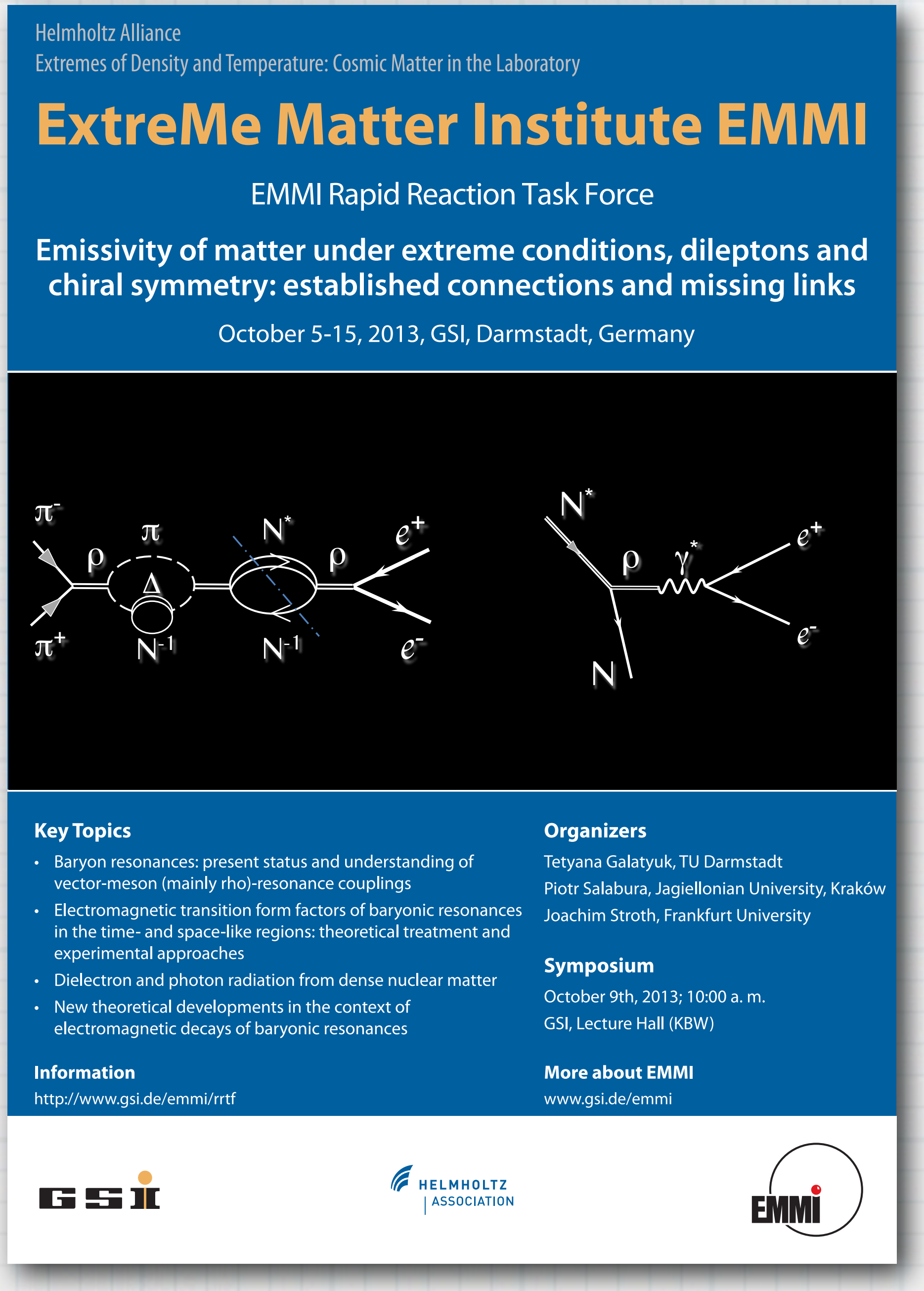
Electromagnetic Radiation from Heavy-Ion Collisions: From Microscopic Aspects to Bulk Dynamics



Helmholtz Alliance
Extremes of Density and Temperature: Cosmic Matter in the Laboratory

ExtreMe Matter Institute EMMI

EMMI Rapid Reaction Task Force

Emissivity of matter under extreme conditions, dileptons and chiral symmetry: established connections and missing links

October 5-15, 2013, GSI, Darmstadt, Germany

Key Topics

- Baryon resonances: present status and understanding of vector-meson (mainly rho)-resonance couplings
- Electromagnetic transition form factors of baryonic resonances in the time- and space-like regions: theoretical treatment and experimental approaches
- Dielectron and photon radiation from dense nuclear matter
- New theoretical developments in the context of electromagnetic decays of baryonic resonances

Organizers

Tetyana Galatyuk, TU Darmstadt
Piotr Salabura, Jagiellonian University, Kraków
Joachim Stroth, Frankfurt University

Symposium

October 9th, 2013; 10:00 a. m.
GSI, Lecture Hall (KBW)

Information

http://www.gsi.de/emmi/rrtf

More about EMMI

www.gsi.de/emmi

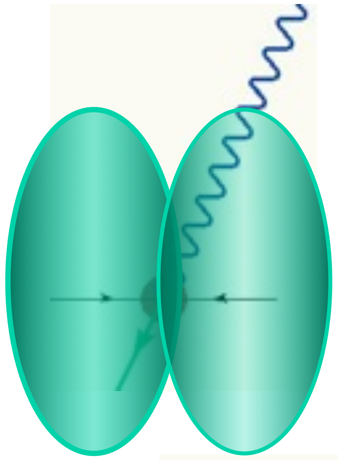
GSI HELMHOLTZ ASSOCIATION EMMI

Charles Gale
McGill University

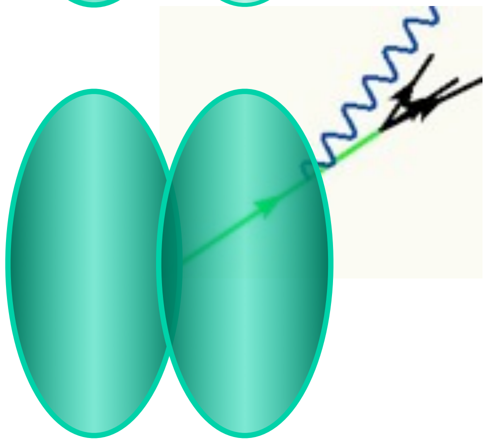
OUTLINE

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

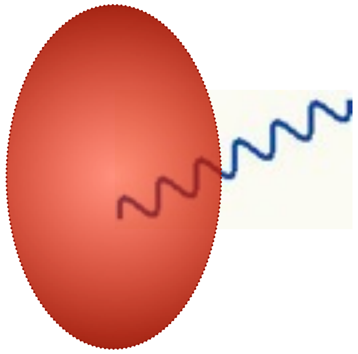
Sources of photons in a relativistic nuclear collision:



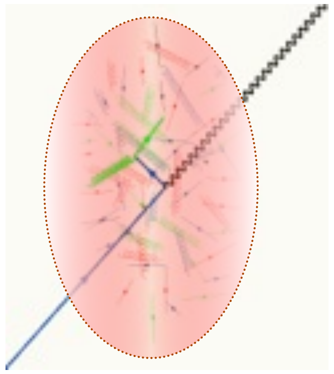
Hard direct photons. pQCD with shadowing
Non-thermal



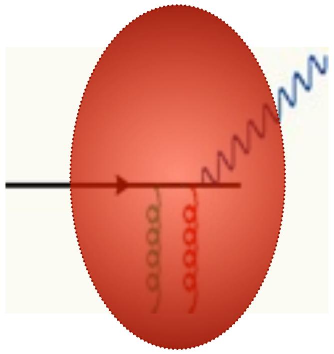
Fragmentation photons. pQCD with shadowing
Non-thermal



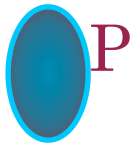
Thermal photons
Thermal



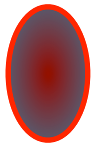
Jet-plasma photons
Thermal



Jet in-medium bremsstrahlung
Thermal



Pre-equilibrium?



INFO CARRIED BY THE 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

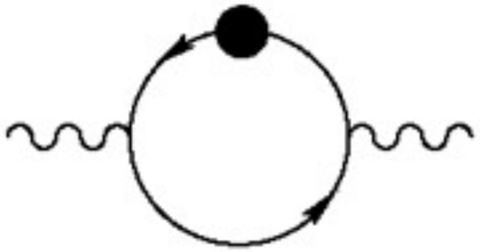
Emission rates:

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

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

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

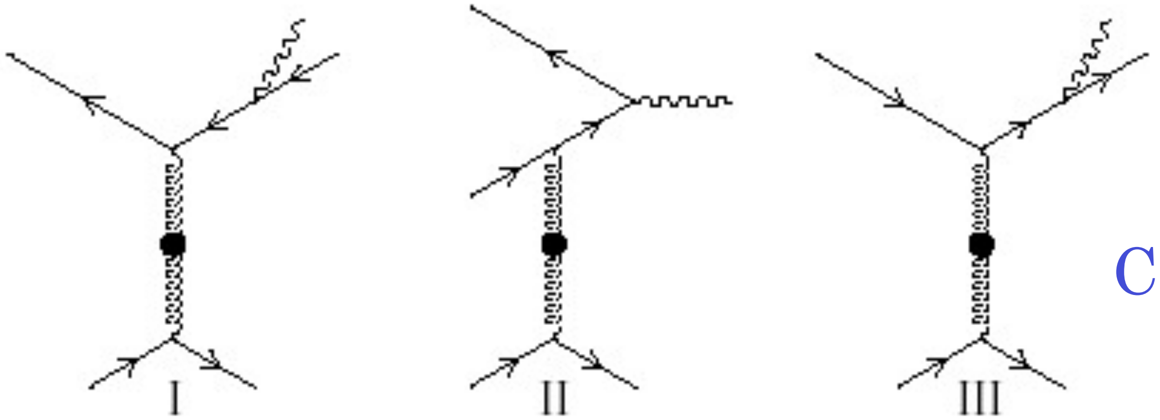
Thermal Photons from hot QCD: HTL program (Klimov (1981), Weldon (1982), Braaten & Pisarski (1990); Frenkel & Taylor (1990))



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

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

Going to two loops: Aurenche, Kobes, 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 $O(\alpha_s)$

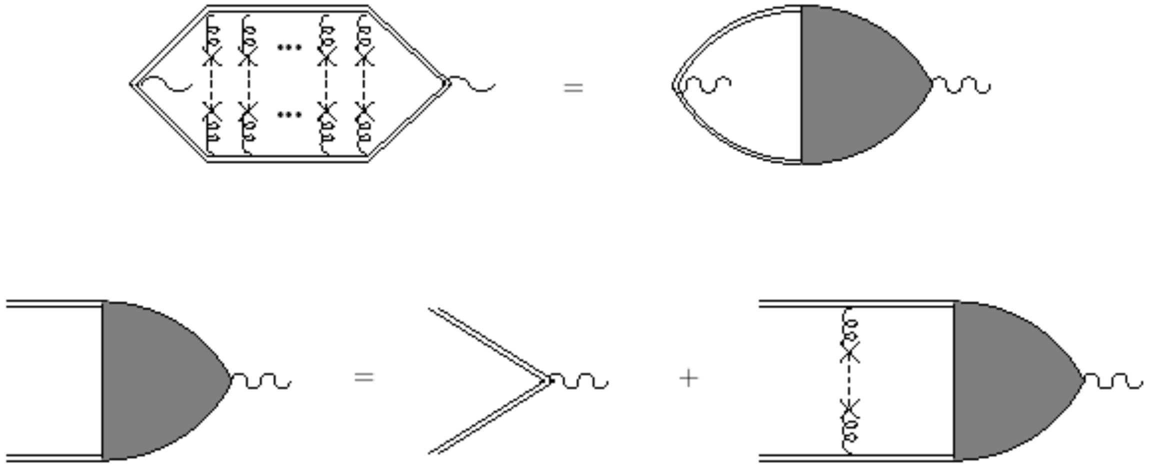
Arnold, Moore, and Yaffe JHEP **12**, 009 (2001); JHEP **11**, 057 (2001)
Incorporate LPM; Inclusive treatment of collinear enhancement, photon and gluon emission

Going beyond LO AMY rates?

- Approach is LO, but

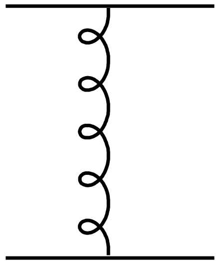
$$\alpha_s \sim 0.2 - 0.3$$

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



which contains a scattering kernel:

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



Aurenche, Gélis, Zaraket (2002)

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

$$gT \ll T$$

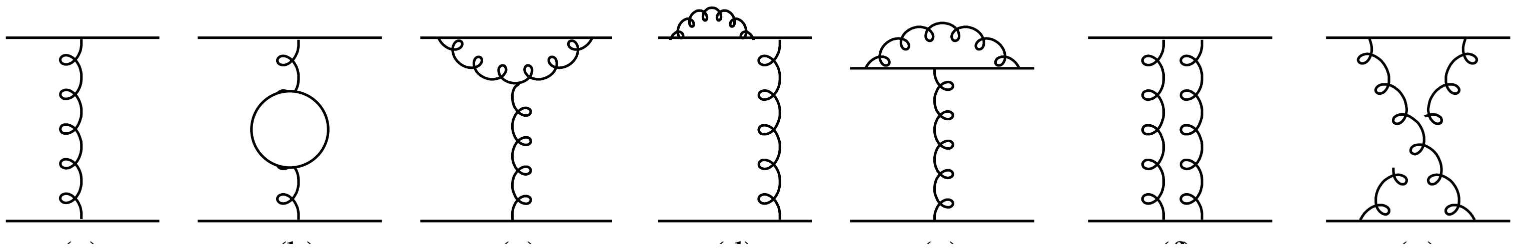
$$\text{soft} \ll \text{hard}$$

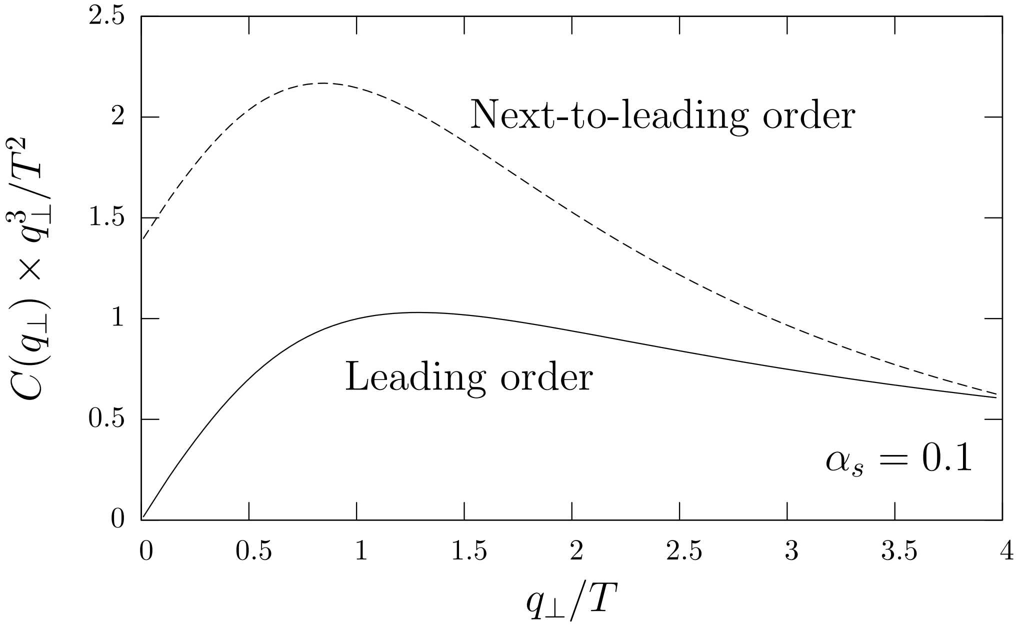
The LO-NLO scattering kernel(s)

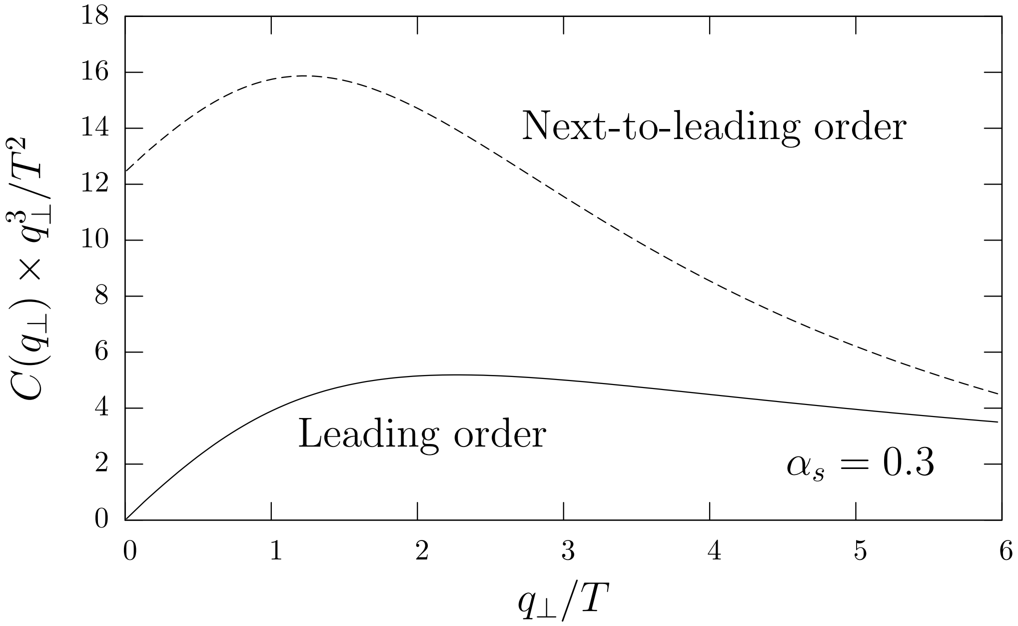
Clue that NLO effects might be important: Heavy quark diffusion

$$C(q_\perp)\big|_{\mathrm{LO}} \to C(q_\perp)\big|_{\mathrm{NLO}}$$

Simon Caron-Huot PRD (2009)





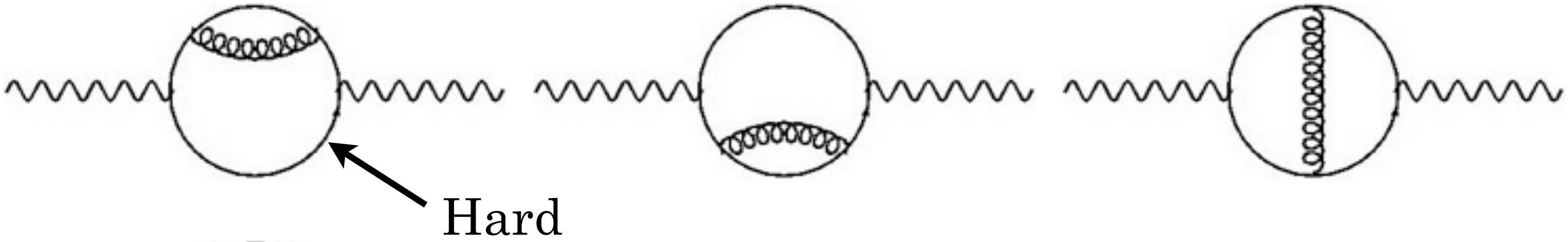


Possible large effects on photon production!?

