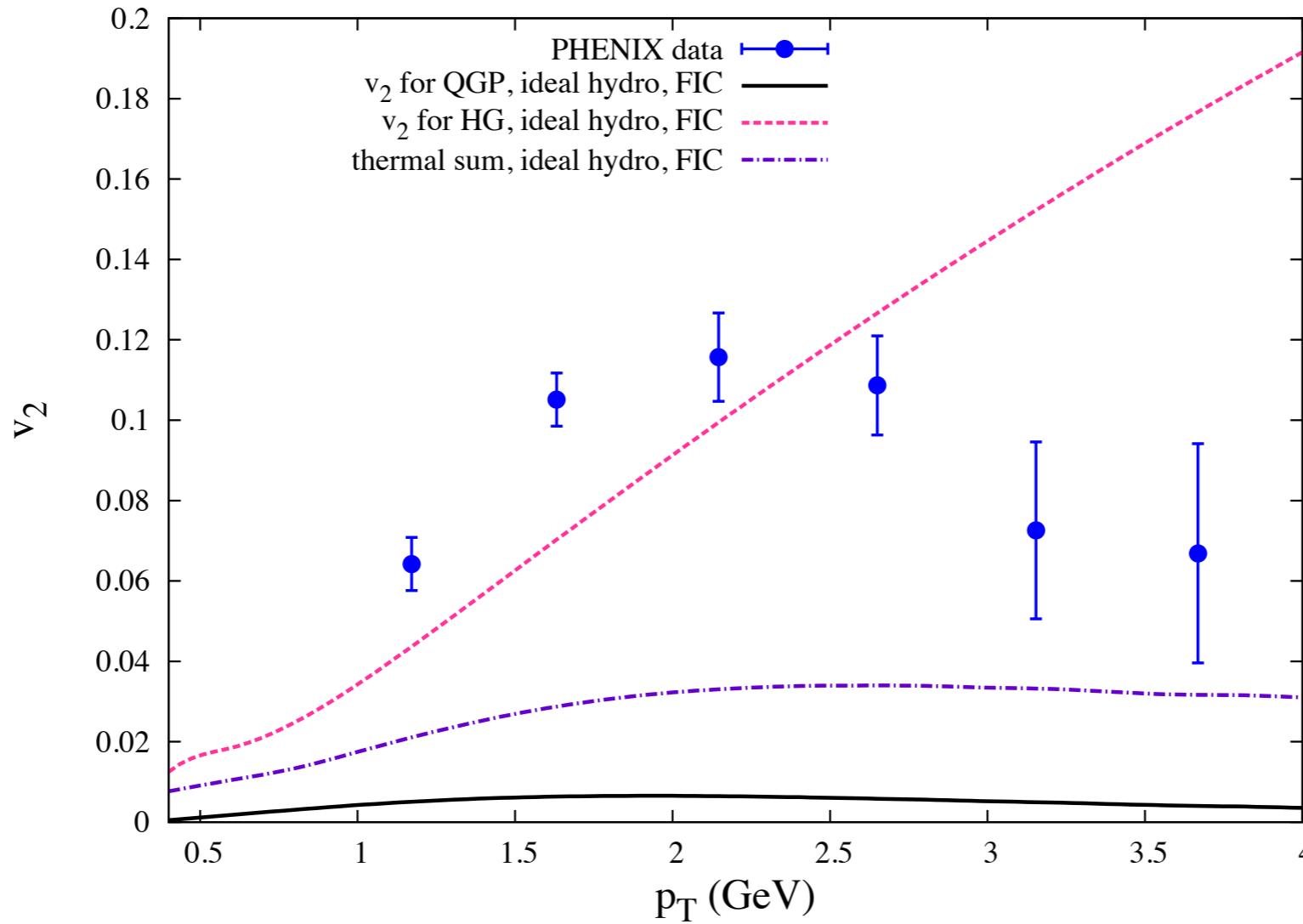
FICs AND THERMAL PHOTON v_2



- FICs enhance v_2 in this centrality class (0-20%), as for hadrons
- For hadrons measured in events belonging to large centrality, FICs will *decrease* v_2
- Net v_2 is comparable in size to that with ideal medium.



PHOTON v_2 DATA?

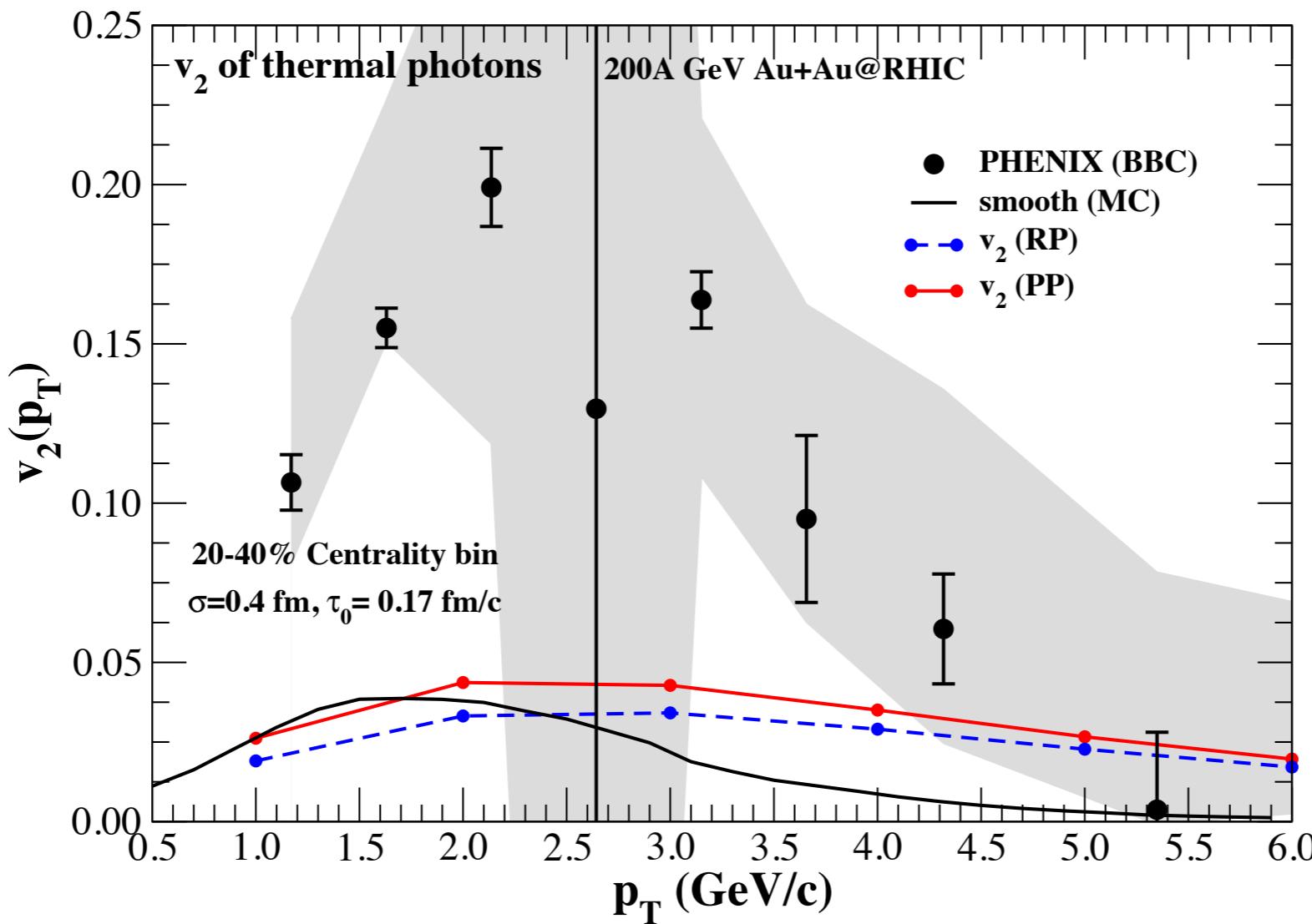


Dion et al. (2011)

- Data is higher than calculation, even with e-b-e initial state fluctuations, and ideal hydro
- Size comparable with HG v_2



PHOTON v_2 DATA?