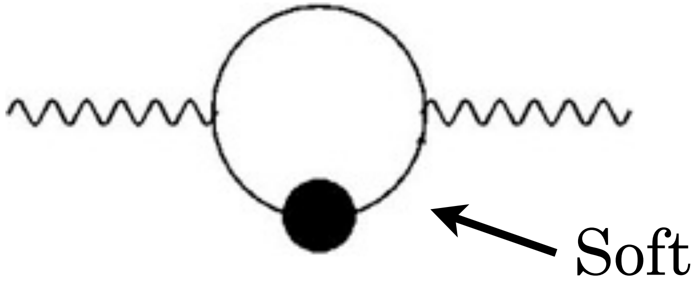
Photon emission at LO

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

$$\left.\frac{d\Gamma_\gamma}{d^3k}\right|_{\mathrm{hard}} \rightarrow$$

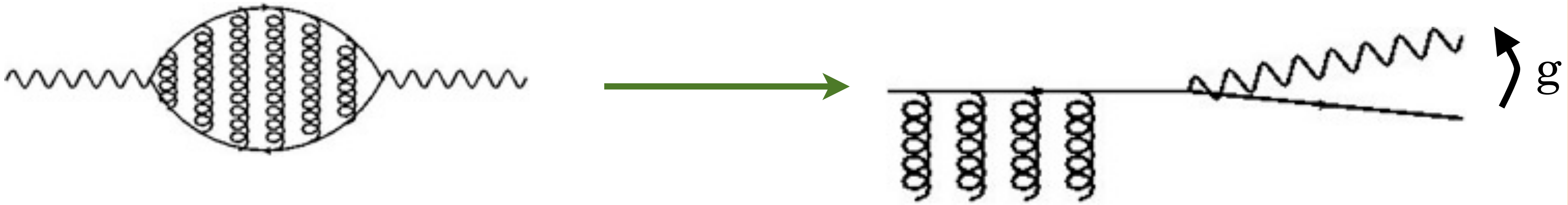

Hard

$$\left.\frac{d\Gamma_\gamma}{d^3k}\right|_{\mathrm{soft}} \rightarrow$$


Soft

(Conversion)

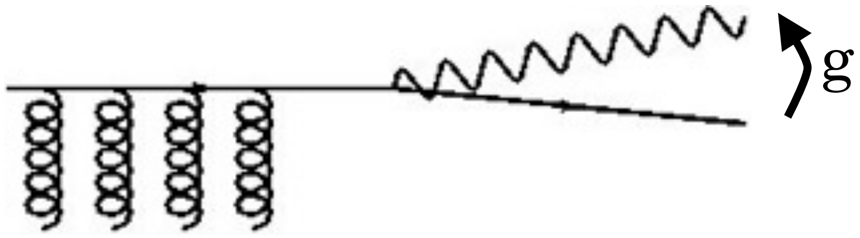
$$\left.\frac{d\Gamma_\gamma}{d^3k}\right|_{\mathrm{coll}} \rightarrow$$



The LO-NLO scattering kernels

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

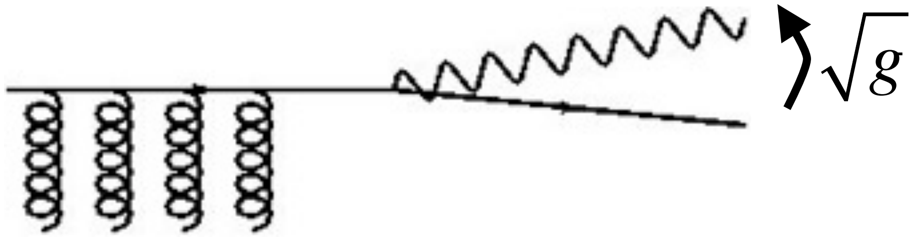
The two main contributions:



$$C(q_T)_{\mathrm{LO}} = \frac{Tg^2 m_D}{q_T(q_T + m_D)} \Rightarrow \mathrm{NLO}$$

Simon Caron-Huot PRD (2009)

Enhanced at NLO



Larger angle bremmstrahlung

Suppressed at NLO

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

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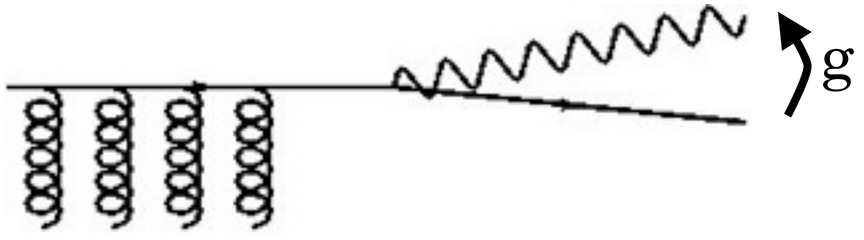

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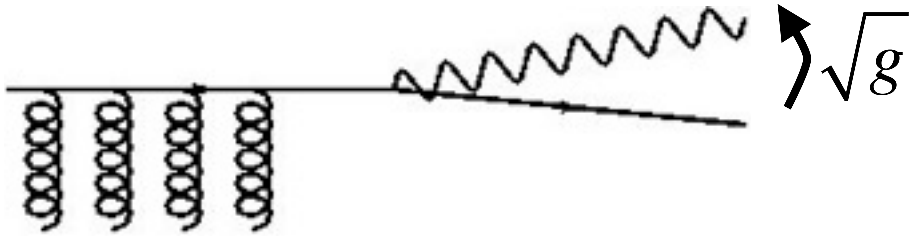

Larger angle bremmstrahlung

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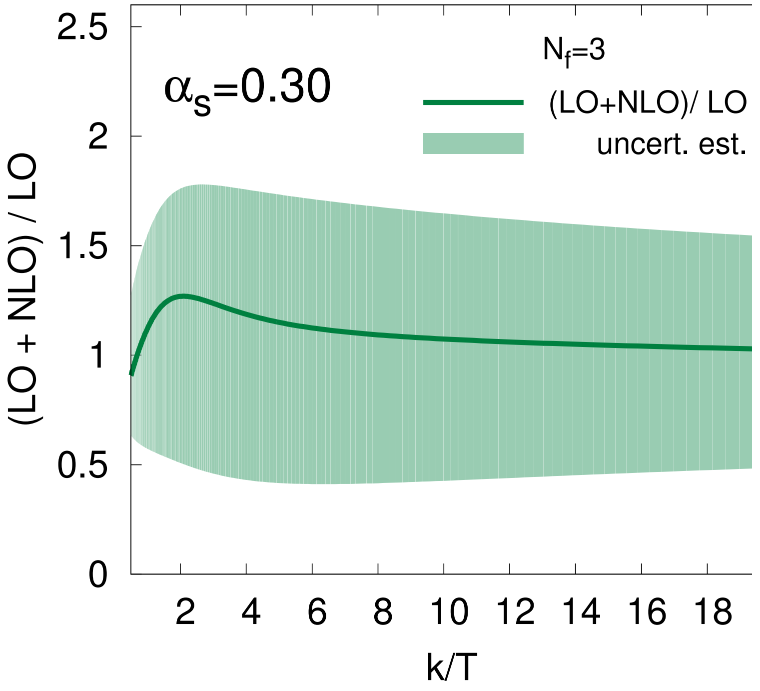
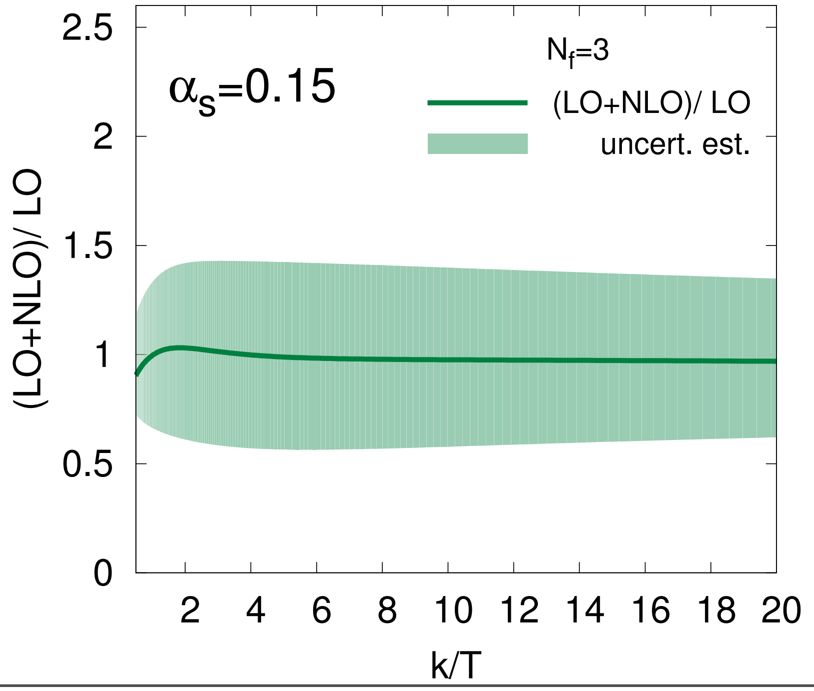




- Net correction to photon production rate is modest up to high k/T
- Techniques developed here have many more applications in FTFT

ELECTROMAGNETIC RADIATION FROM HADRONS

Chiral, Massive Yang-Mills:

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

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

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

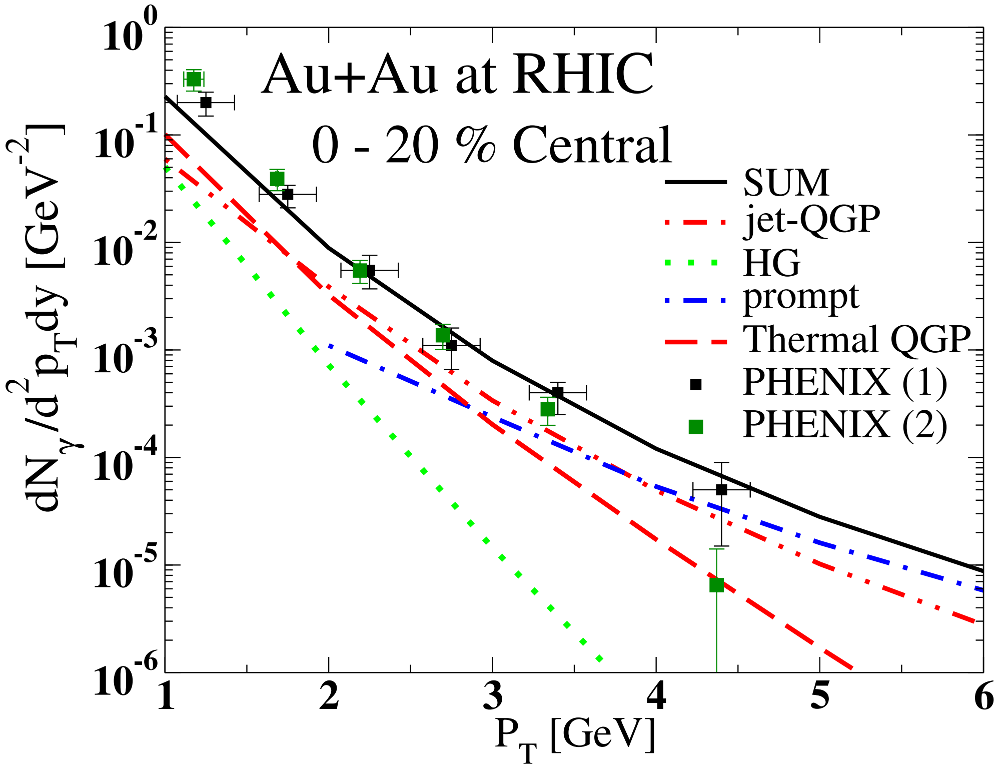
+ non-minimal terms

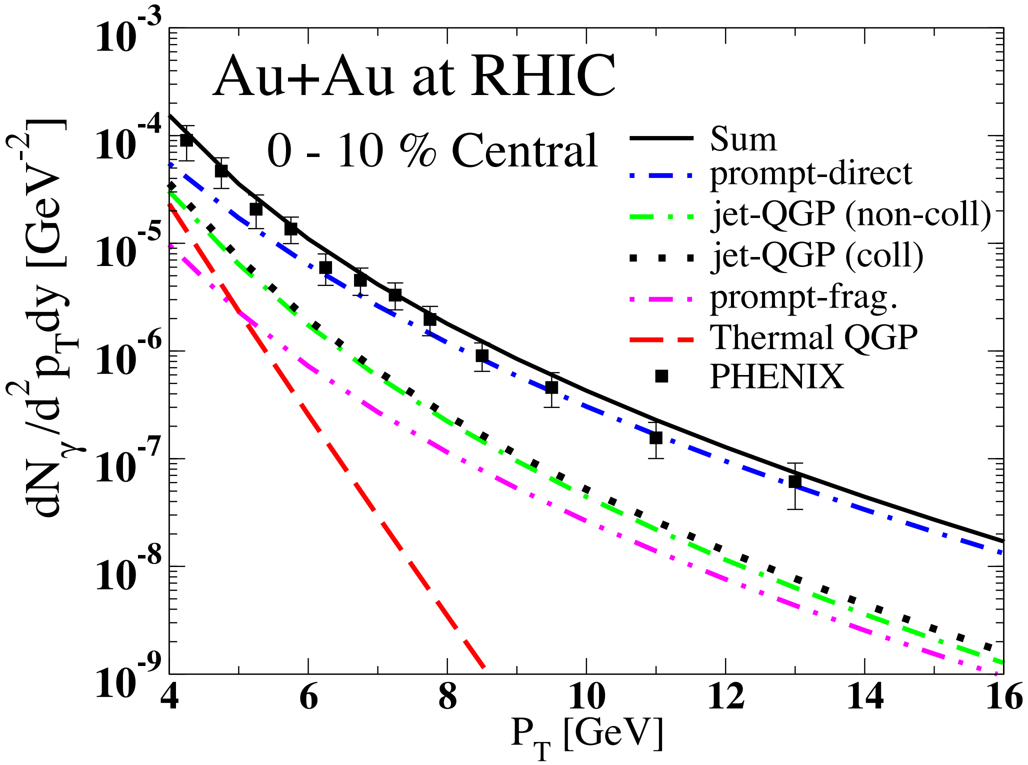
Parameters and form factors are constrained by hadronic phenomenology:

- Masses & strong decay widths
- Electromagnetic decay widths
- Other hadronic observables:
  - *e.g.* $a_1 \longrightarrow \pi\rho \quad D/S$ (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)

APPLYING THIS TO INTERPRET PHOTONS MEASURED @ RHIC: RATES ARE INTEGRATED USING RELATIVISTIC HYDRODYNAMIC MODELING

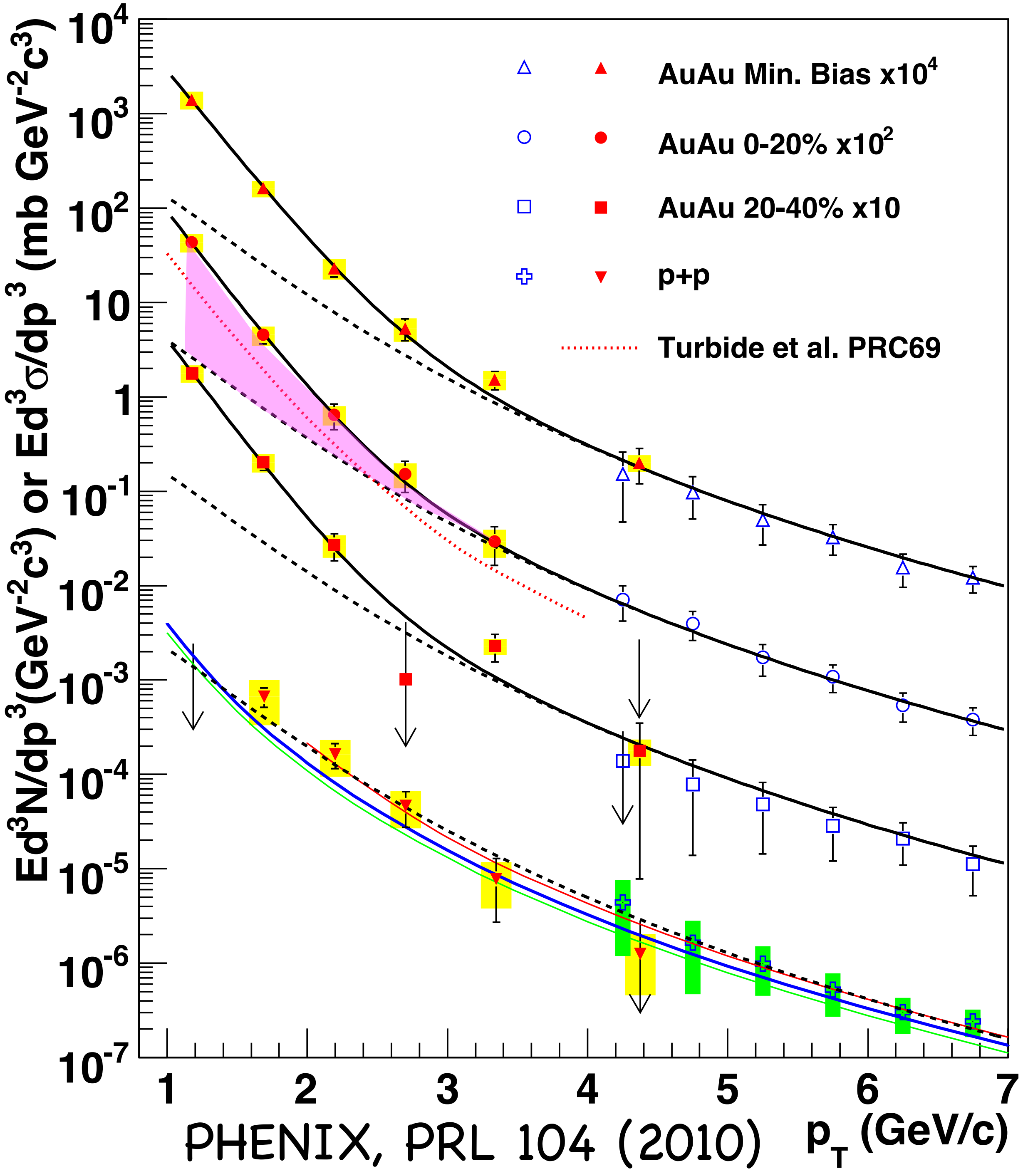




- At low p_T, spectrum dominated by thermal components (HG, QGP)
- At high p_T, spectrum dominated by pQCD
- Window for jet-QPG contributions at mid-p_T?

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

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



PHENIX, PRL 104 (2010)

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

Charles Gale

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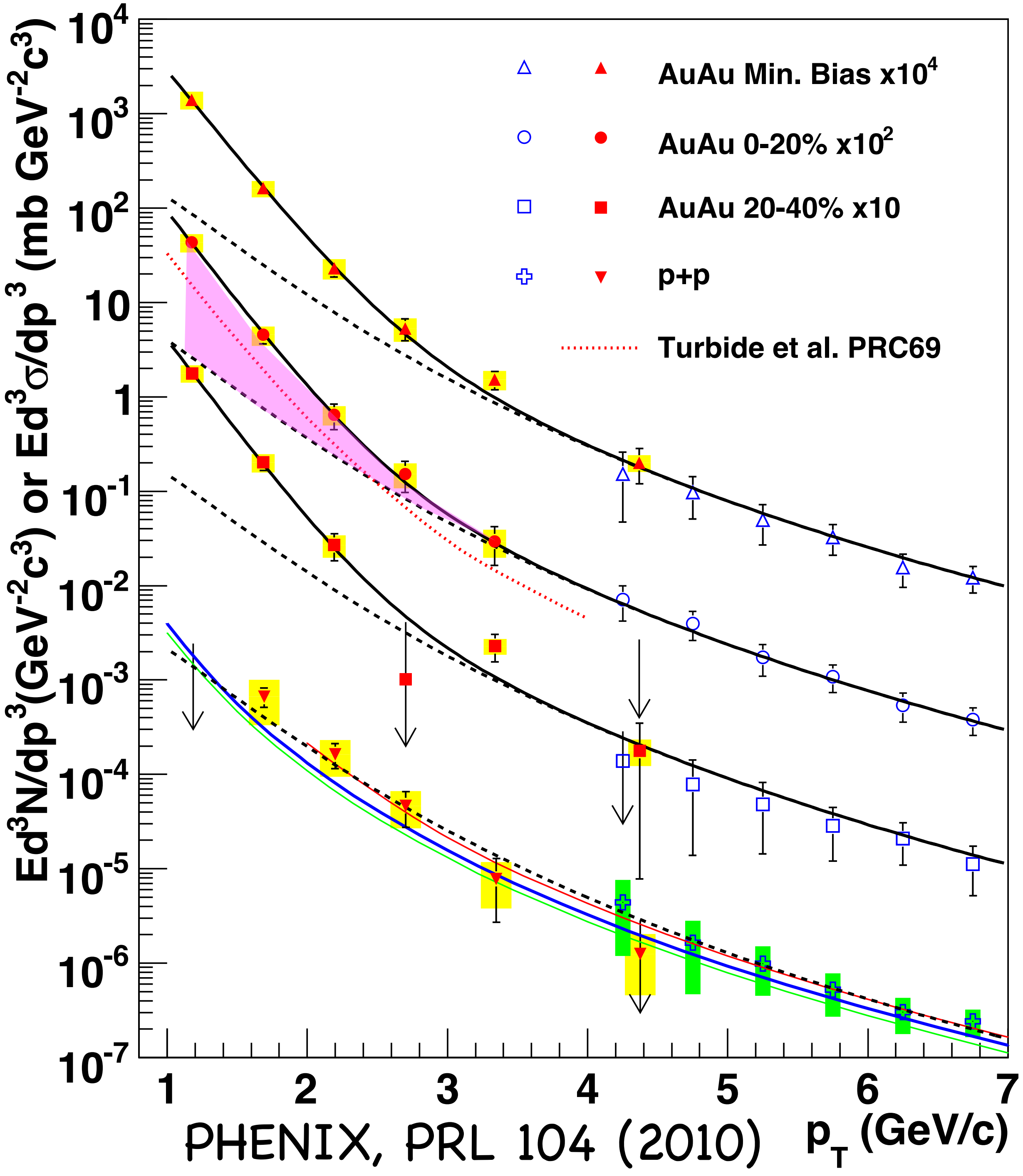


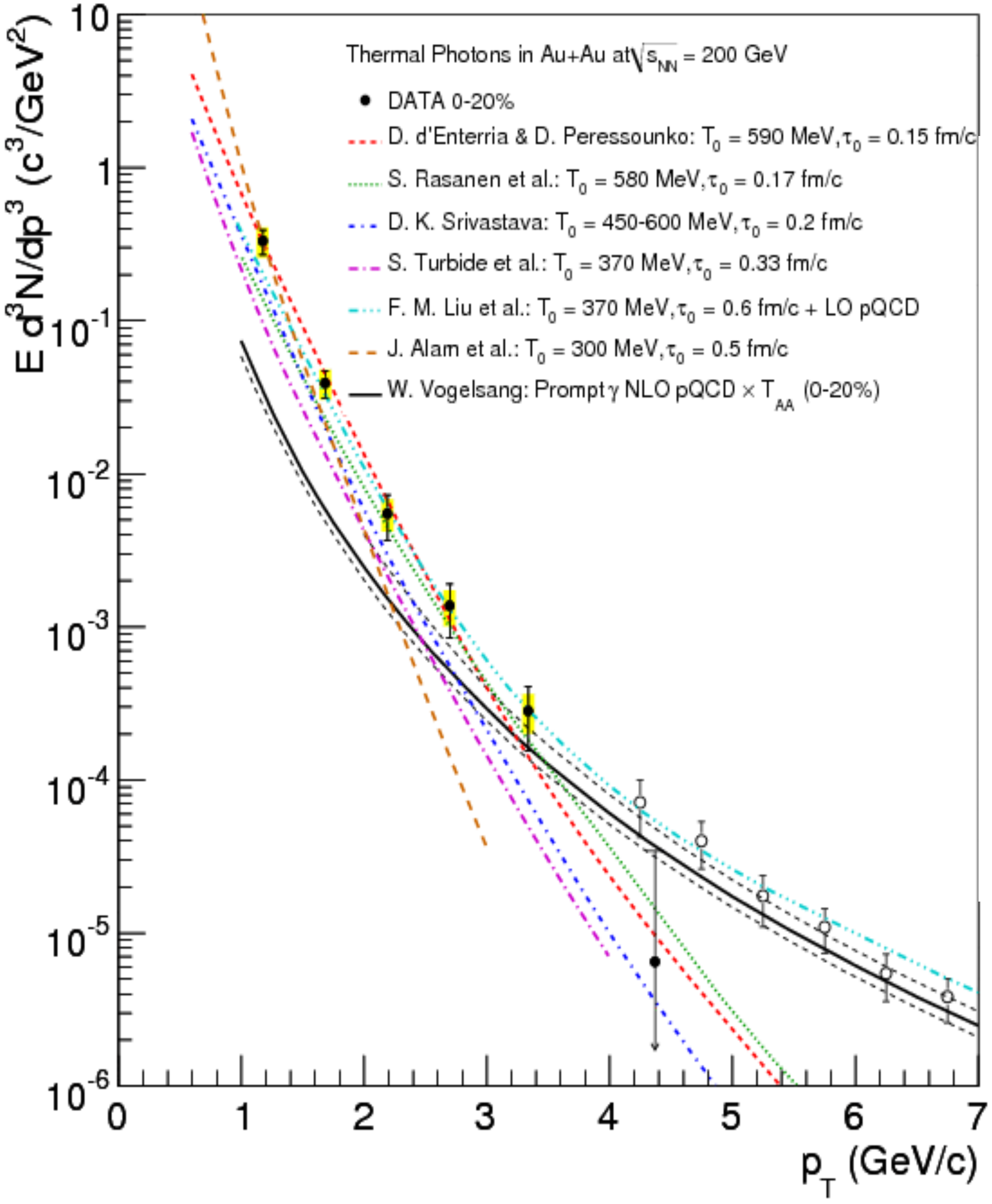
PHENIX, PRL 104 (2010)

$$T_{\mathrm{excess}} = 221 \pm 19 \pm 19\,\mathrm{MeV}$$

Flow effects will be important

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

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



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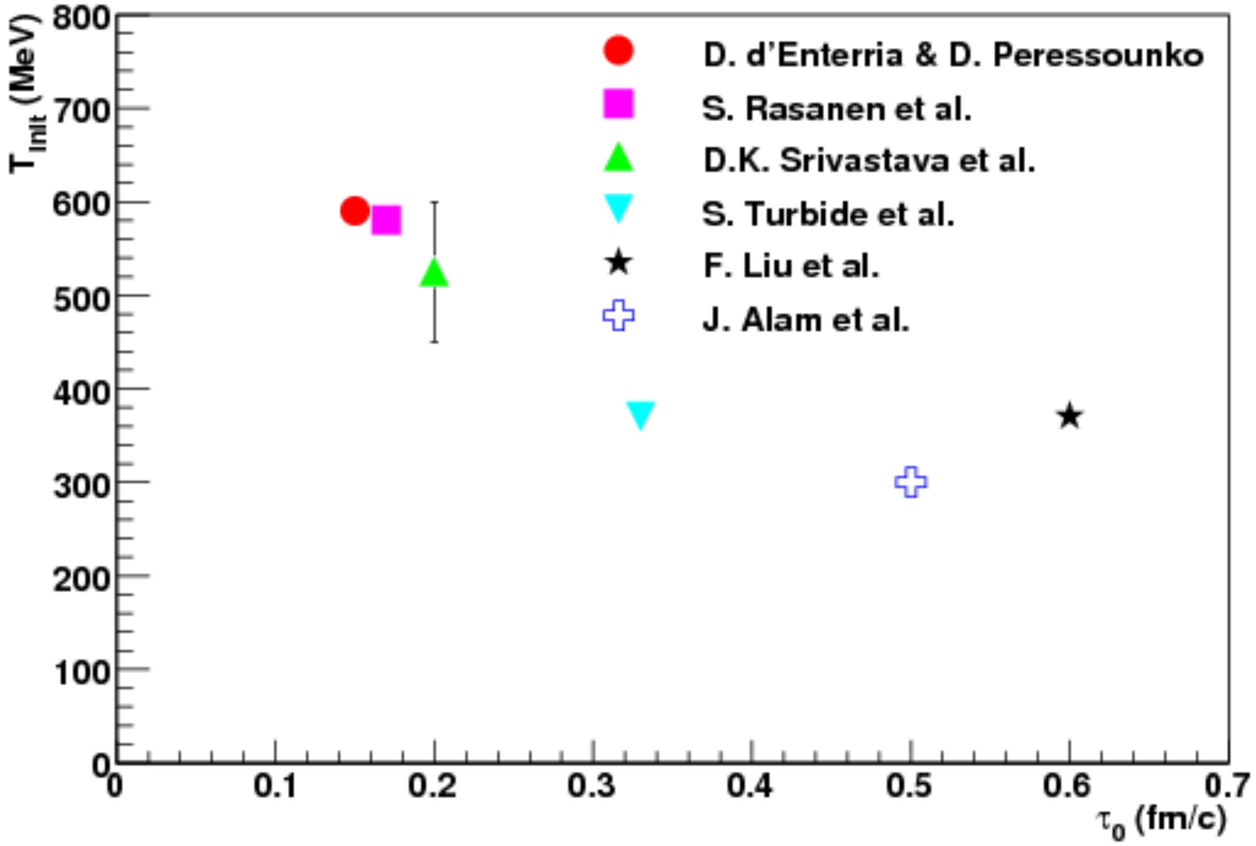
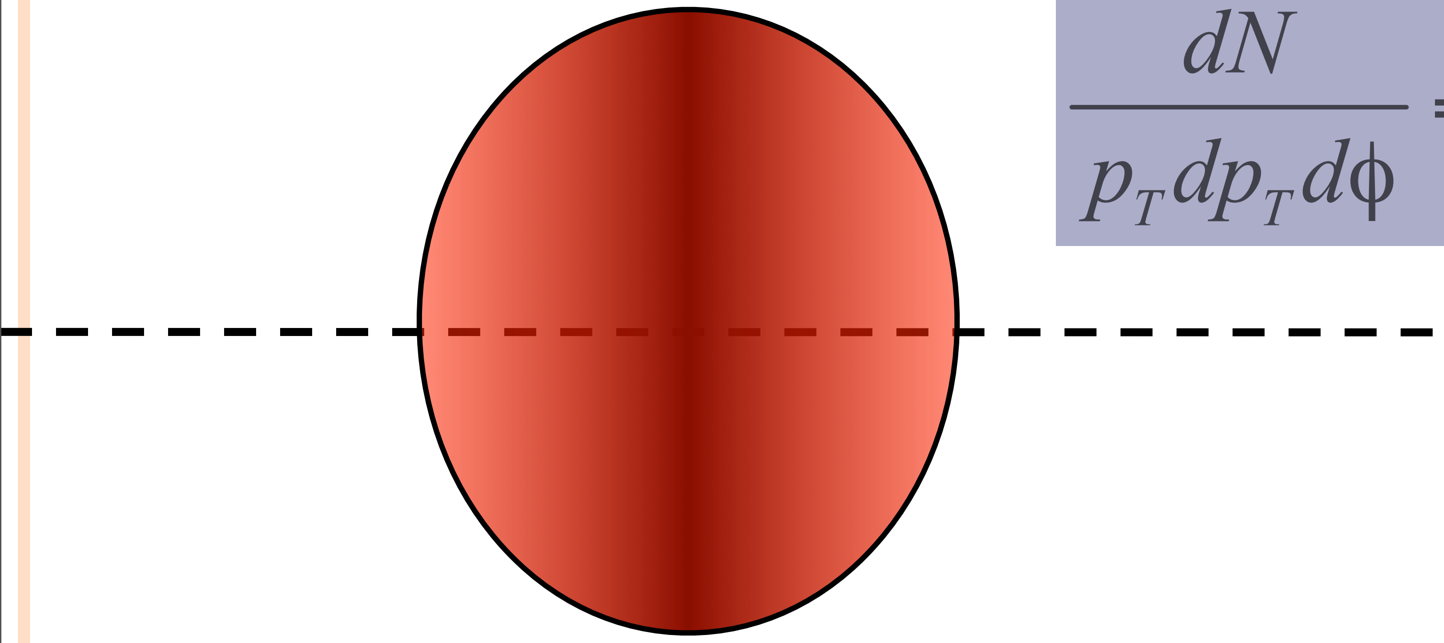


T_{ini} = 300 to 600 MeV
t_0 = 0.15 to 0.5 fm/c

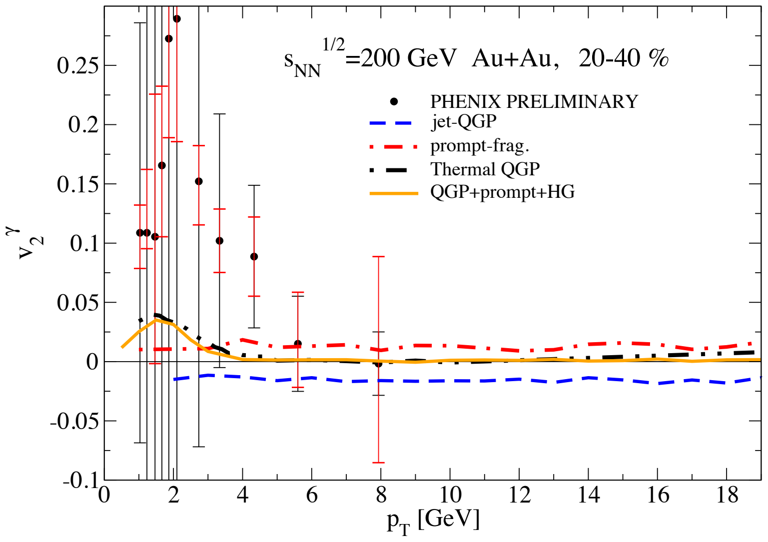
D’Enteria & Peressounko, Eur. Phys. J. (2006)

Knowing rates alone is not enough to guarantee predictive power or even characterization ability

BEYOND SIMPLE SPECTRA: FLOW AND CORRELATIONS



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

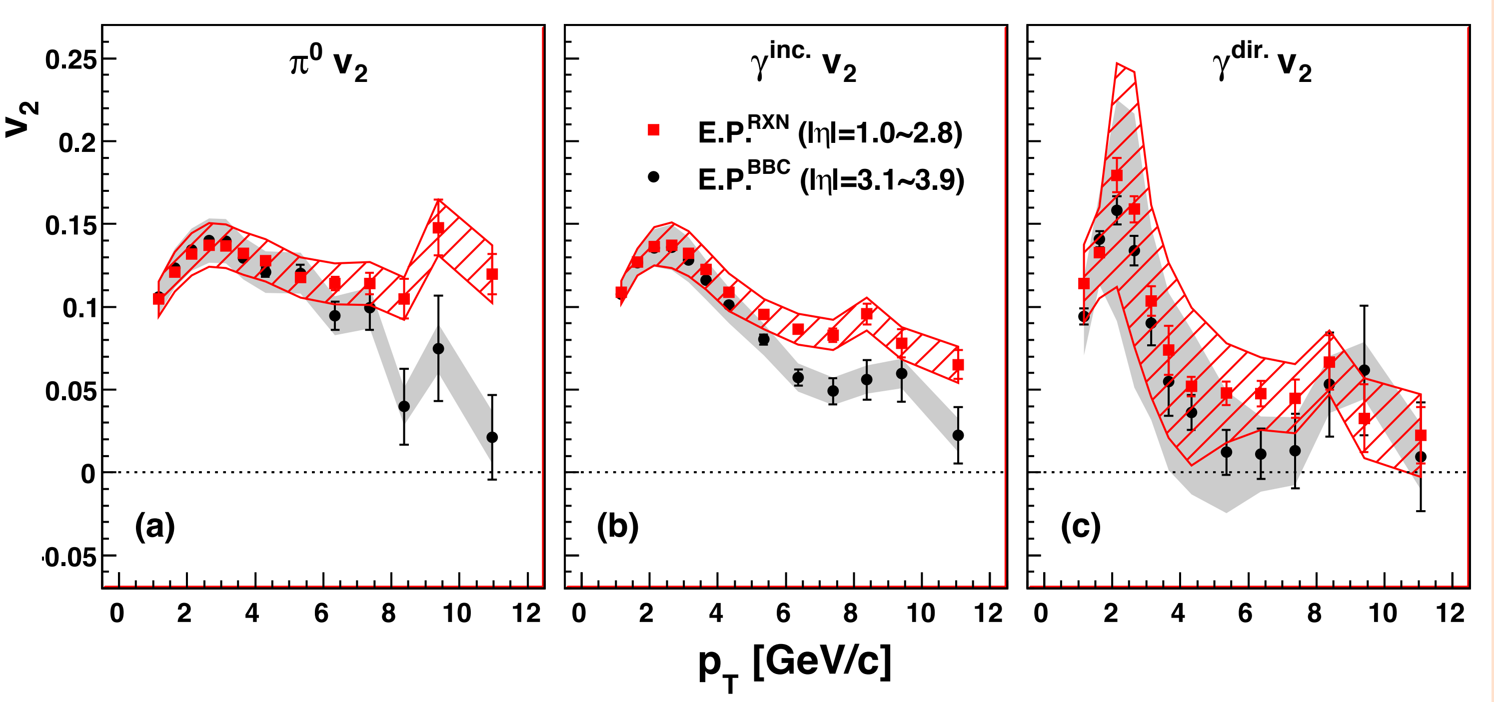


(2008)

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

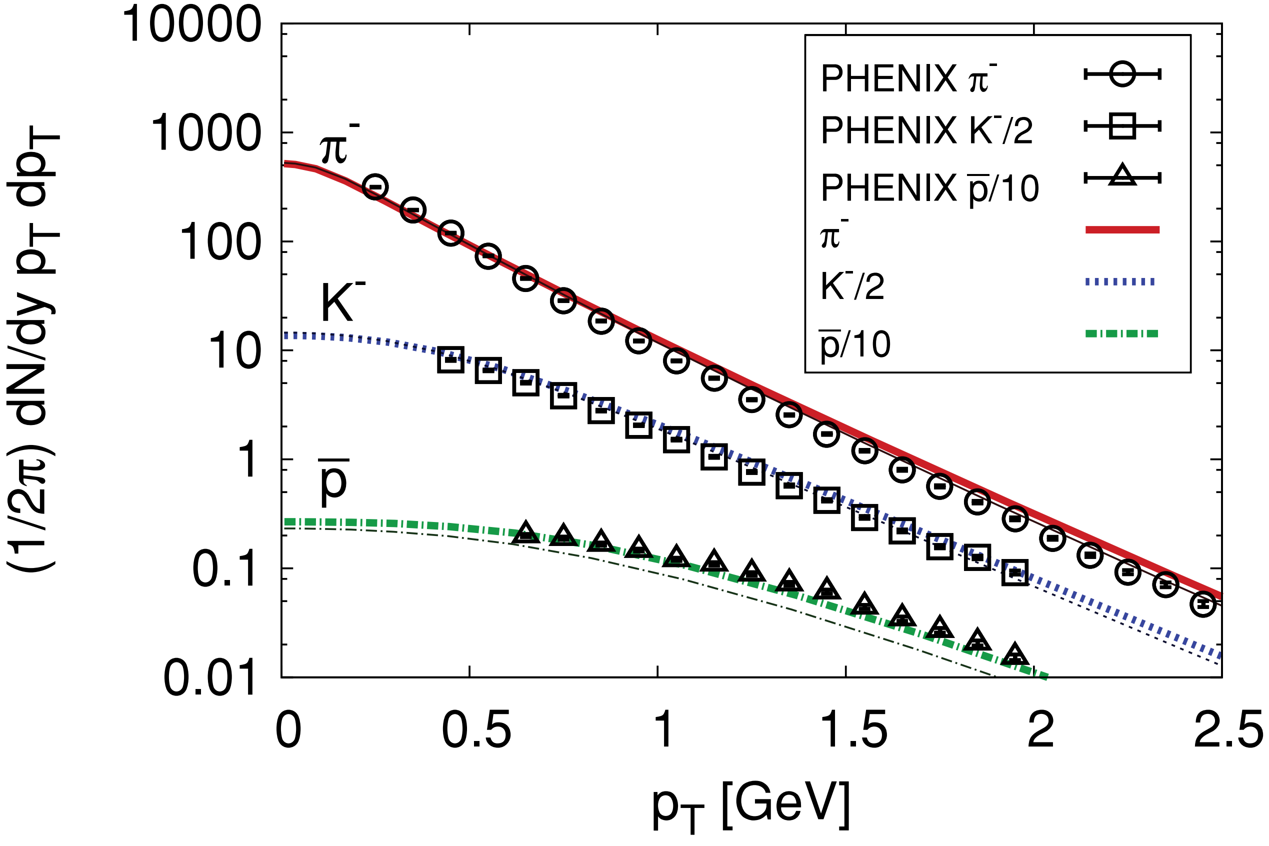
Turbide, Gale, Fries PRL (2006)
Low p_T: Chatterjee *et al.*, PRL (2006)
All p_T: Turbide *et al.*, PRC (2008)