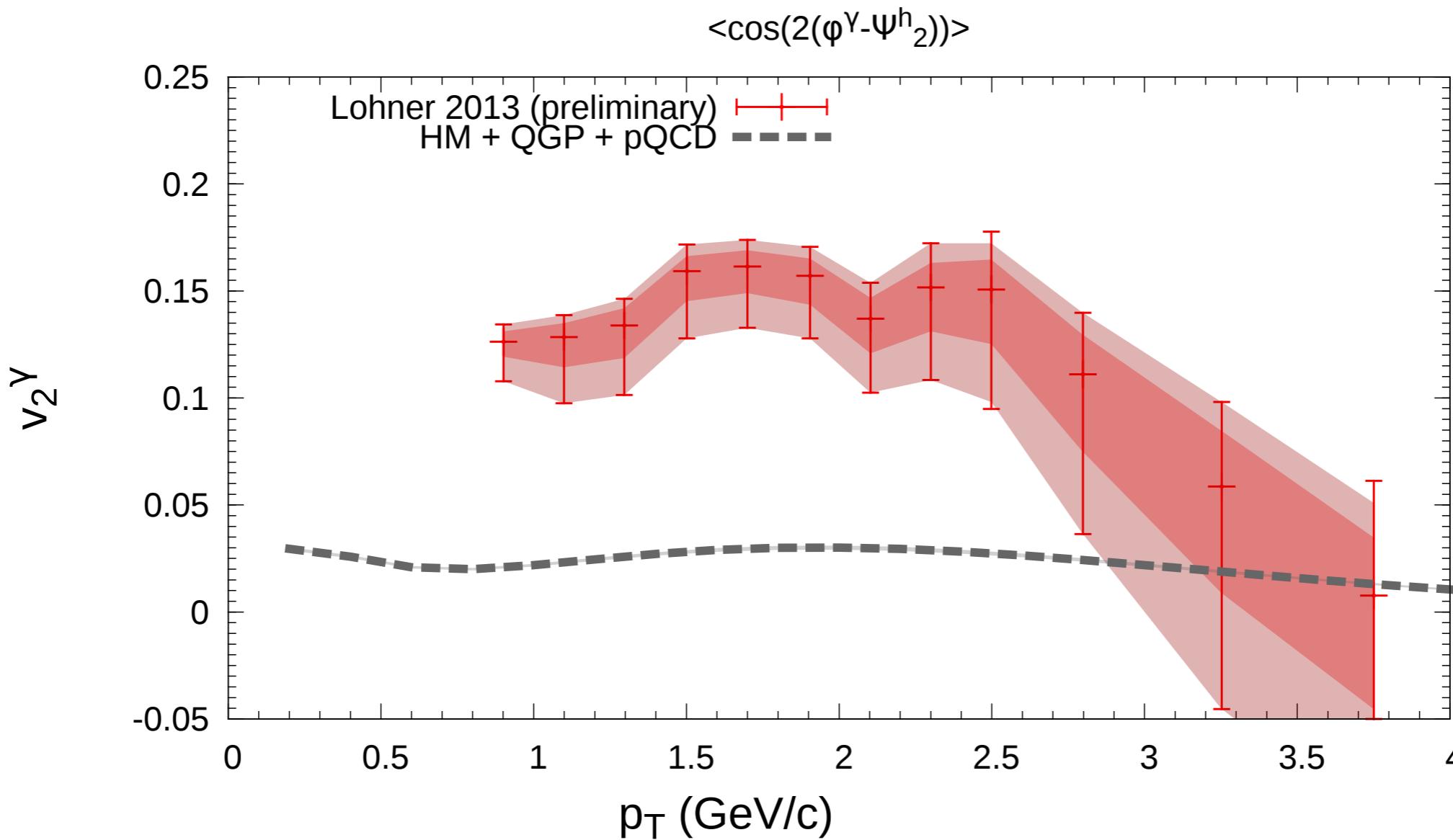
Chatterjee et al. (2013)

- Data is higher than calculation, even with e-b-e initial state fluctuations, and ideal hydro
- Size comparable with HG v_2



PHOTON v_2 DATA?

LHC Pb+Pb, 2.76 TeV 20-40%



Paquet et al., (2014)



SOME FACTS AND SOME LEADS

- FICs are here to stay. “Initial temperature” is ill-defined.
- Some room to explore systematically hydro initialization and parameters. This requires consistency with the hadronic data.
- Making the QGP signal **larger** will *decrease* the v_2 . The $T=0$ photons, *decrease* v_2 . Suppose 2 sources:

$$\frac{v_2 = \int d\phi \frac{dN}{d\phi} \cos(2(\phi - \psi))}{\int d\phi \frac{dN}{d\phi}} = \frac{\int d\phi \frac{dN^1}{d\phi} \cos(2(\phi - \psi))}{\int d\phi \frac{dN}{d\phi}} + \frac{\int d\phi \frac{dN^2}{d\phi} \cos(2(\phi - \psi))}{\int d\phi \frac{dN}{d\phi}}$$

- For each source:

$$\frac{v_2^i = \int d\phi \frac{dN^i}{d\phi} \cos(2(\phi - \psi))}{\int d\phi \frac{dN^i}{d\phi}}, \quad \therefore v_2 = \frac{\sum_i N^i v_2^i}{\sum_i N^i}$$

- Tension between rates and elliptic flow for QGP signal
- Missing strength in the hadronic sector(?)

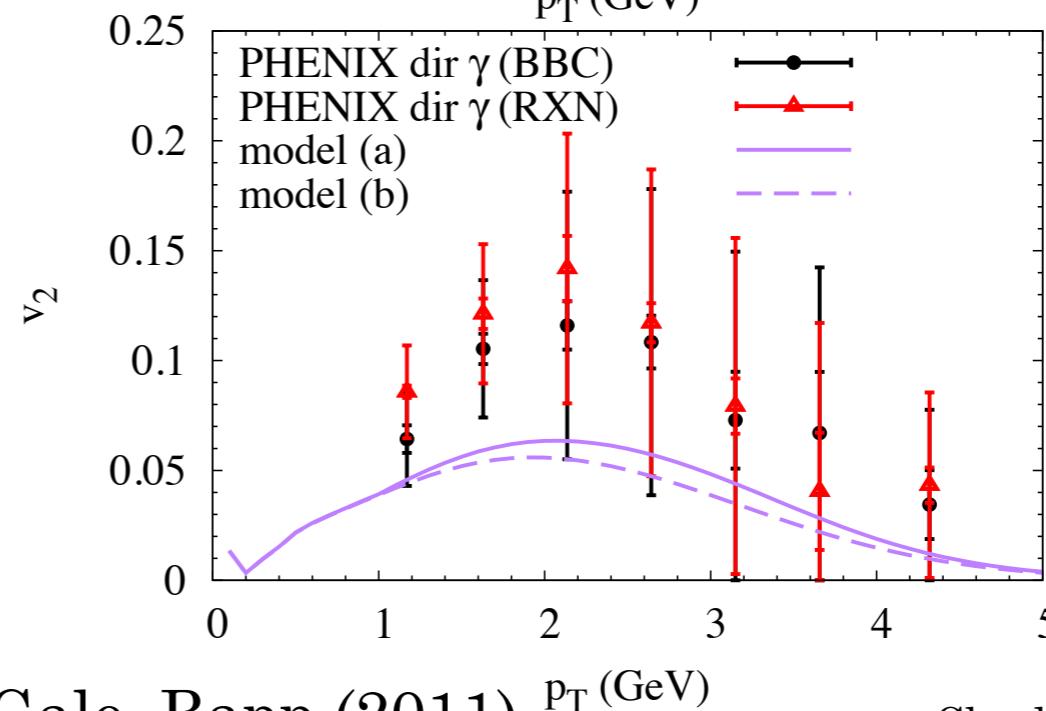
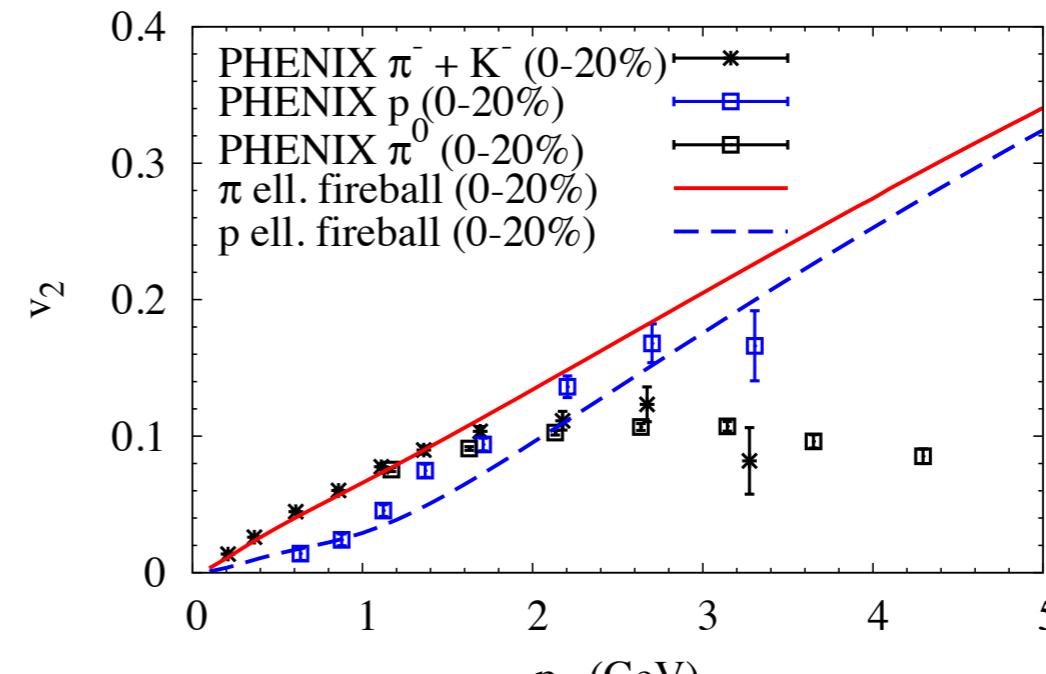
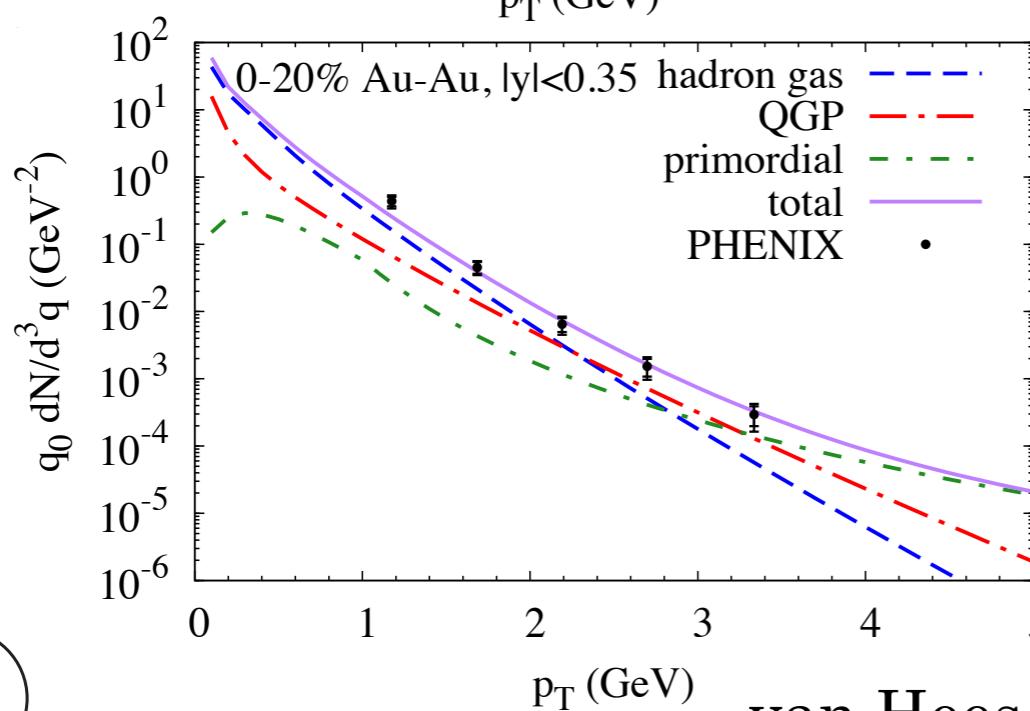
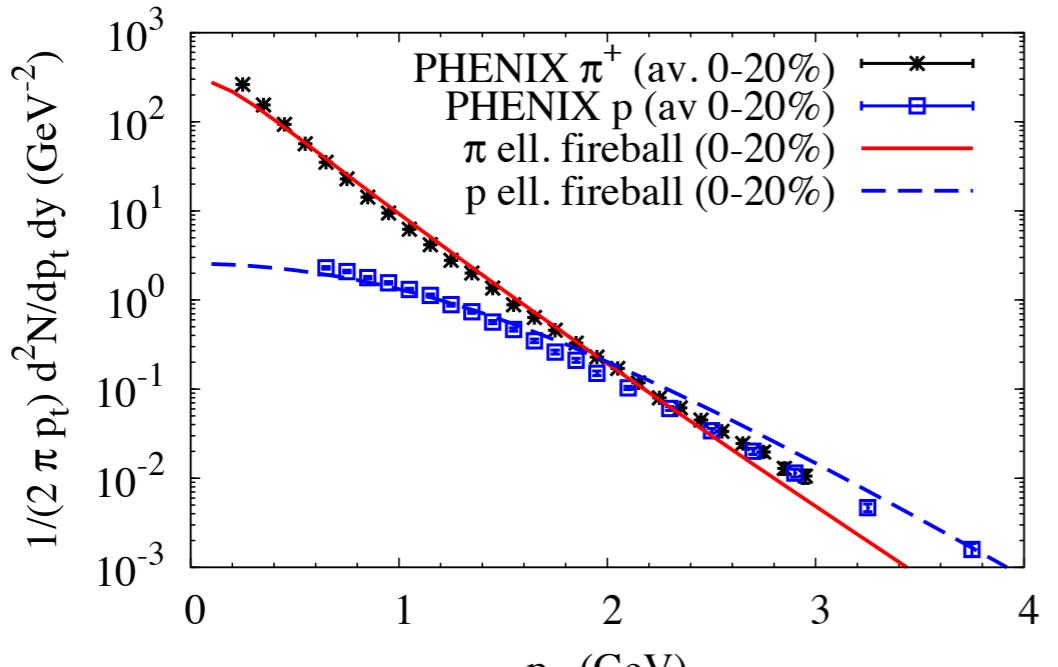
SOME FACTS AND SOME LEADS