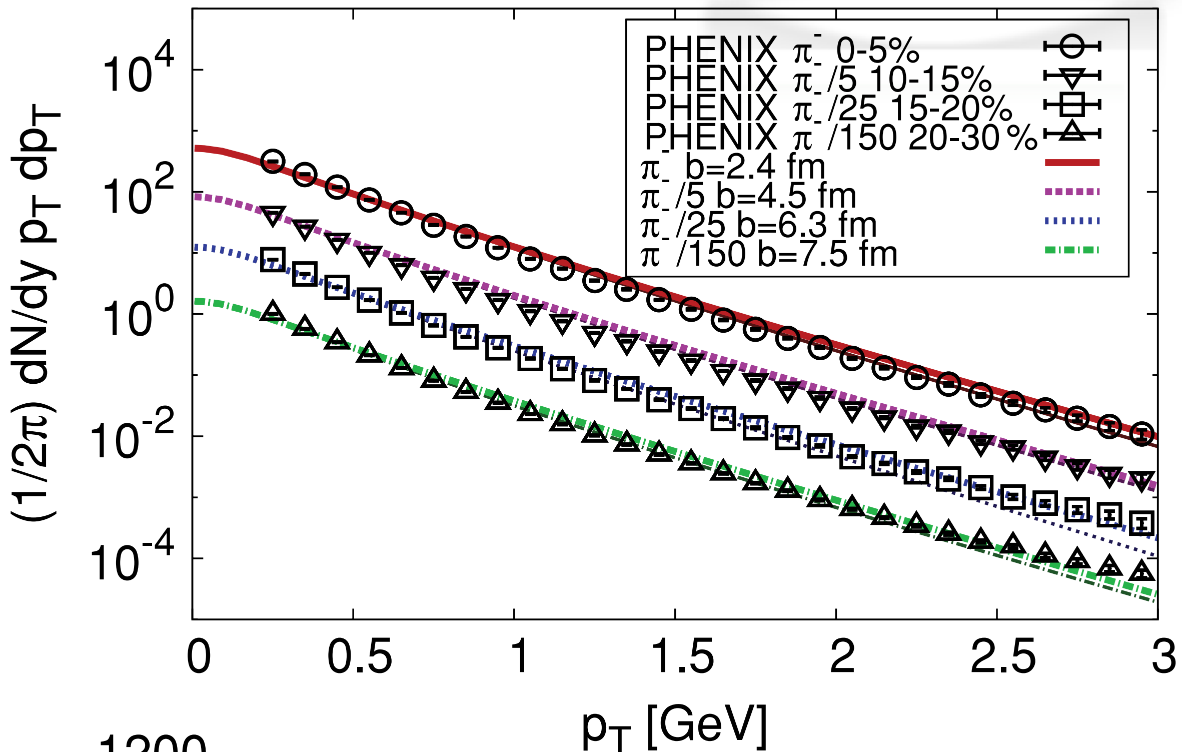
(2011)

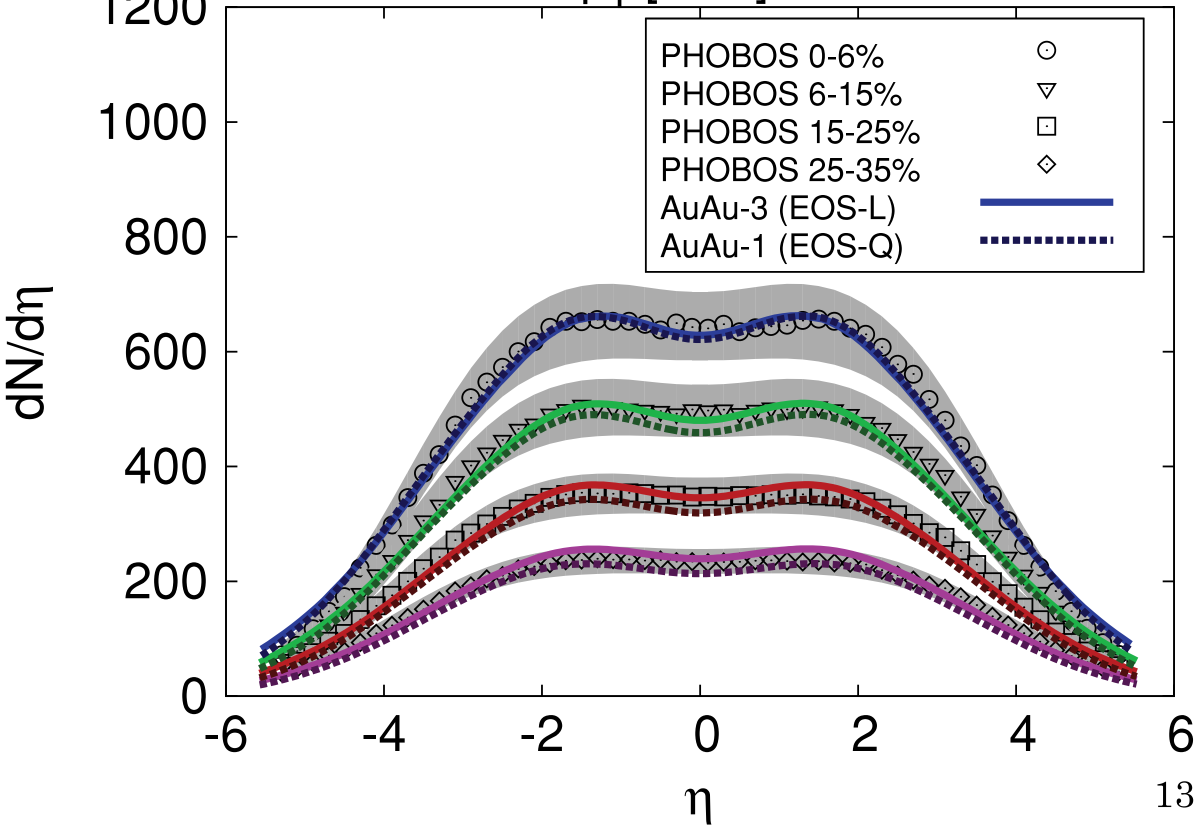


PROGRESS IN CHARACTERIZATION TOOL: 3D VISCOUS RELATIVISTIC HYDRODYNAMICS

MUSIC:







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

Viscosity effects on EM observables?

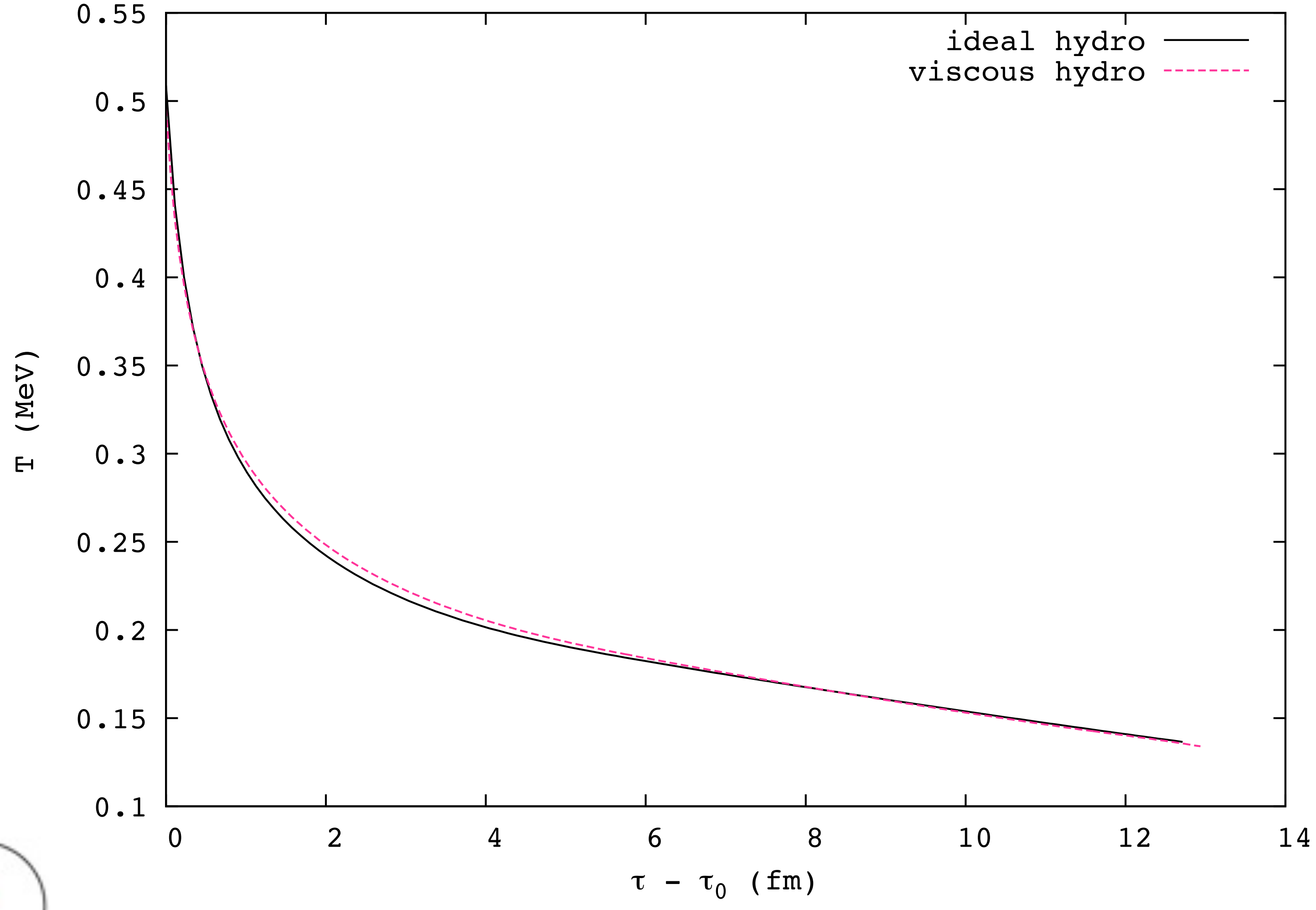
THE EFFECTS OF SHEAR VISCOSITY ON BULK DYNAMICS

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

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

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

THE EFFECTS OF SHEAR VISCOSITY ON BULK DYNAMICS

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

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

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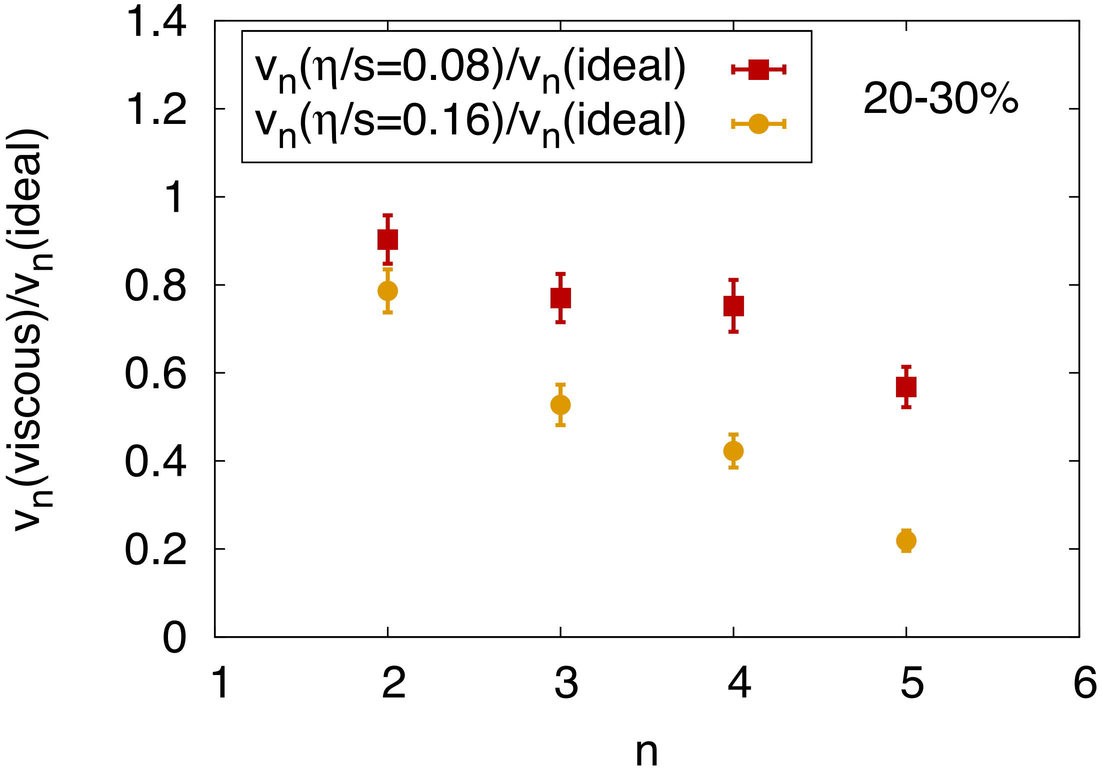
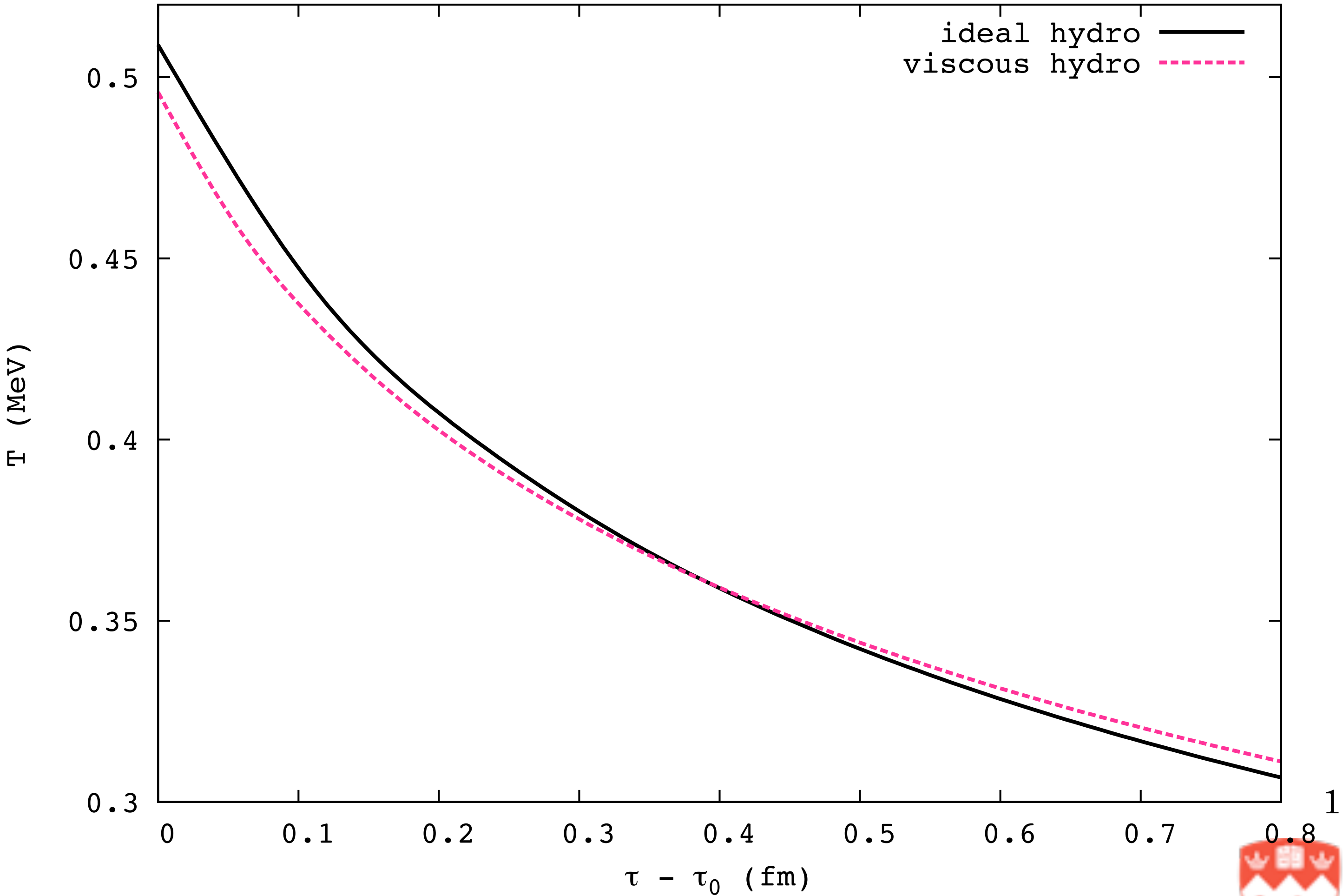
Israël & Stewart, Ann. Phys. (1979), Baier et al., JHEP (2008), Luzum and Romatschke, PRC (2008)





Charles Gale

THE EFFECTS OF SHEAR VISCOSITY ON THE PHOTON DISTRIBUTION

In-medium **hadrons**:

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

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

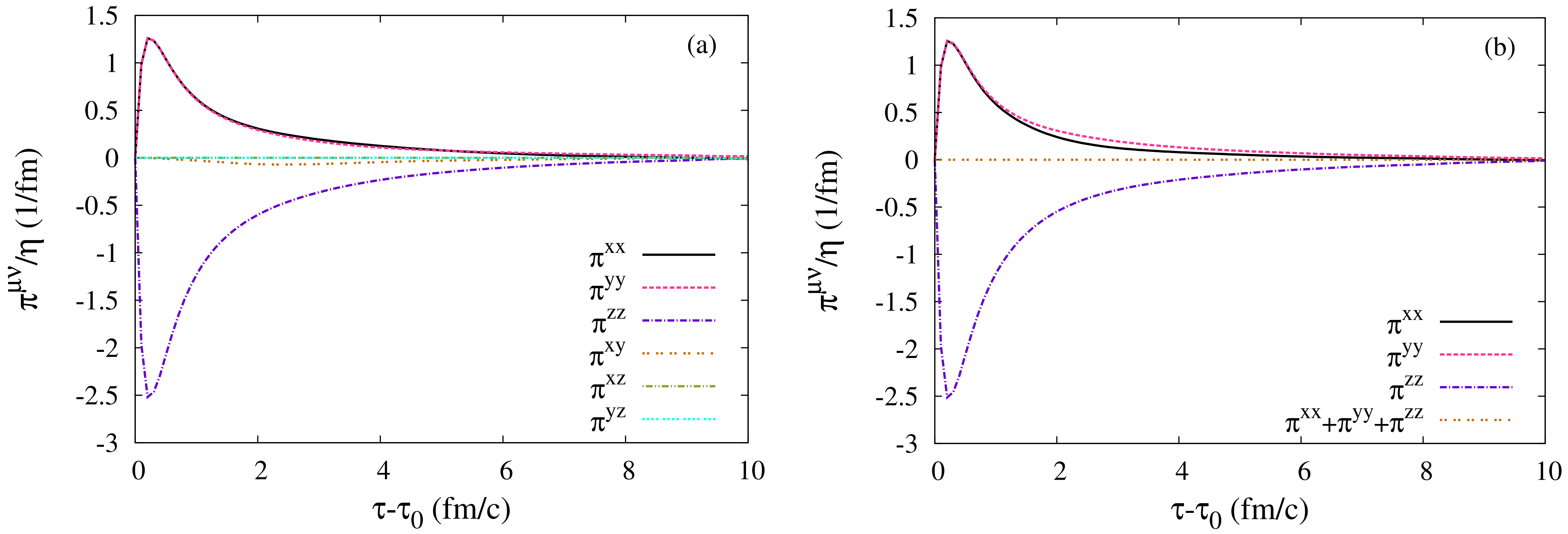
$$q_0 \frac{d^3R}{d^3q} = \int \frac{d^3p_1}{2(2\pi)^3 E_1} \frac{d^3p_2}{2(2\pi)^3 E_2} \frac{d^3p_3}{2(2\pi)^3 E_3} (2\pi)^4 |M|^2 \delta^4(\ldots) \frac{f(E_1) f(E_2) [1 \pm f(E_3)]}{2(2\pi)^3}$$

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

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

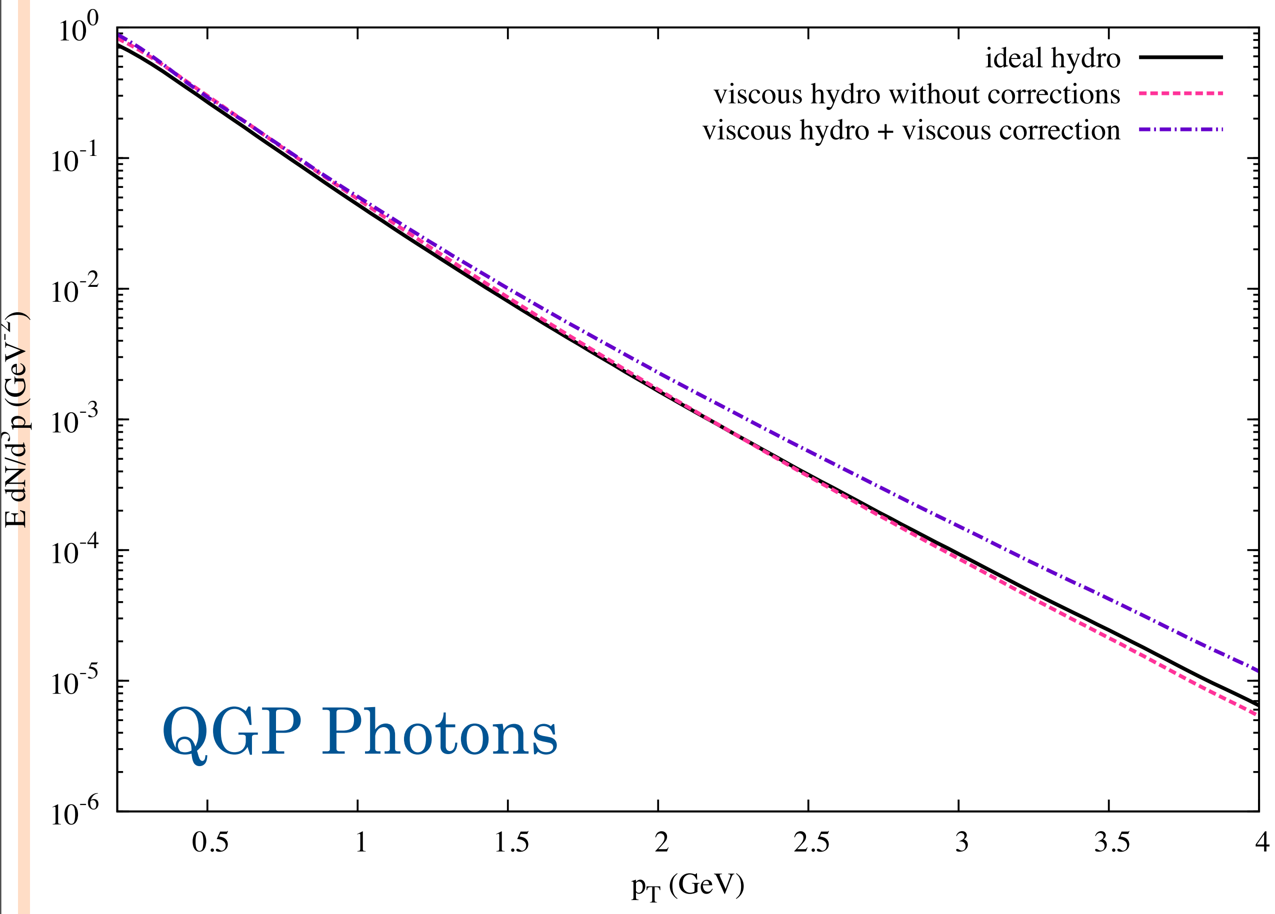
+ QGP Photons

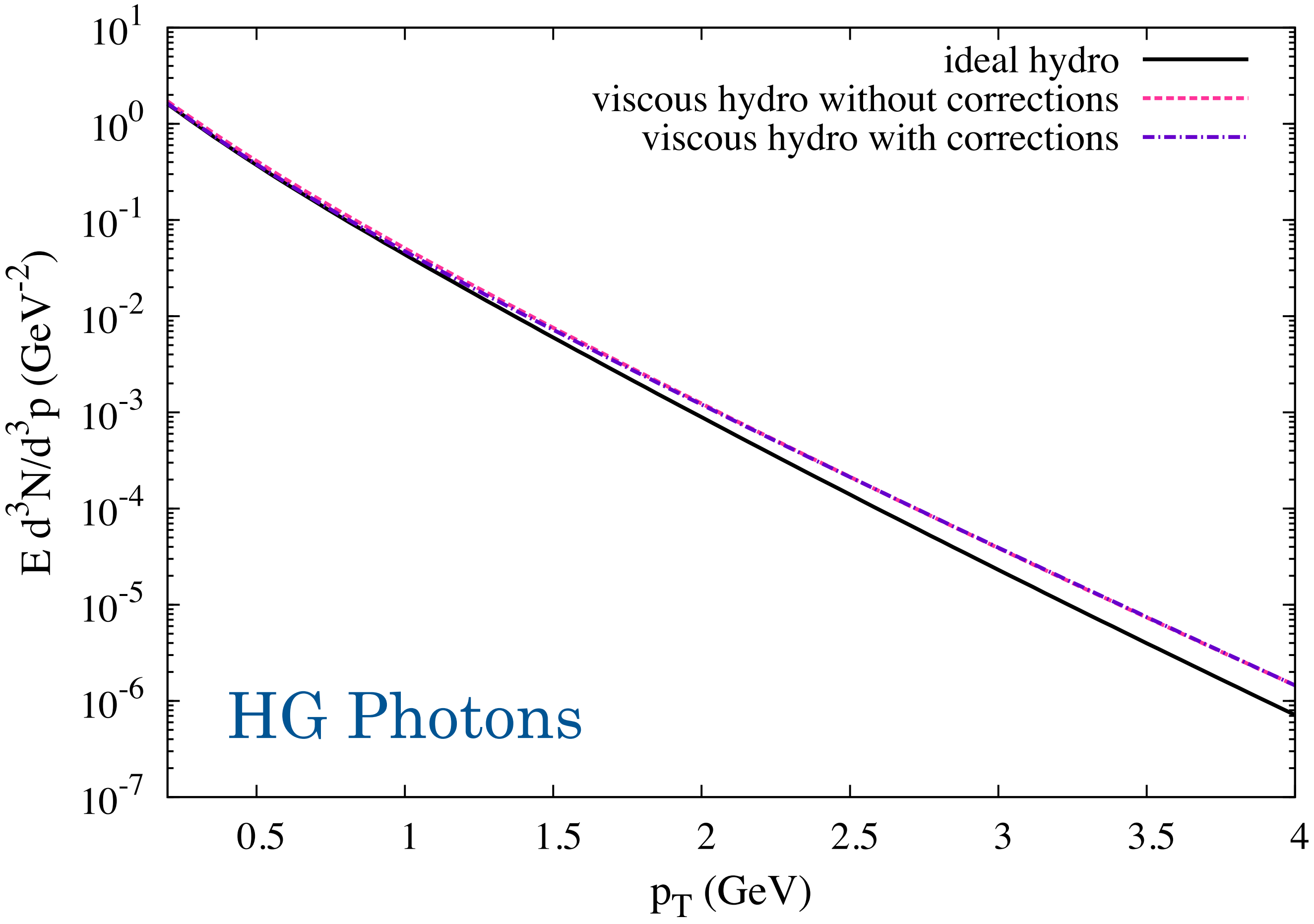
THE EFFECTS OF SHEAR VISCOSITY ON THE BULK DYNAMICS



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

THE EFFECTS OF SHEAR VISCOSITY ON THE PHOTON DISTRIBUTION



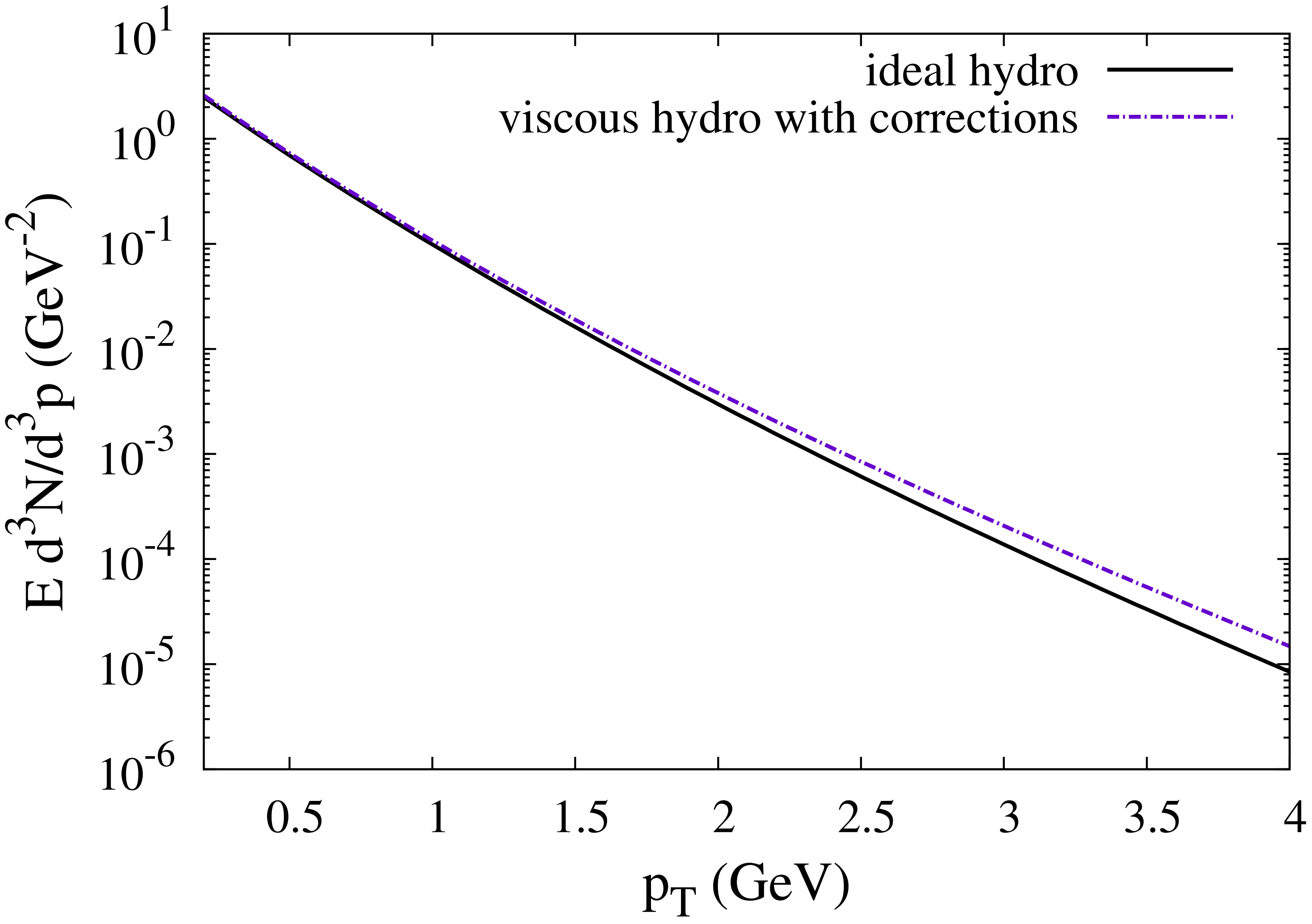


K. Dusling NPA (2010)
Chaudhuri & Sinha, PRC (2011)

Viscous effects harden the photon spectrum

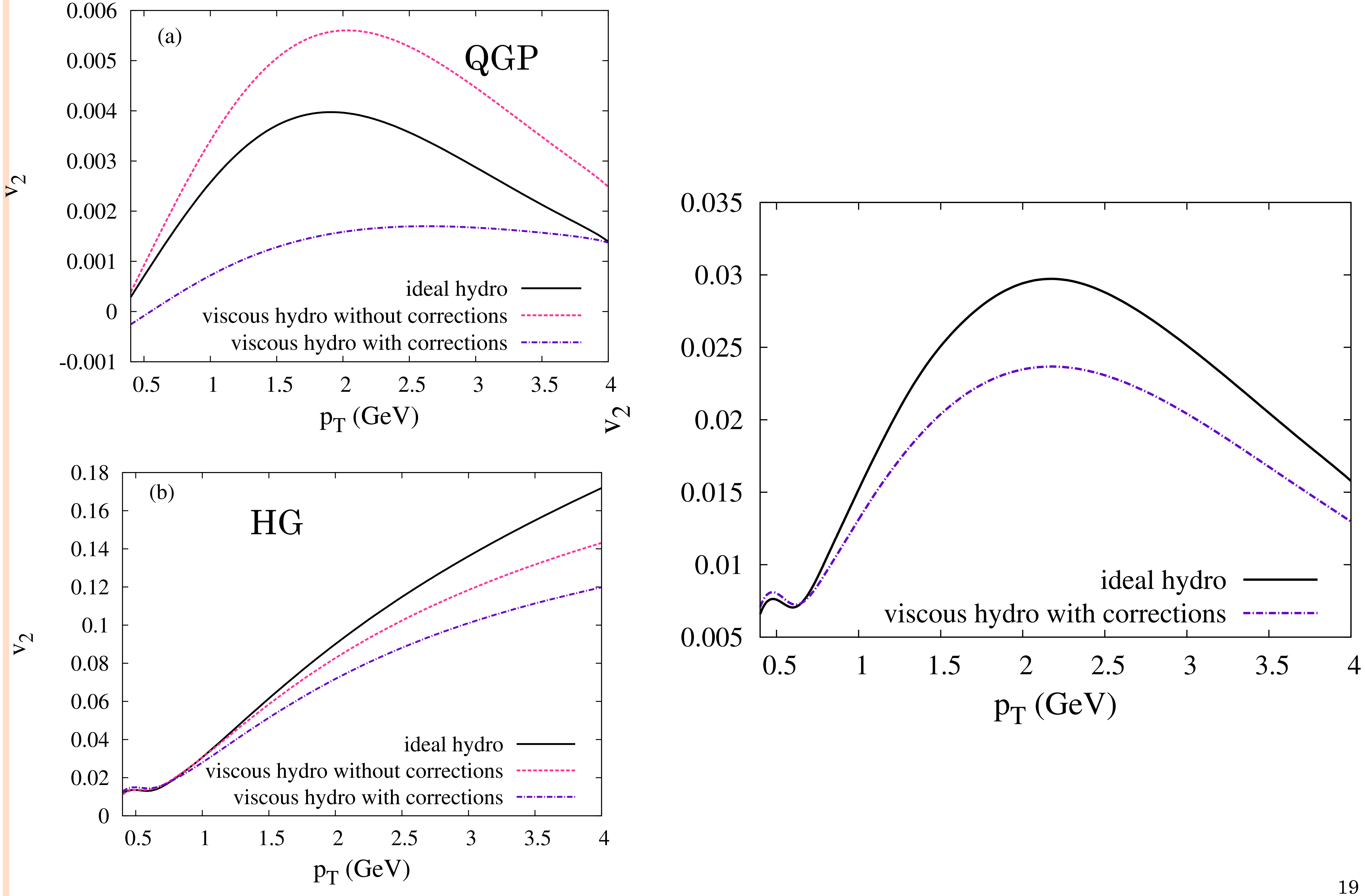
M. Dion et al., PRC (2011)

THE NET THERMAL PHOTON YIELD



- Viscous corrections make the spectrum harder, ≈100% at p_T = 4 GeV.
- Increase in the slope of ≈15% at p_T = 2 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