- Can we improve on the hadronic rates? Baryons? Baryons +mesons?
- Early-times magnetic field effects? (Basar, Kharzeev, Skokov, PRL (2012); Basar, Kharzeev, Shuryak, arXiv: 1402.2286)
- Glasma effects (see L. McLerran's talk)
- Is the large photon elliptic flow telling us about the dynamics?
- Non-zero initial shear tensor? Primordial flow? Can we improve on the hydro initial states?
- Can we improve on the hydrodynamic evolution?



ELLIPTIC FLOW AND SPACE-TIME DYNAMICS

- In a thermal fireball picture, the net photon yield is sensitive to the value of the acceleration parameter, and to details of the initial state. The photons **do** report on the details of the dynamics.
- How uniquely determined are these? How unique is the entire evolution?

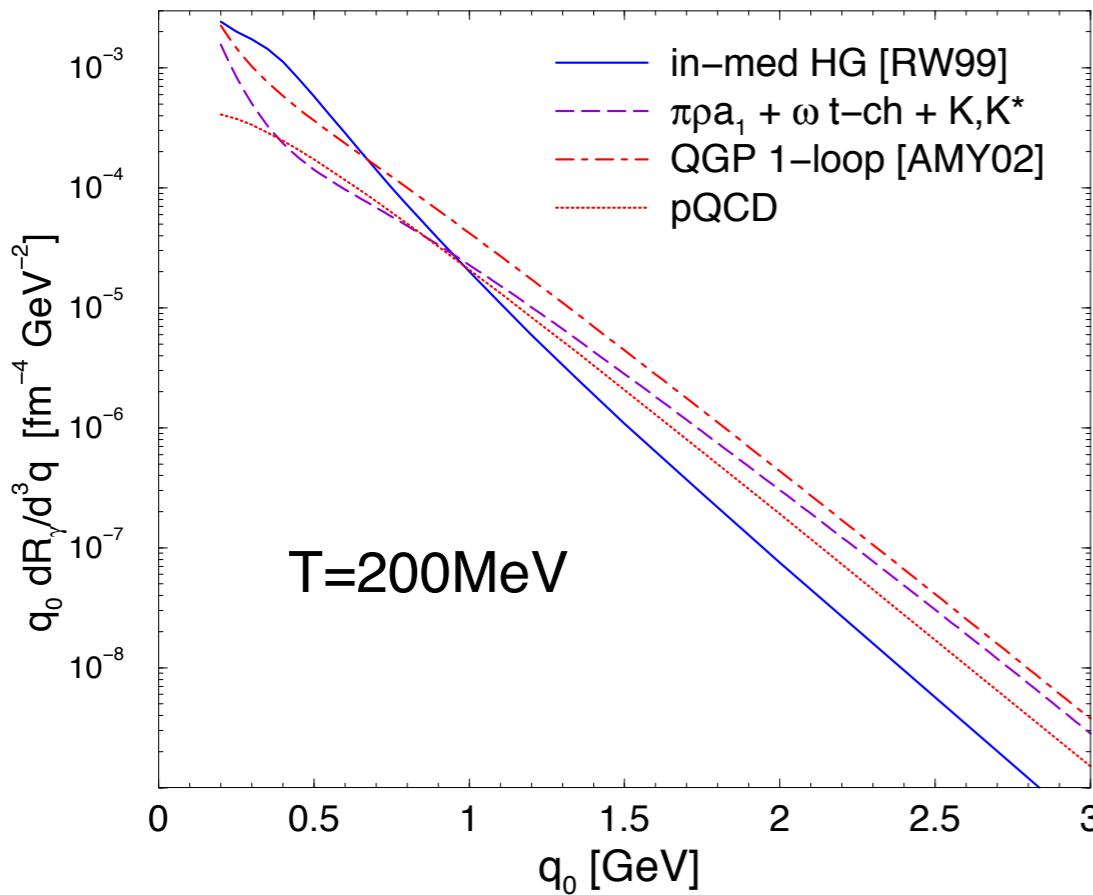


van Hees, Gale, Rapp (2011)

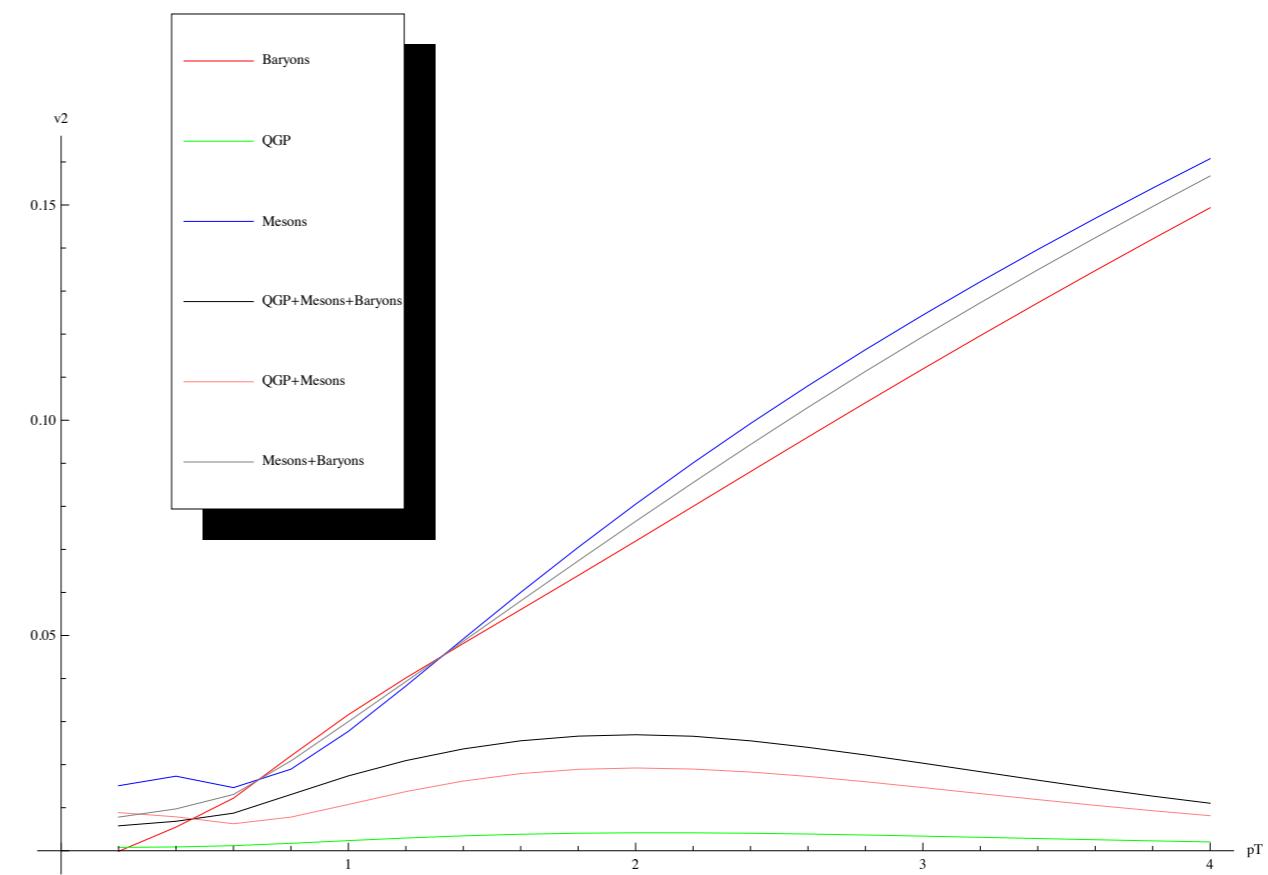
Charles Gale



EFFECTS OF BARYONS ON PHOTON v_2 ?