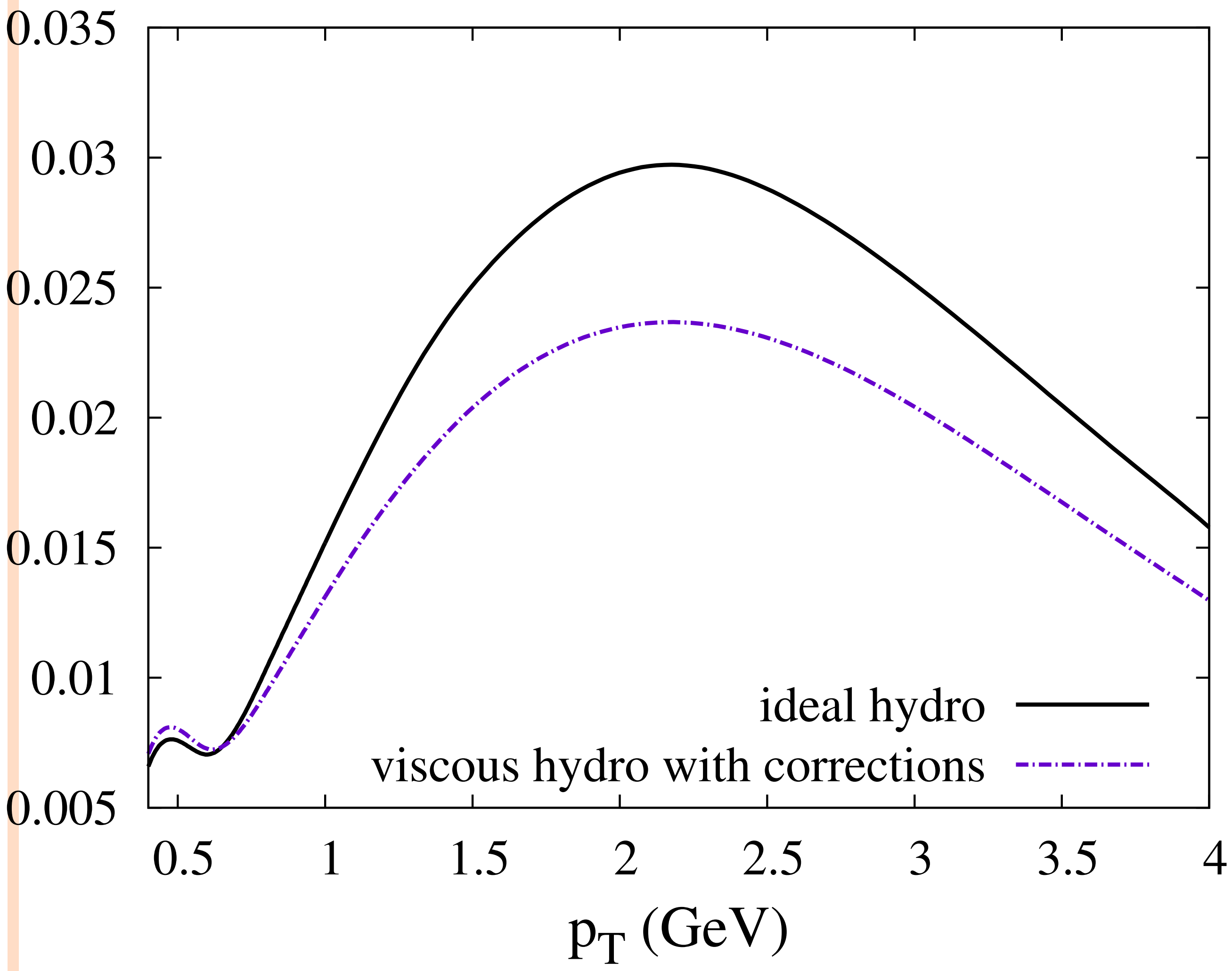
SHEAR VISCOSITY AND PHOTON V_2



M. Dion *et al.*, PRC 2011

Charles Gale

SHEAR VISCOSITY AND PHOTON V_2

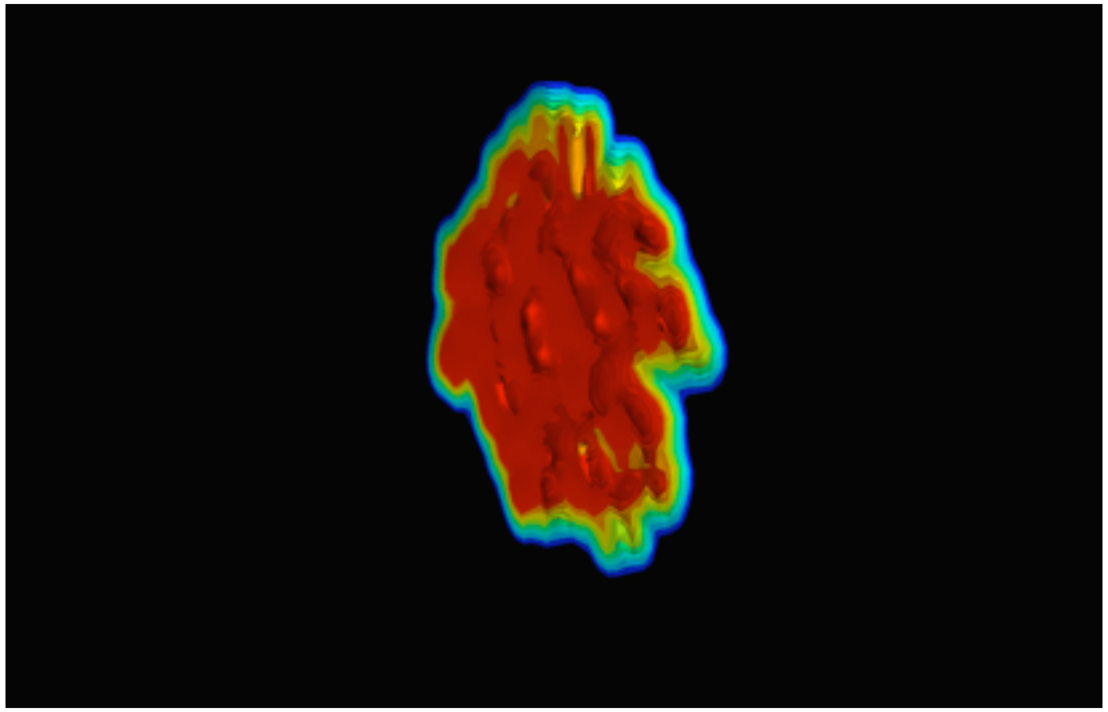


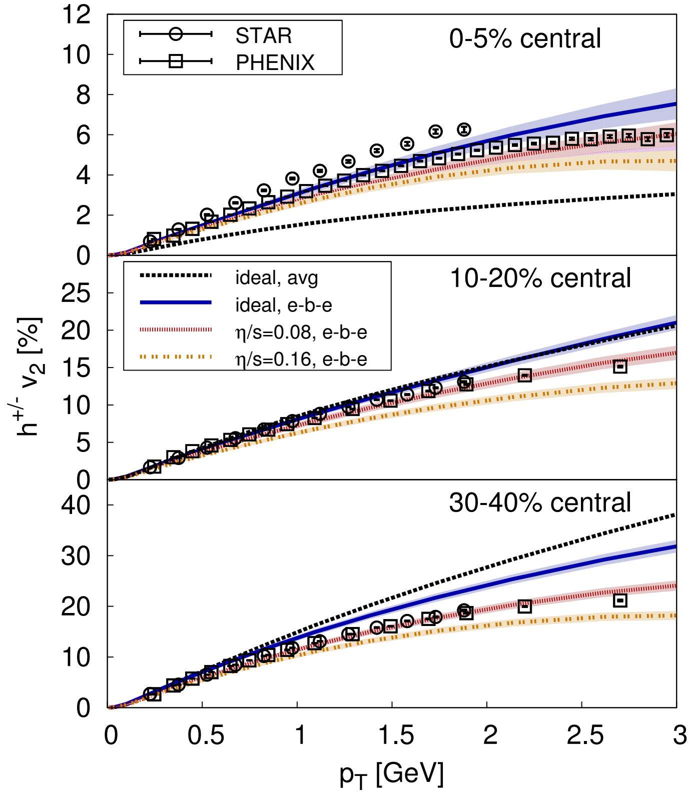
- The net elliptic flow is a *weighted average*. A larger QGP yield will yield a smaller v_2. Same story - *mutatis mutandis* - for the HG
- The turnover at $p_T \approx 2$ GeV could be QGP-driven and/or pQCD-driven
- The net effect of viscous corrections makes the photon elliptic flow *smaller*, as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

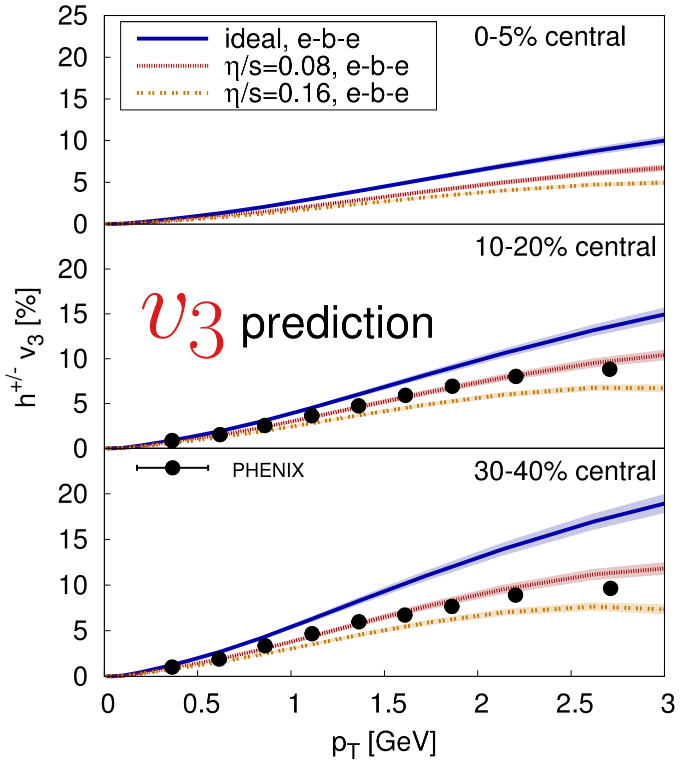
M. Dion *et al.*, PRC 2011

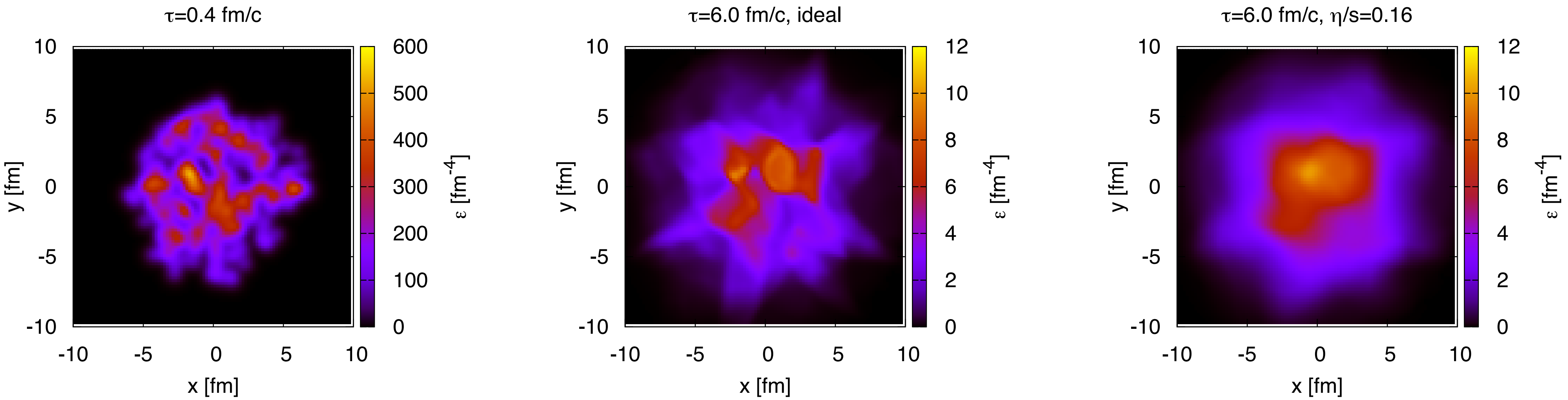
INITIAL STATE FLUCTUATIONS: A PARADIGM SHIFT IN HEAVY ION ANALYSES

Lumpy
MUSIC



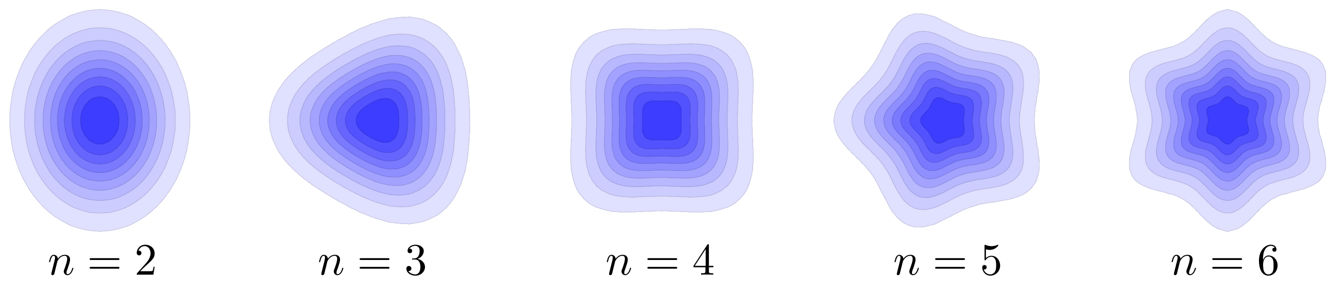


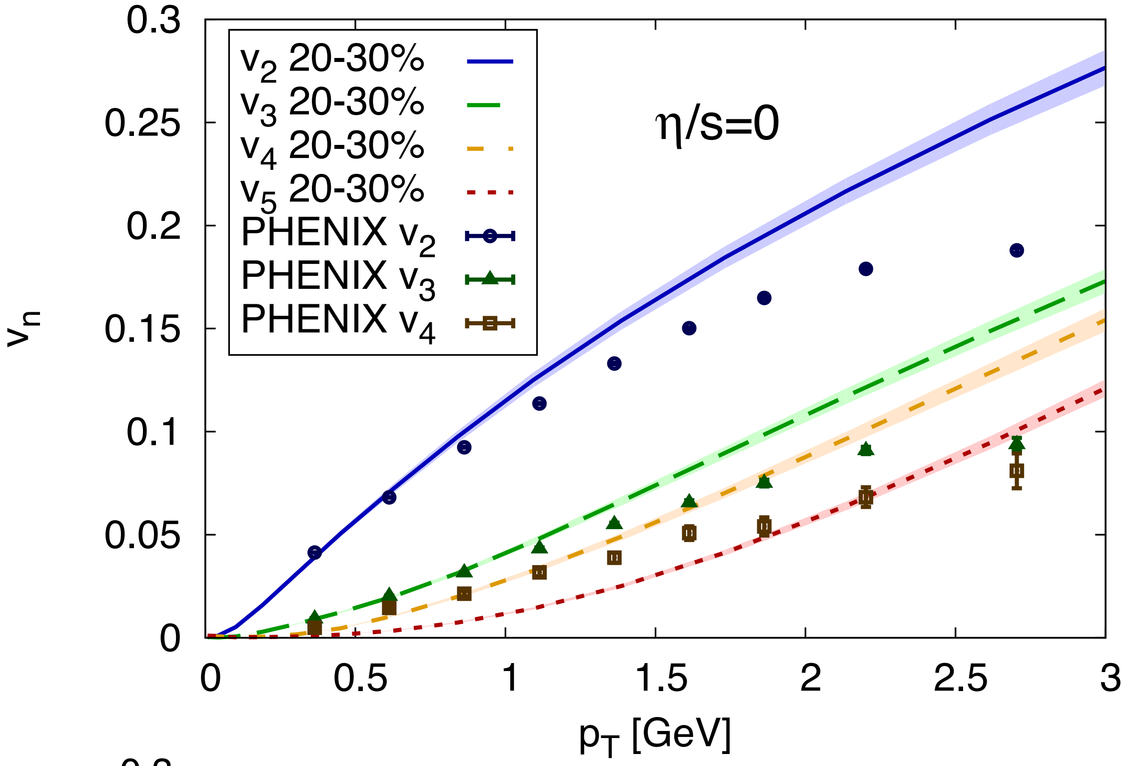


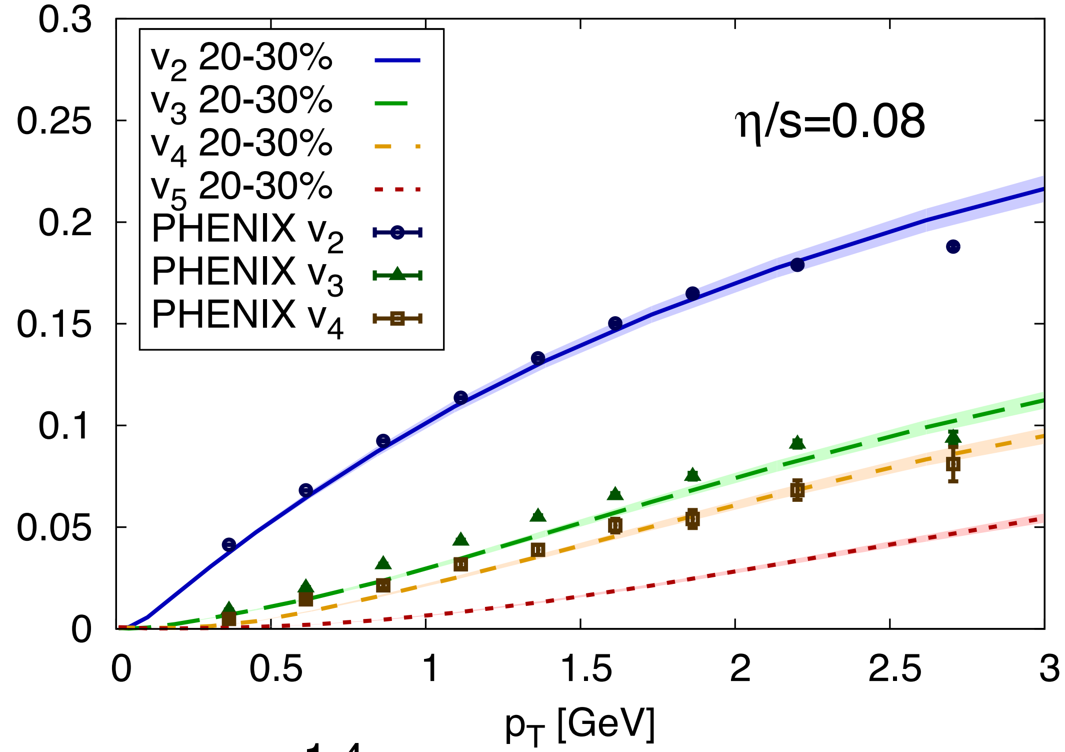


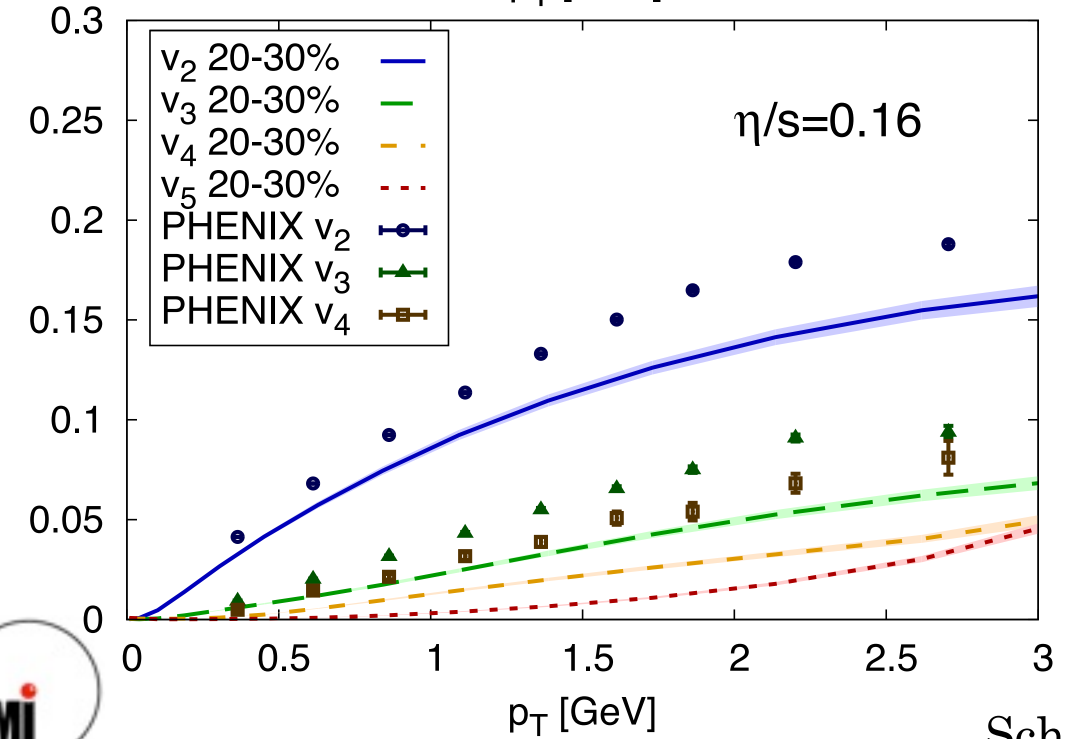
Schenke, Jeon, Gale, PRL (2011)

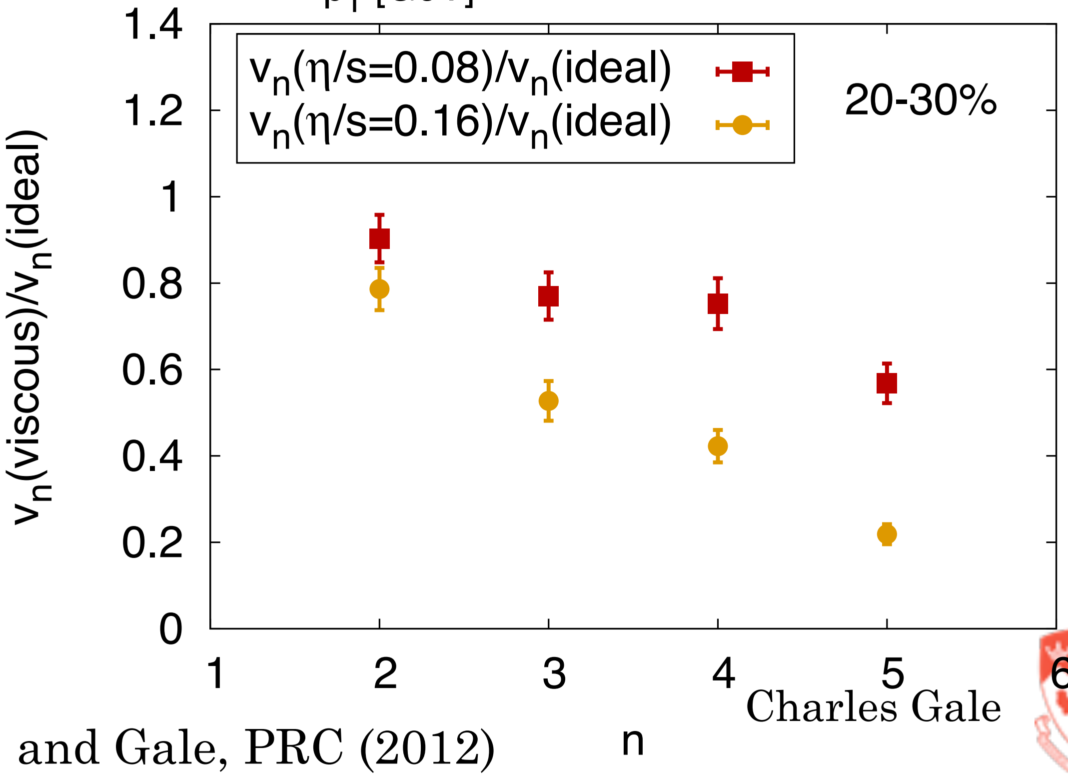
MOVING INTO THE "CHARACTERIZATION" PHASE…





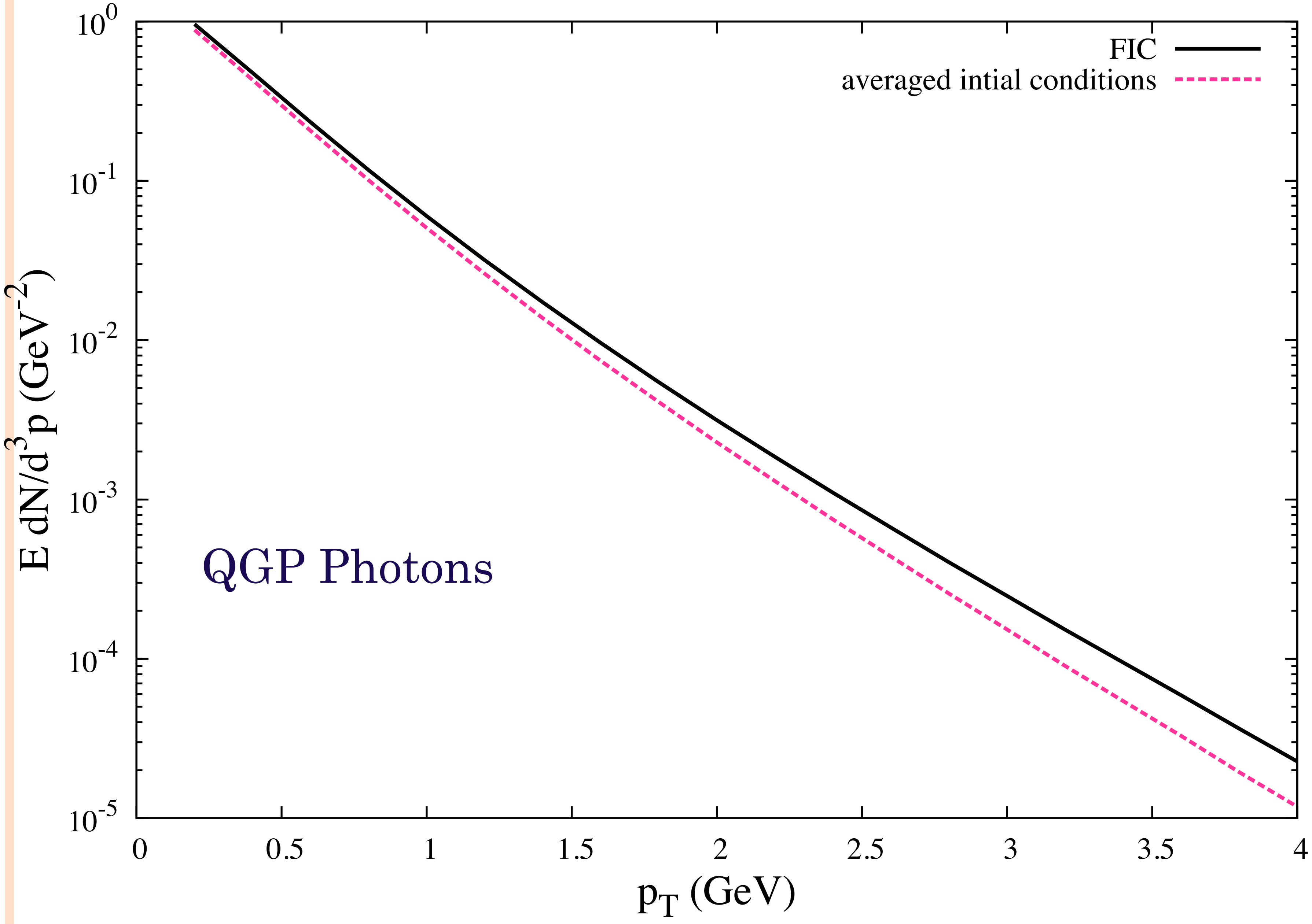






Schenke, Jeon, and Gale, PRC (2012)

THE EFFECT OF FIC ON THE THERMAL PHOTON SPECTRUM



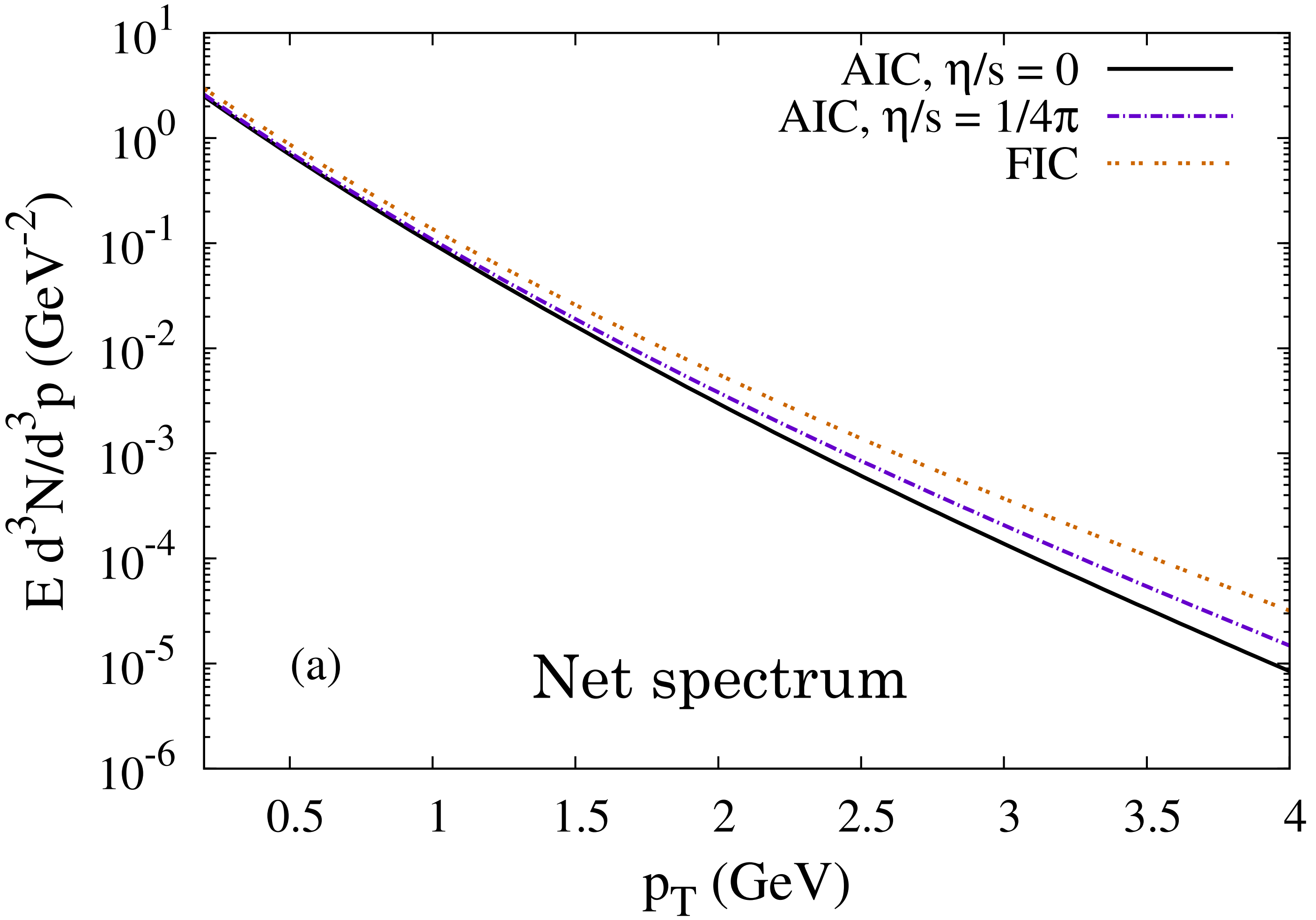
- FIC produces higher initial T (hot spots), and higher initial gradients
- FIC conditions are demanded by hadronic data (v_{odd})
- These lead to a harder spectrum, *as for hadrons*

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

ALL TOGETHER: FICS + VISCOSITY



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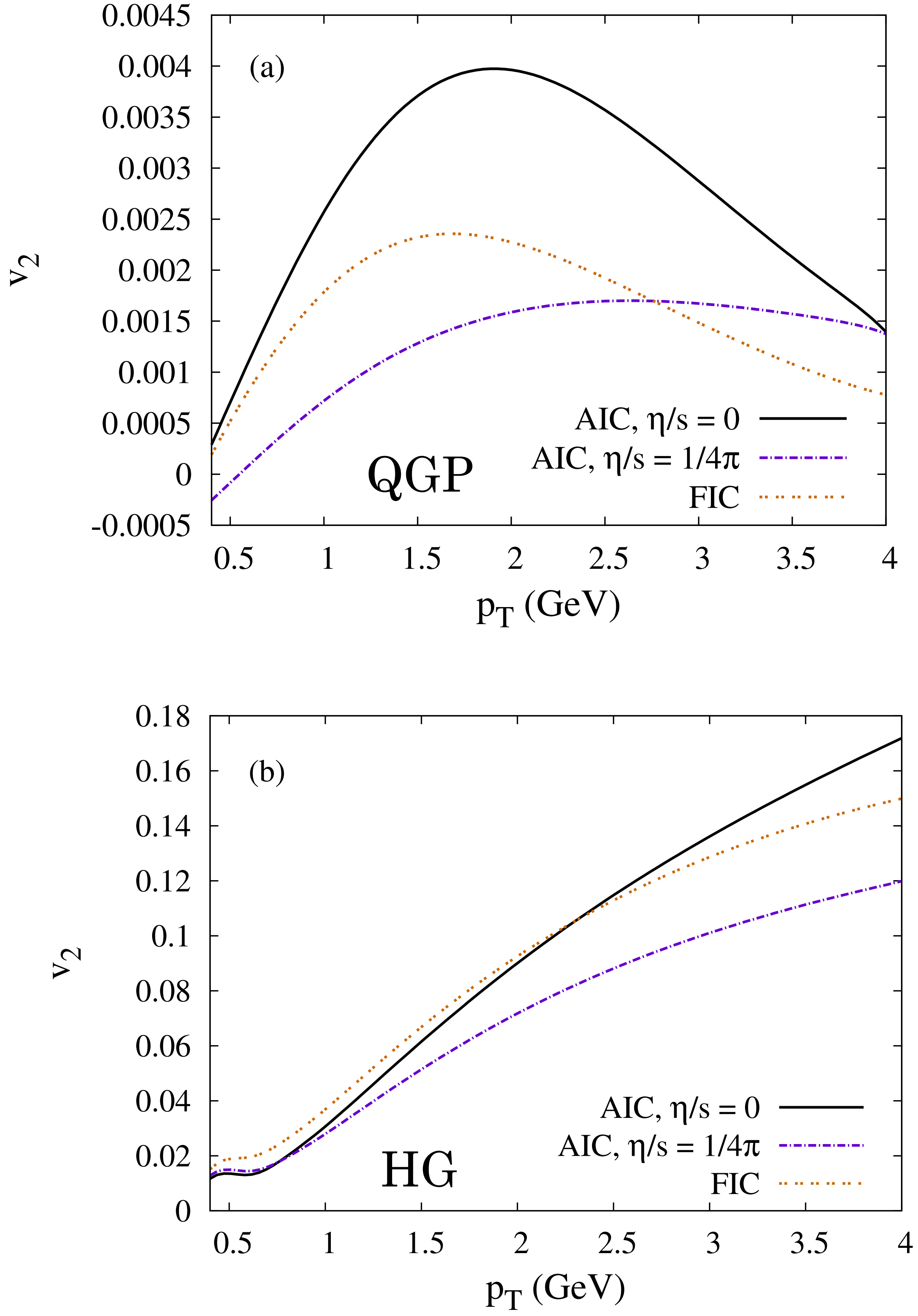
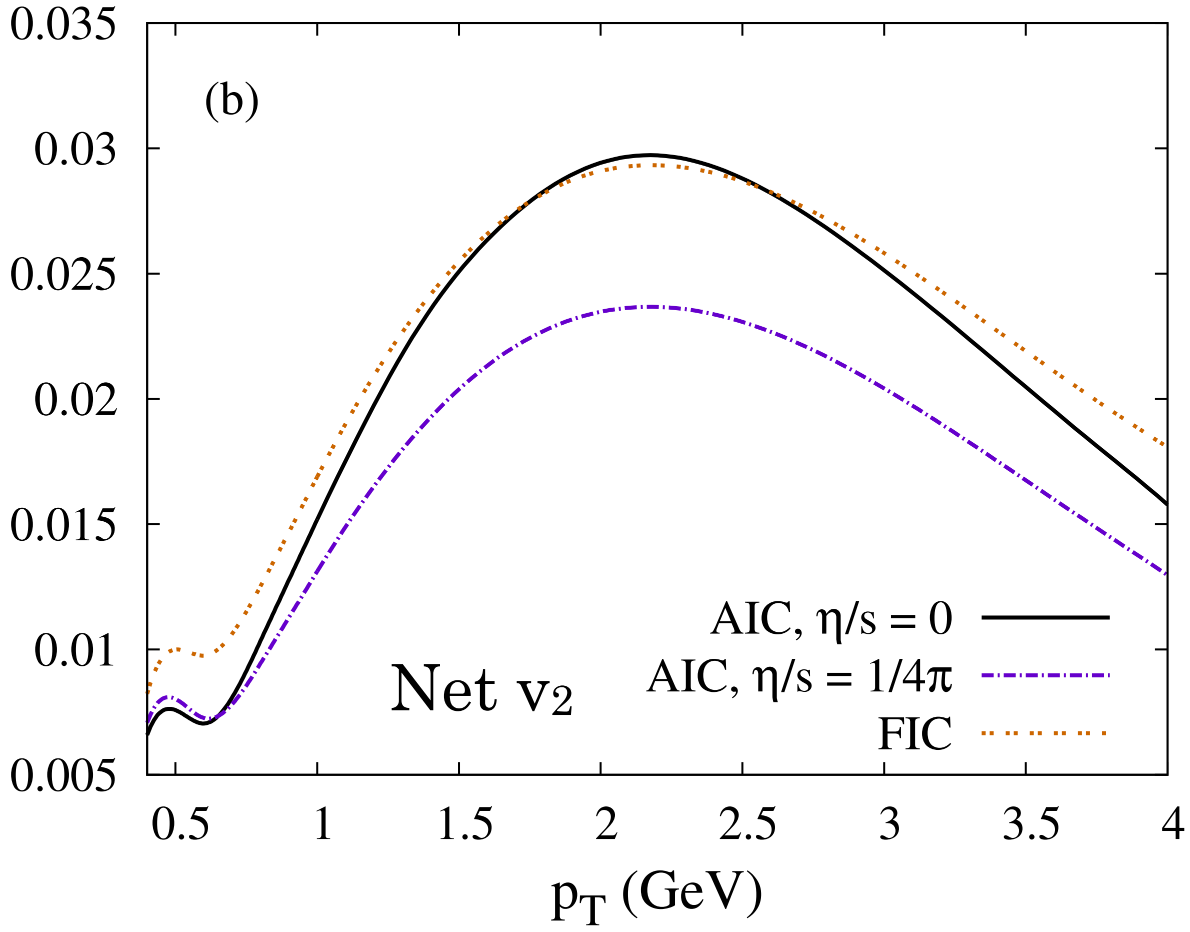
FICs AND THERMAL PHOTON v_2



- 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
- HG elliptic flow is much larger than QGP elliptic flow, but remember net v_2 is a weighted average

FICS AND THERMAL PHOTON V_2



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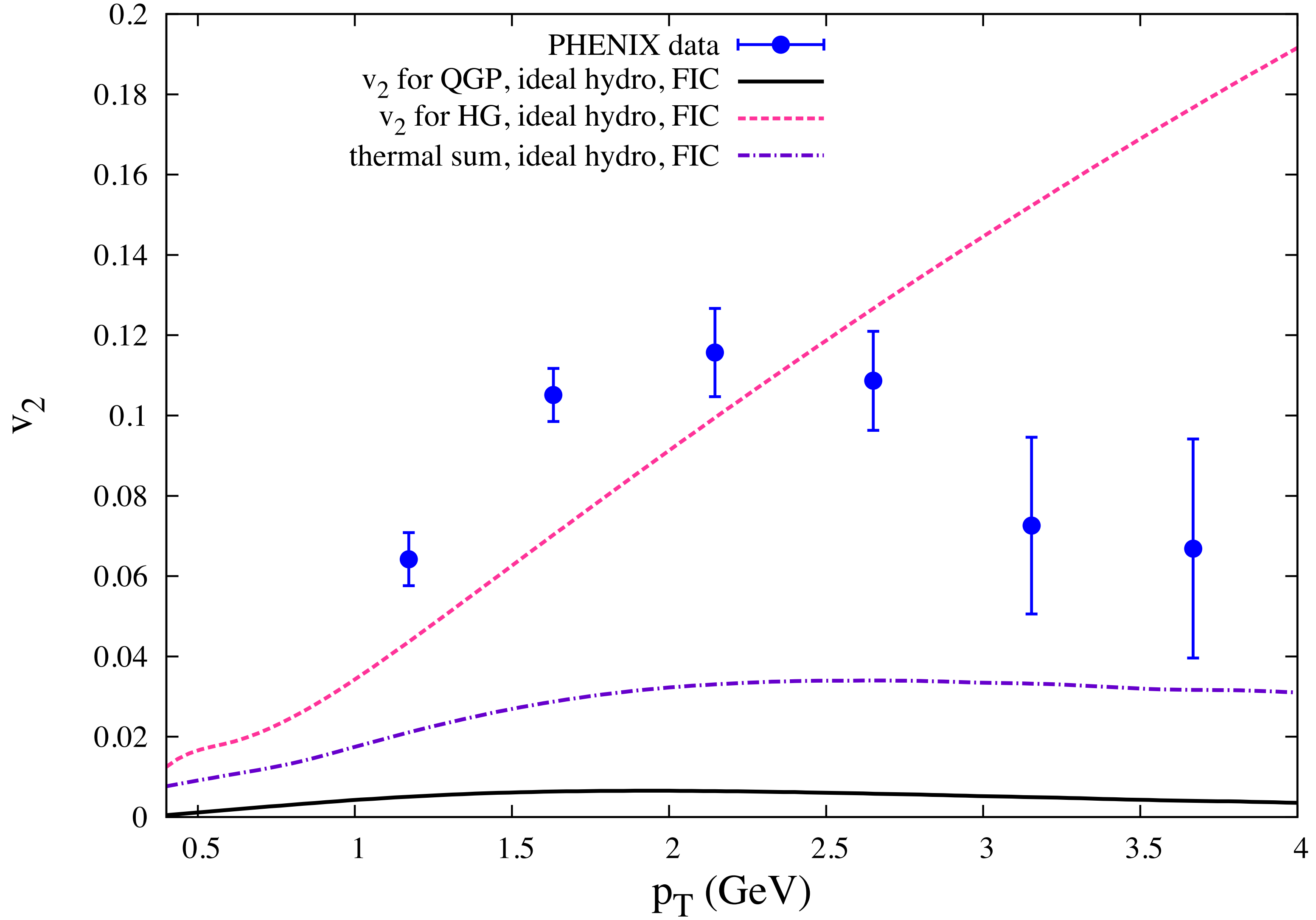
- For hadrons measured in events belonging to large centrality, FICs will *decrease* v_2
- HG elliptic flow is much larger than QGP elliptic flow, but remember net v_2 is a weighted average
- Net v_2 is comparable in size to that with ideal medium.