Turbide, Rapp, Gale, PRC (2004)



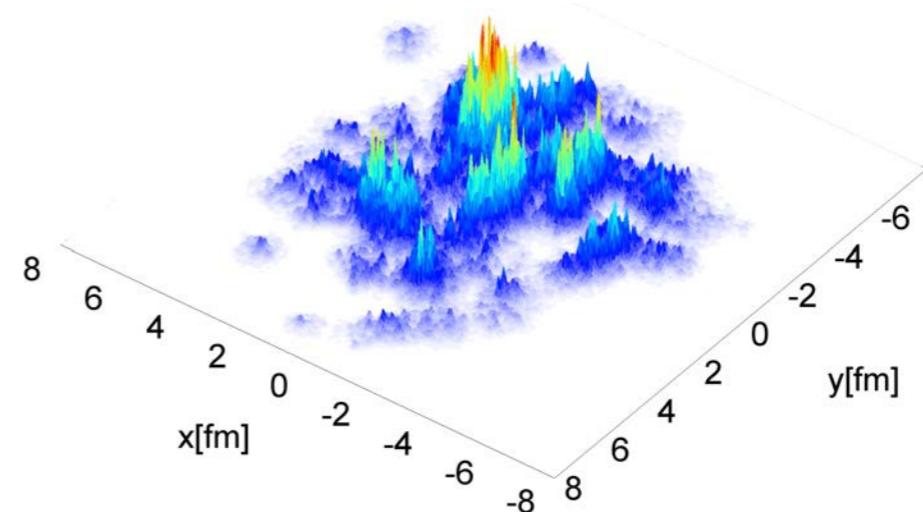
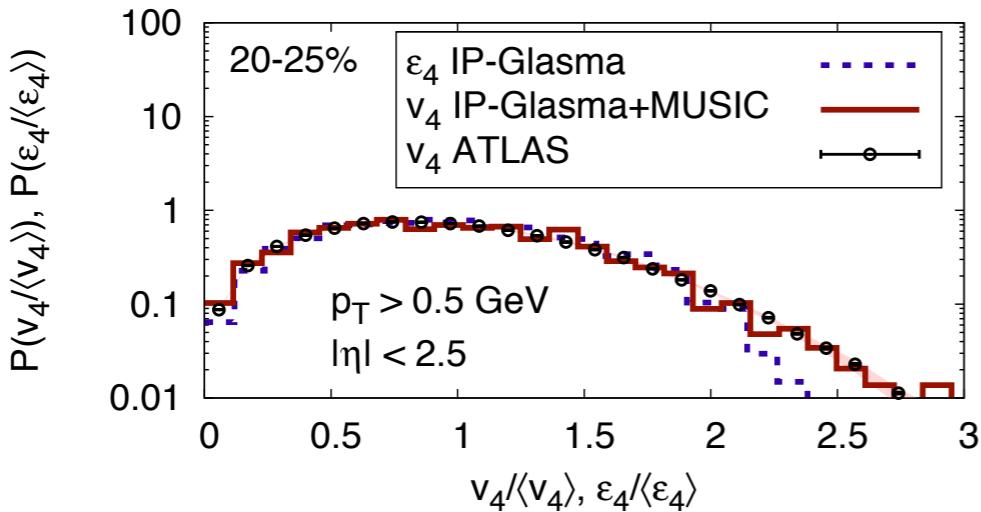
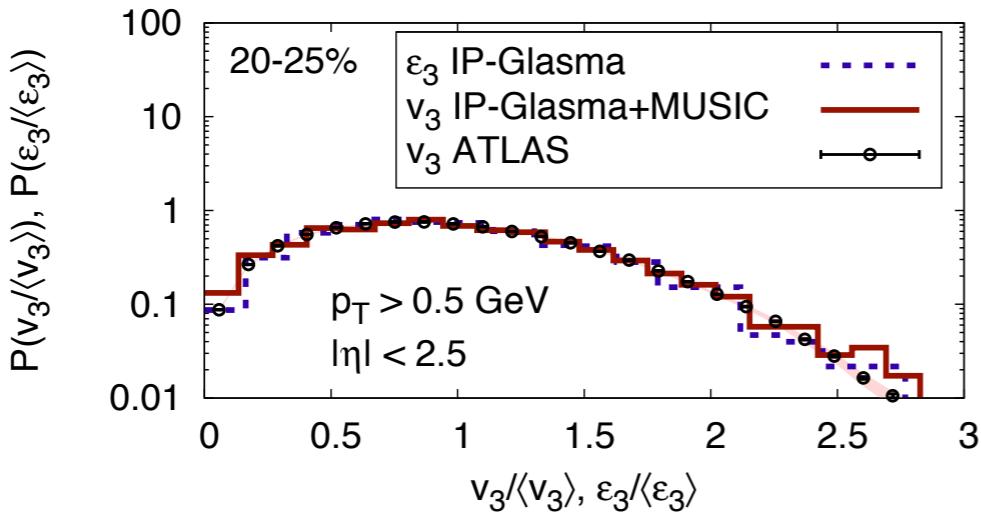
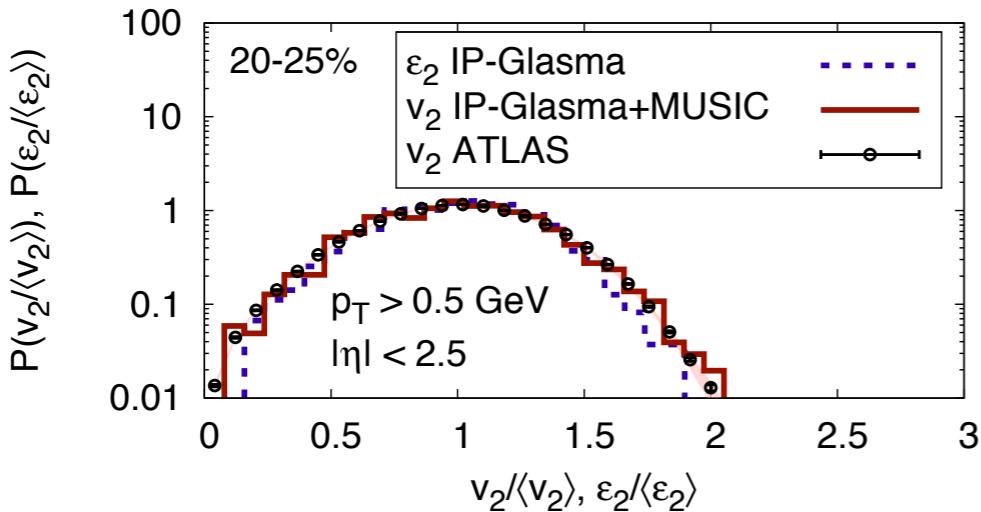
J.-F. Paquet et al., (2013)

- Adds to meson elliptic flow (~ 2)
- Promising. Still needs a proper, consistent calculation

BEYOND GLAUBER: IP-GLASMA + MUSIC

EFFECT ON HADRONIC OBSERVABLES

- Flow harmonics reproduced up to v_5 at RHIC and LHC
- Distributions of v_n at LHC:



- IP-Glasma + MUSIC provides consistent flow systematics at RHIC & LHC
- Contains an initial flow: Investigating the effects on EM variables

Gale, Jeon, Schenke, Tribedy, Venugopalan
PRL (2013)



Is the hydrodynamic modelling complete?

- In the last ~5-8 years, relativistic hydrodynamics has undergone a revolution
 - 3D
 - 3D - Shear viscosity
 - 3D - Shear viscosity - Fluctuating initial conditions
 - 3D - Shear viscosity - Fluctuating initial conditions also in y
- What's left?

$$T^{\mu\nu} = -Pg^{\mu\nu} + \omega u^\mu u^\nu + \Delta T^{\mu\nu}$$

The dissipative terms:

$$\Delta T^{\mu\nu} = \eta (\Delta^\mu u^\nu + \Delta^\nu u^\mu) + \left(\frac{2}{3} \eta - \zeta \right) H^{\mu\nu} \partial_\rho u^\rho - \chi (H^{\mu\alpha} u^\nu + H^{\nu\alpha} u^\mu) Q_\alpha$$

No simulation incorporates all of these



BULK VISCOSITY?

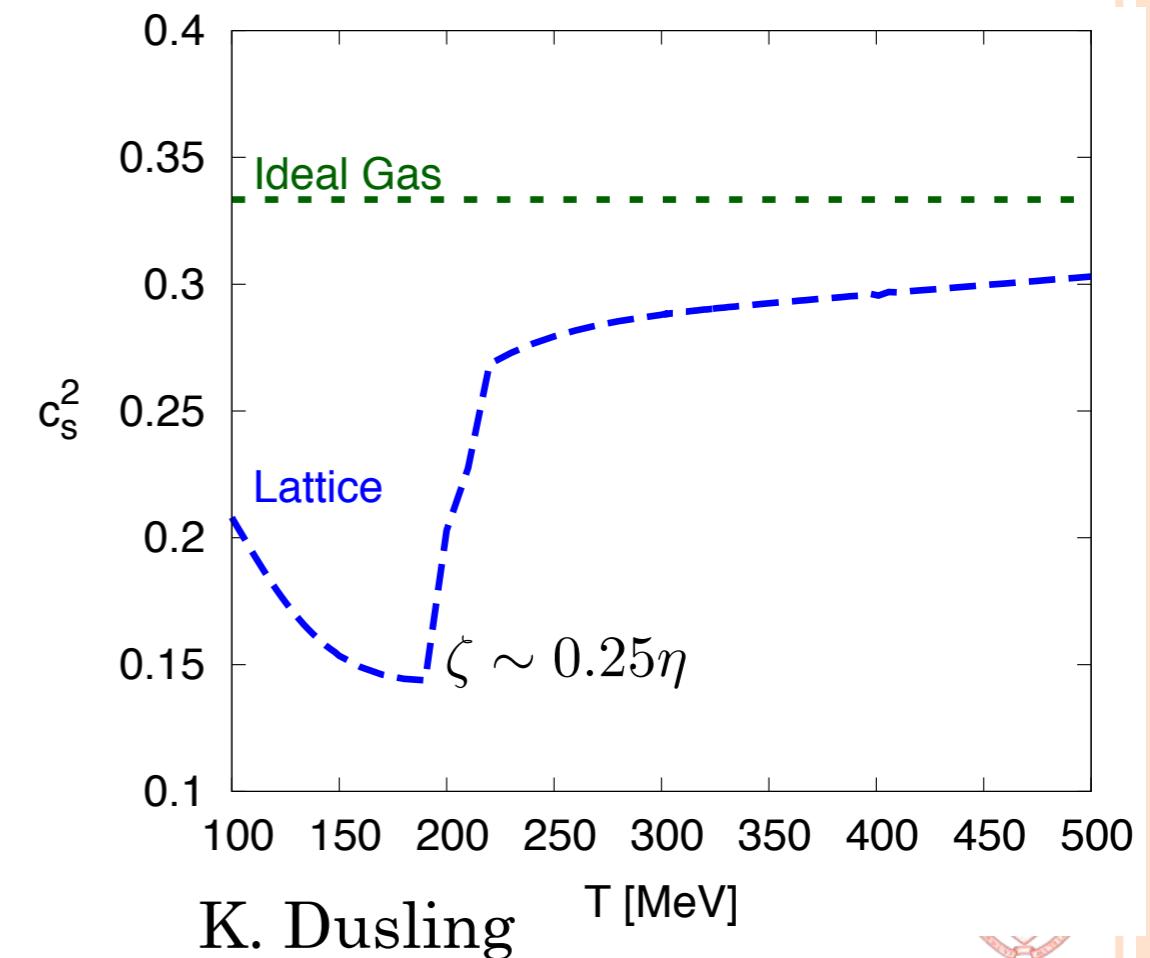
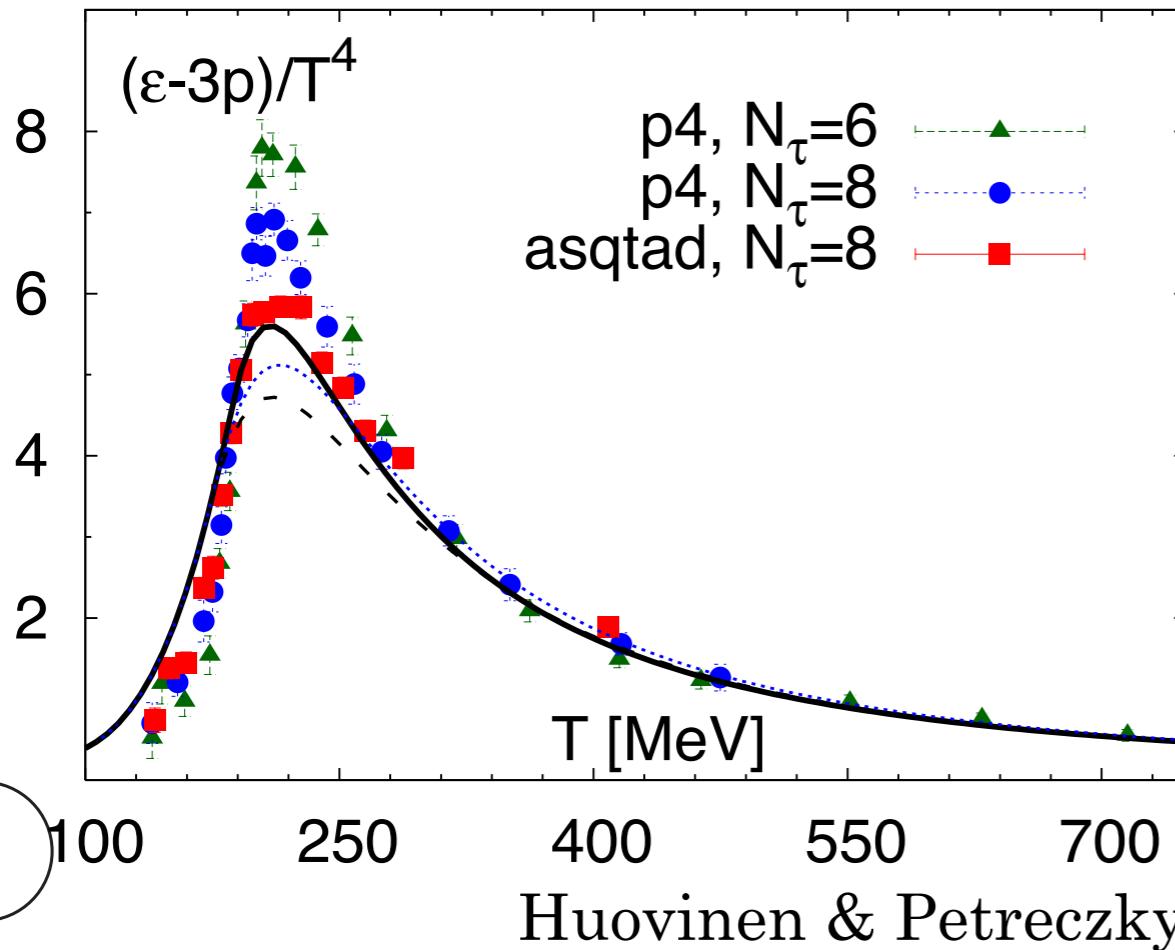
$$\zeta \approx 15\eta \left(\frac{1}{3} - c_s^2 \right)^2$$

S. Weinberg, Ap. J (1971)

$$\zeta \gtrsim 2\eta \left(\frac{1}{3} - c_s^2 \right)$$

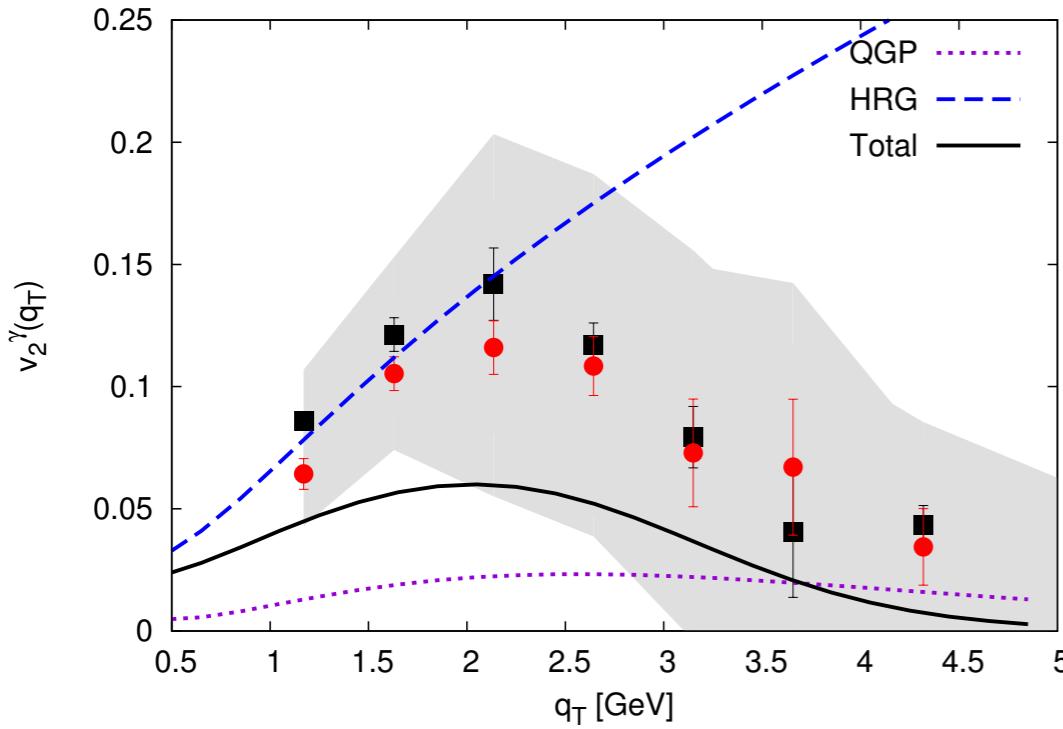
A. Buchel, Phys. Lett. (2008)

Bulk viscosity vanishes in conformal fluids. QCD is only very approximately conformal:

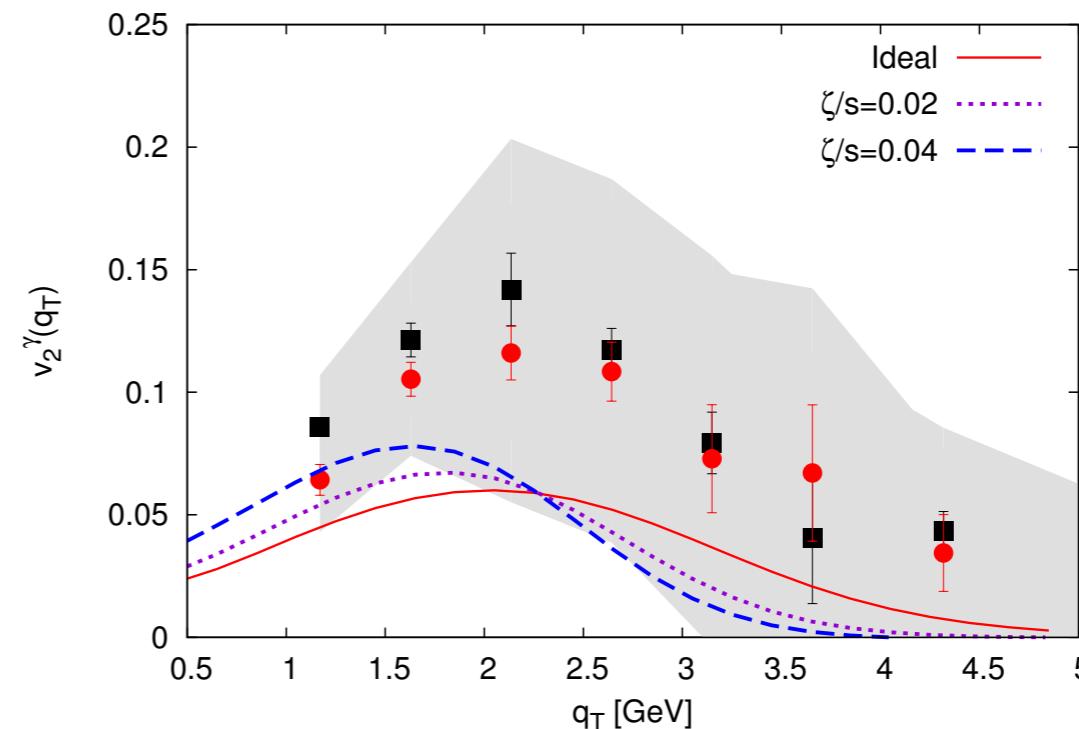


BULK VISCOSITY EFFECTS ON PHOTONS?

Ideal photon $v_2(q_T)$



Viscous photon $v_2(q_T)$



- Bulk viscosity enhances the elliptic flow
- Effects are however large enough: a consistent inclusion of bulk is warranted.

$$\bullet \frac{\zeta}{s}(T) \text{ etc..}$$

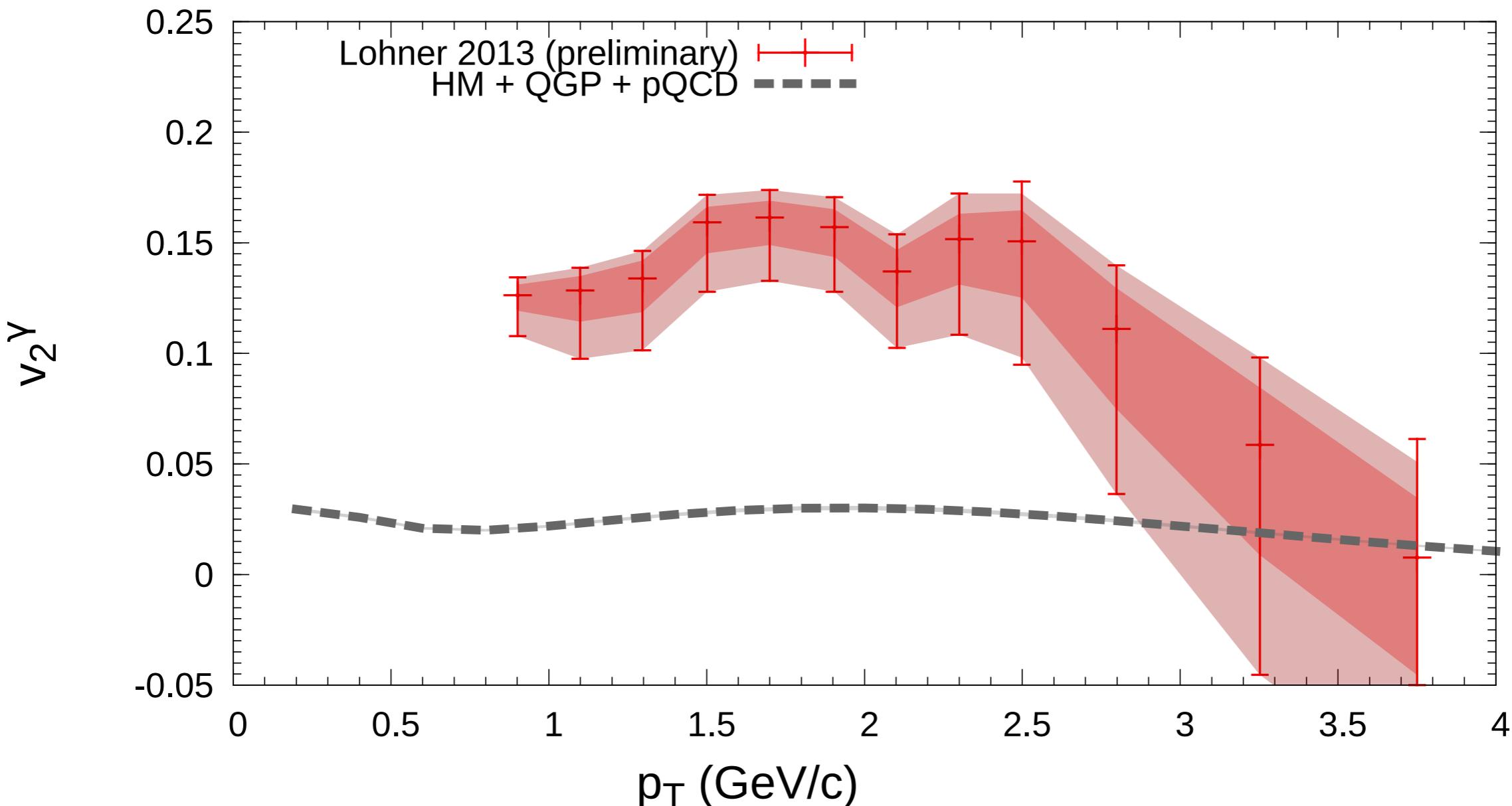
K. Dusling (2012)



SWITCHING OFF THE QGP?

LHC - 2.76 TeV
Pb + Pb 20-40%

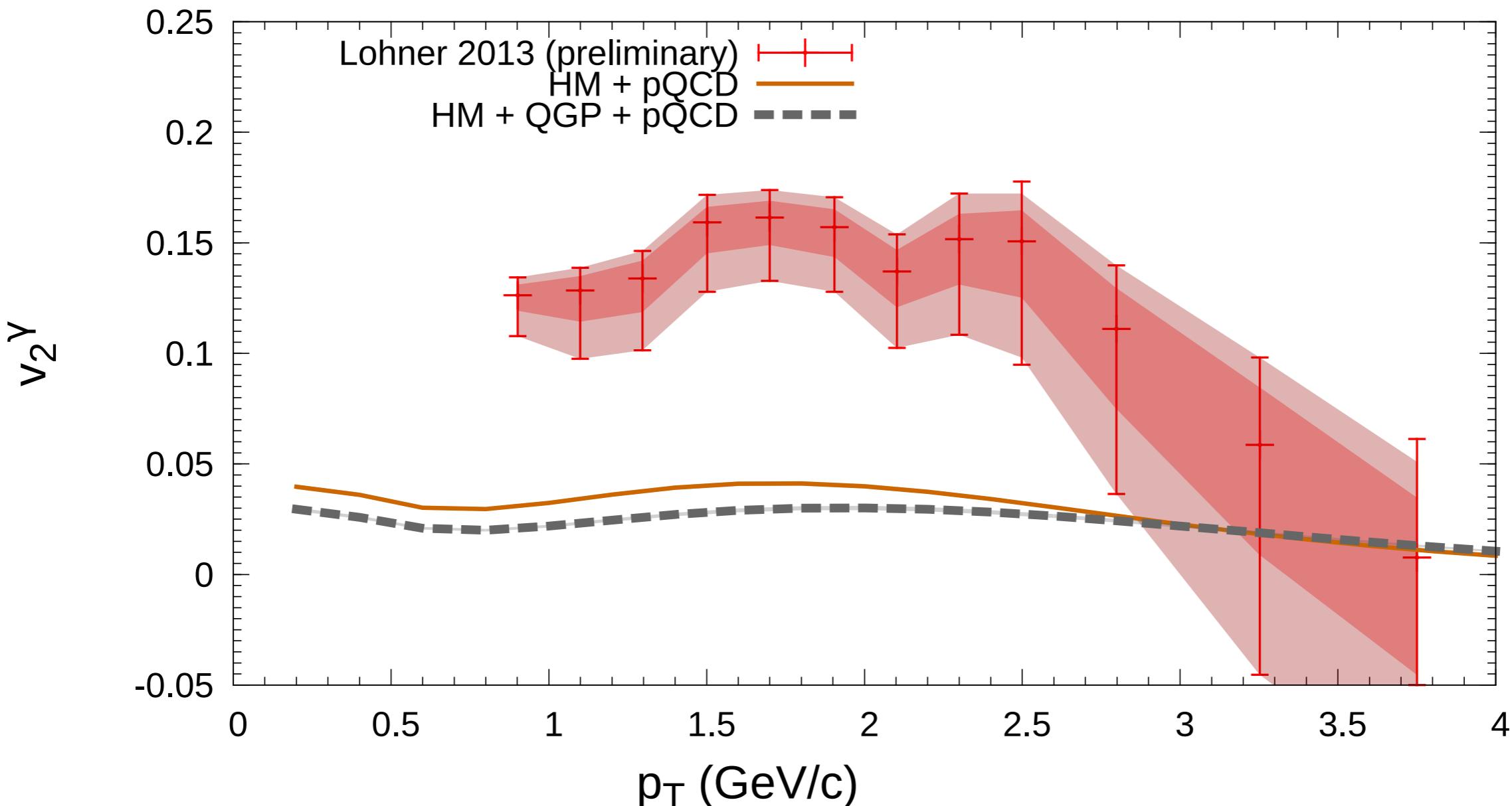
$\langle \cos(2(\phi^\gamma - \Psi_2^h)) \rangle$



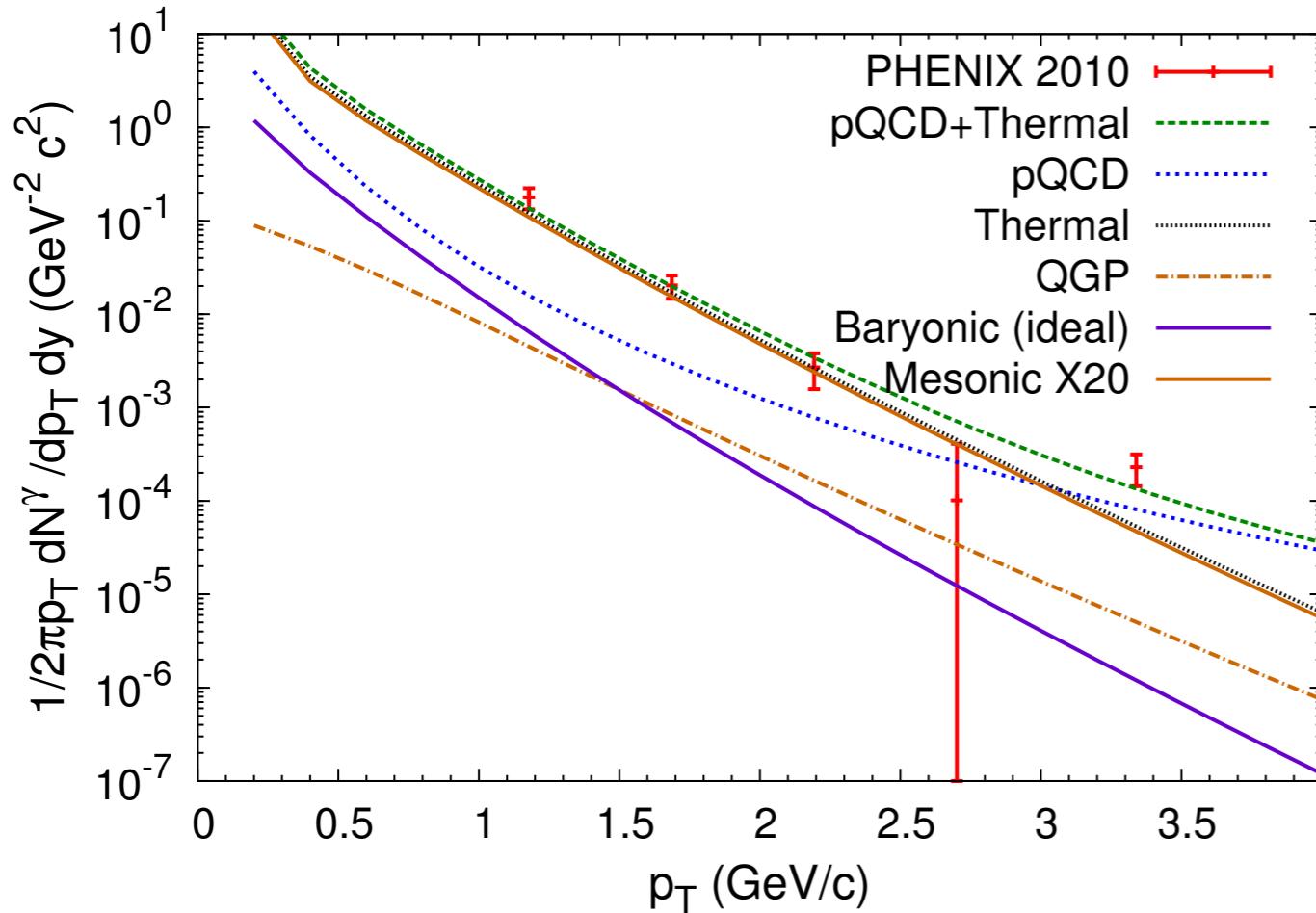
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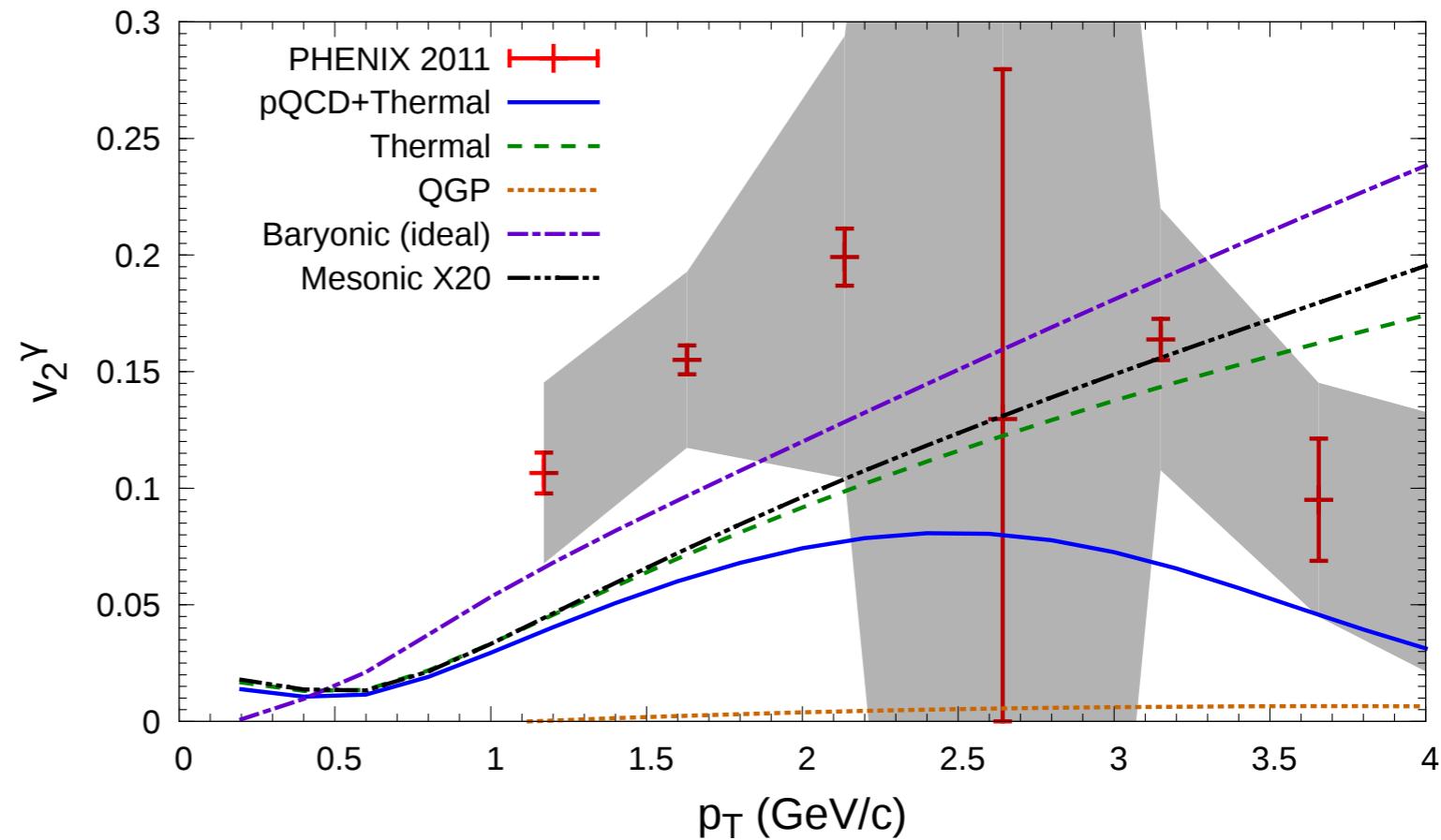
$$\langle \cos(2(\phi^Y - \Psi^h_2)) \rangle$$



MISSING CHANNELS?



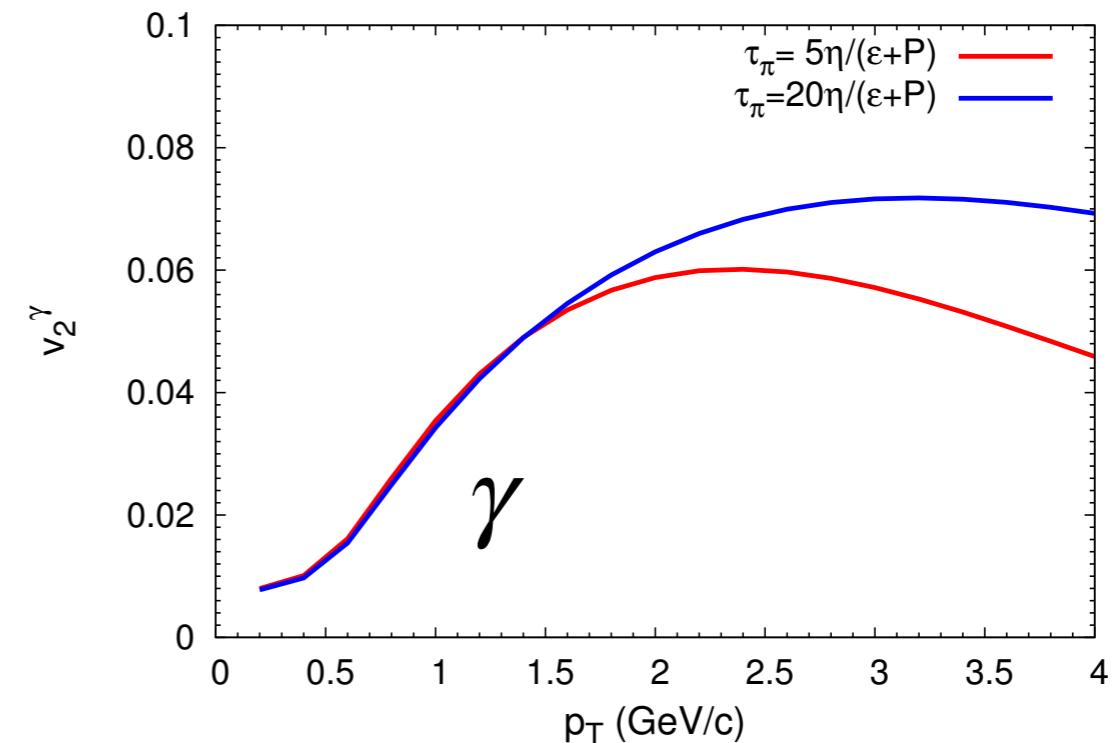
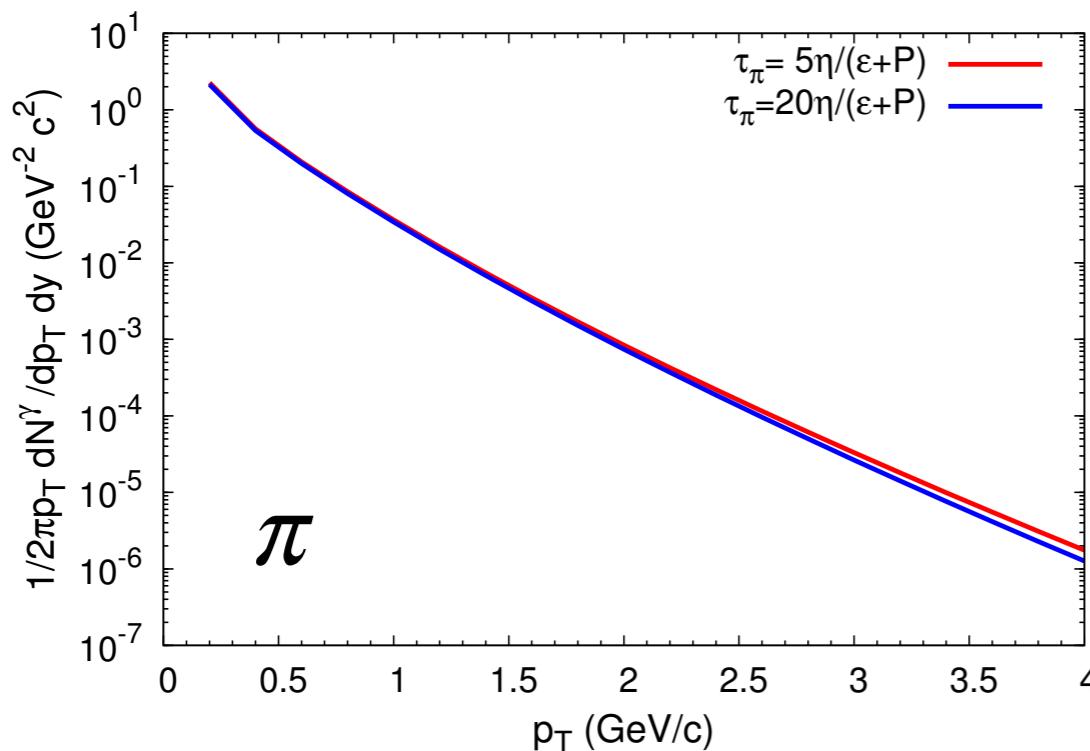
- The yield can be saturated by a “K factor” of approx. 20
- Estimate in line with that of group@Jyväskylä



MORE ON THE HYDRO MODELLING AND PHOTON PRODUCTION

$$\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} - \frac{4}{3}\tau_\pi\pi^{\mu\nu}\theta$$

- Can the relaxation time be changed? Does this affect anything?



Paquet, Vujanovic, Denicol et al. (2013)

40

Photons are sensitive to early time dynamics

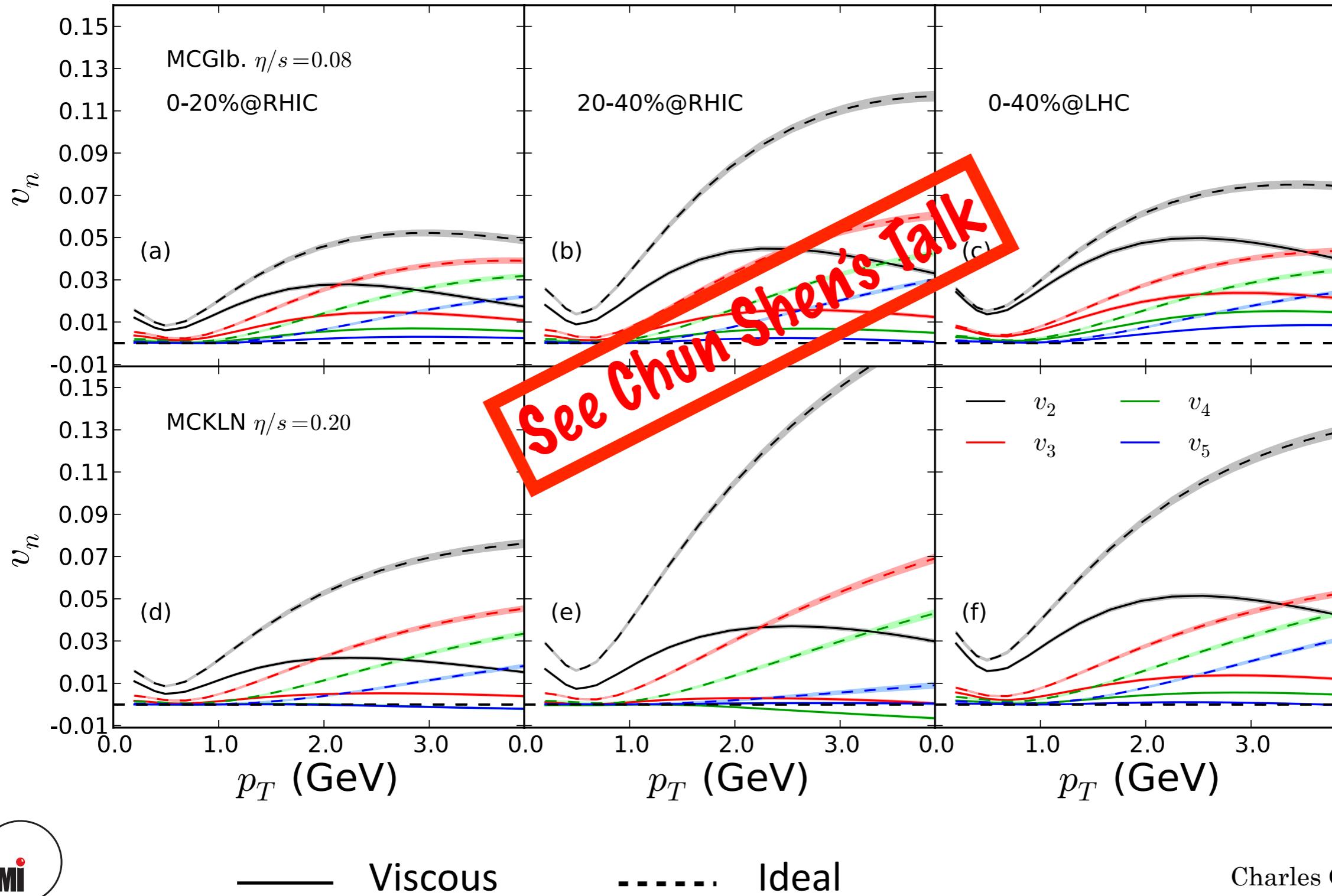
Charles Gale



THERMAL PHOTONS AS A VISCOMETER & THERMOMETER

$$\omega \frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}}{2(\epsilon + P)} \Gamma_{\mu\nu}(p, T)$$

Shen, Heinz, Paquet, Kozlov, Gale, arXiv 1308.2111



CONCLUSIONS

- The status of EM rates and their integration in dynamical models is still in flux
- Photon v_2 is sensitive to the EOS, and to various hydro parameters such as viscosity, and initial conditions (time and FICs). One must be consistent with hadronic data
- Photons are sensitive to non-equilibrium effects (in addition to shear viscosity)
- Current v_2 data: new physics? Measuring photon v_3 , v_n at RHIC and LHC will help complete this picture
- Jet-plasma photons need to be included: MARTINI
- Known unknowns: pre-equilibrium radiation
- . . .



Thanks to

- * G. Denicol
- * U. Heinz (OSU)
- * S. Jeon
- * I. Kozlov
- * M. Luzum
- * J.-F. Paquet
- * R. Rapp (Texas A&M)
- * B. Schenke
- * C. Shen (OSU)
- * H. van Hees (Frankfurt)
- * G. Vujanovic