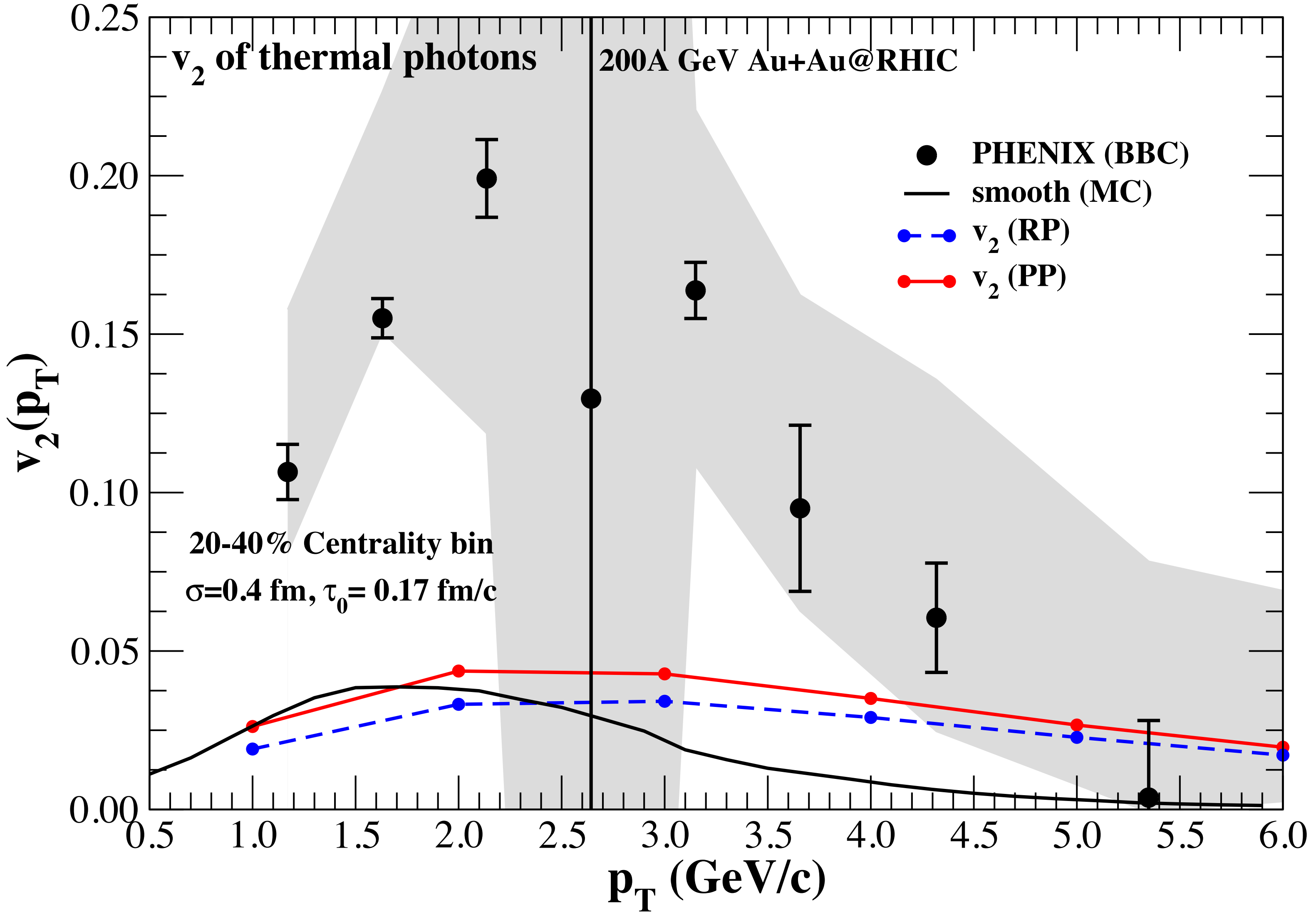
PHOTON V$_2$ DATA?



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)

Dion et al. (2011)

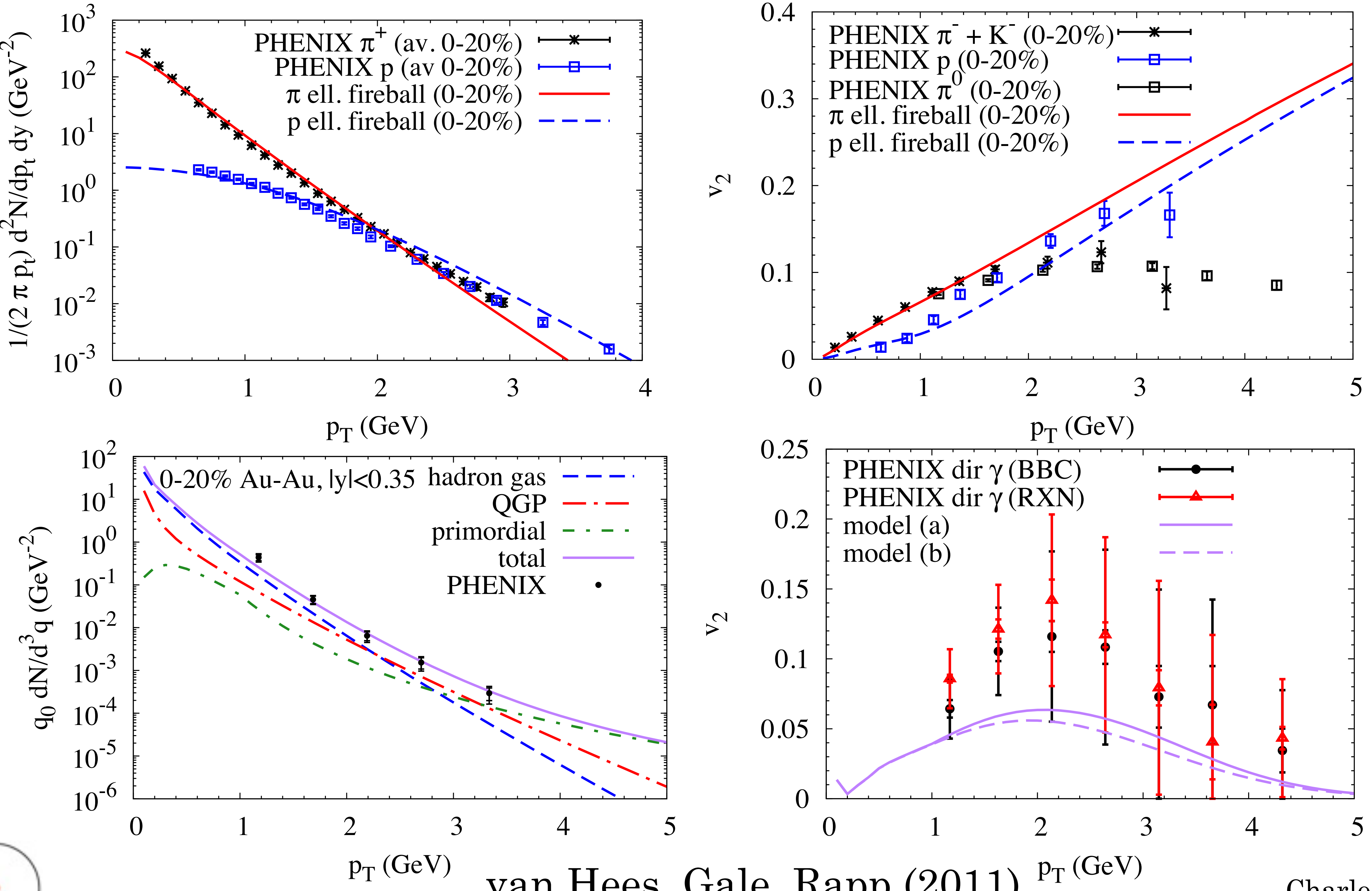
- Data is higher than calculation, even with e-b-e initial state fluctuations, and ideal hydro
- Size comparable with HG v_2

SOME FACTS AND SOME LEADS

- FICs are here to stay. The meaning of "initial temperature" is altered.
- (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.
- Early-times magnetic field effects? (Basar, Kharzeev, Skokov, PRL (2012))
- Is the large photon elliptic flow telling us about the dynamics? Baryons?
- 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?

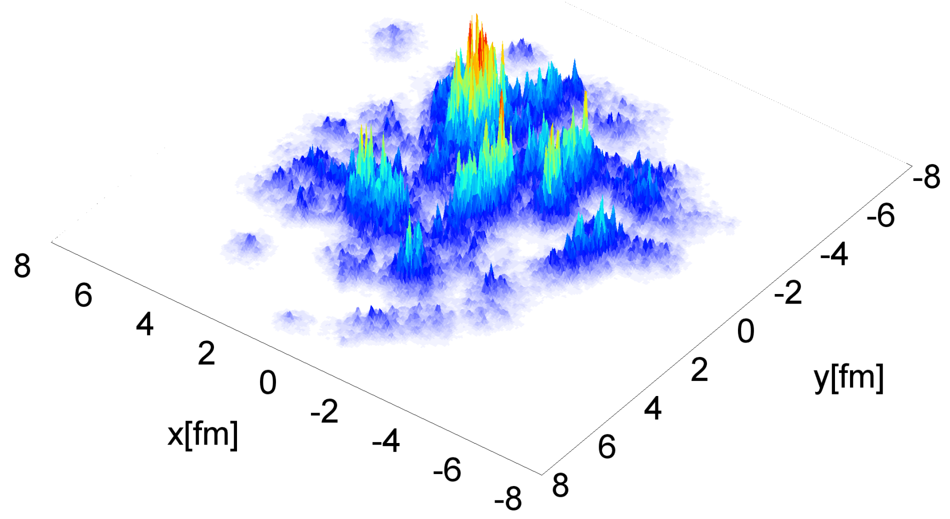


van Hees, Gale, Rapp (2011)

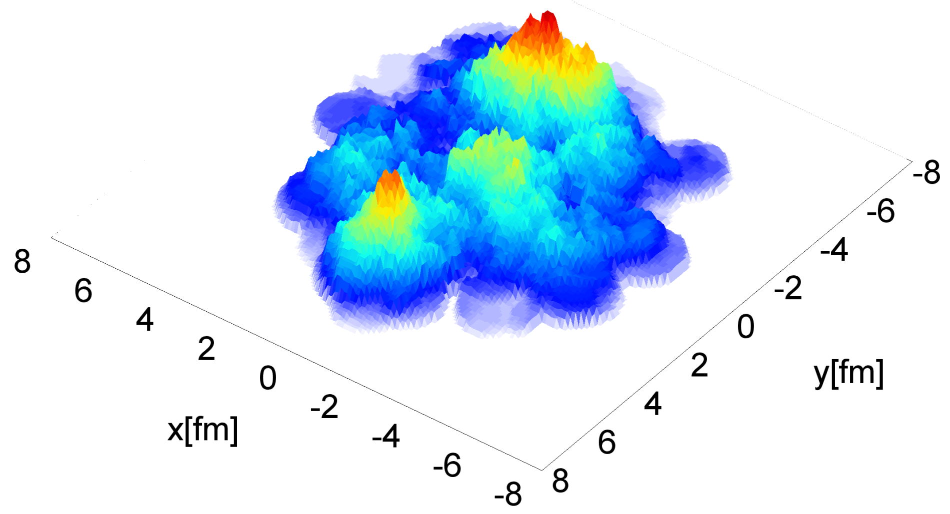
FICS: BEYOND GLAUBER, ADDRESSING INITIAL/PRIMORDIAL FLOW

- Several sources of quantum fluctuations:
  - Fluctuations of nucleon distributions in the nuclear wave function
  - Fluctuations of the colour charges inside a nucleon: Depends on the nuclear saturations scale Q_s
- Using fluctuating glasma initial states: IP-Sat + CYM. Implementation of CGC initial state.
- Couple the IP-Glasma initial state to MUSIC

FICs: Beyond Glauber, addressing initial/primordial flow

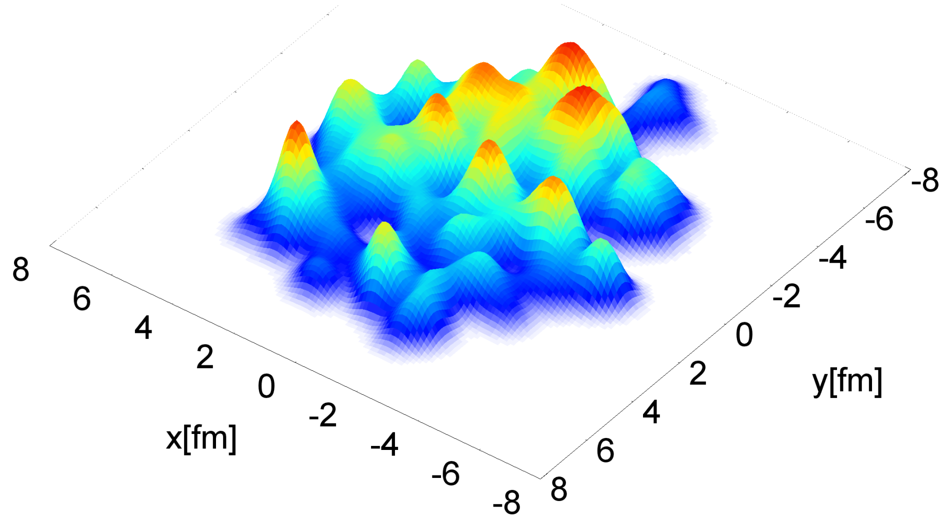


IP-Glasma



MC-KLN

IP-Glasma initial states show structure absent in Glauber

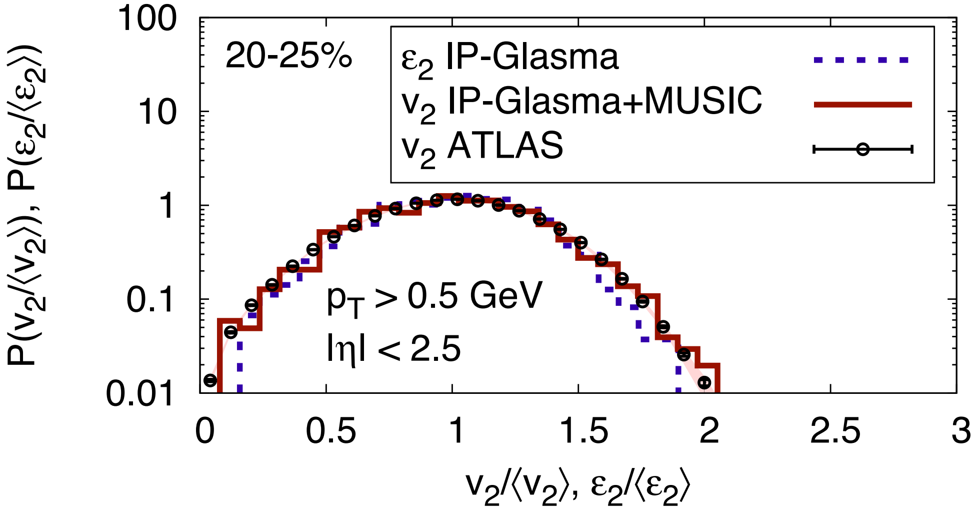


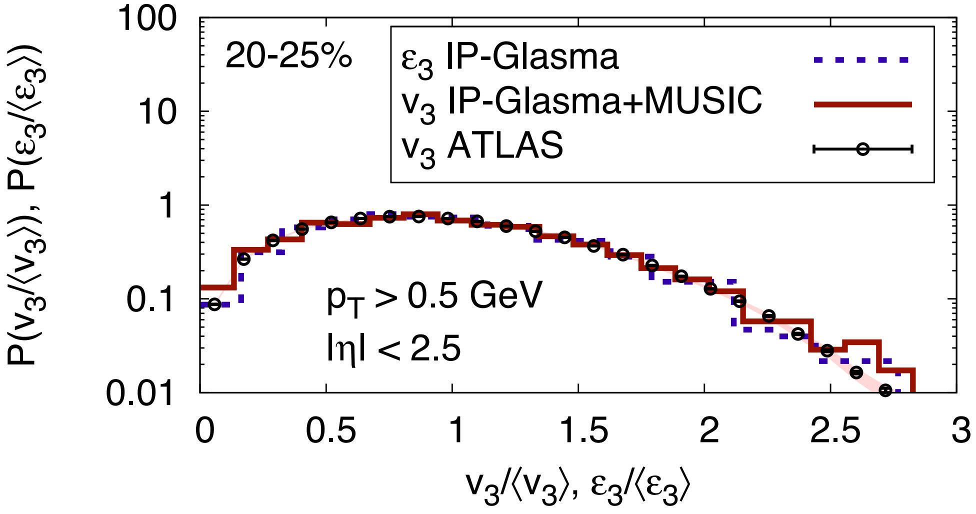
Glauber

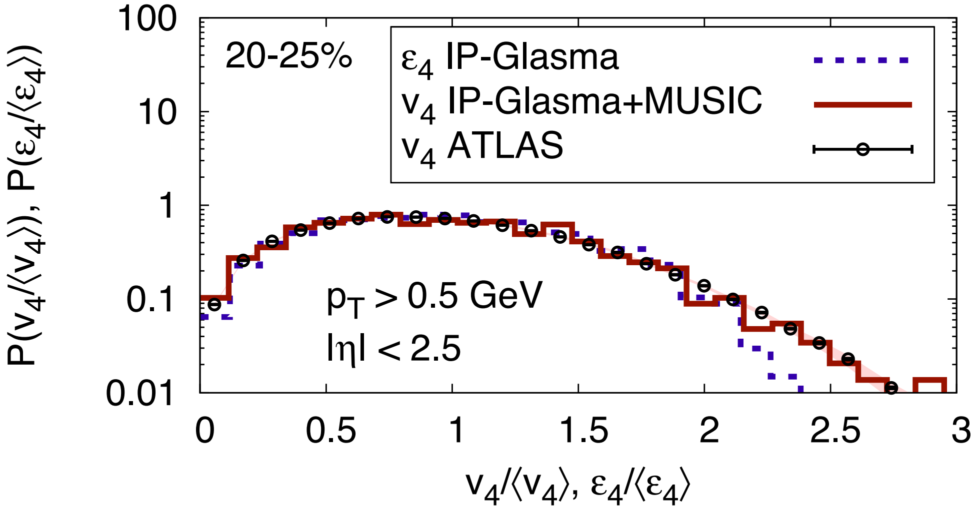
IP-GLASMA + MUSIC

EFFECT ON HADRONIC OBSERVABLES

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







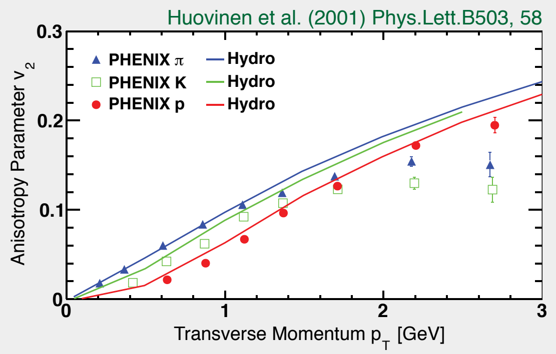
- Initial eccentricity distributions a good approximation to v_n's
- IP-Glasma + MUSIC provides consistent flow systematics at RHIC & LHC
- Investigating the effects on EM variables

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

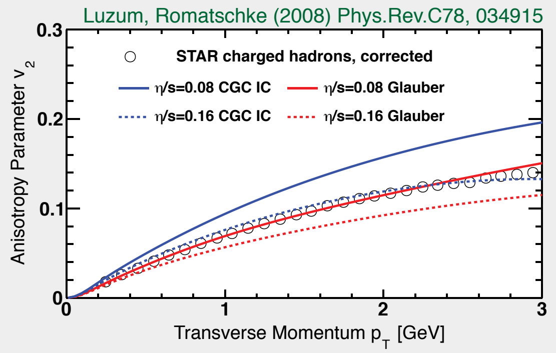
Is the hydrodynamic modeling complete?

- 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?

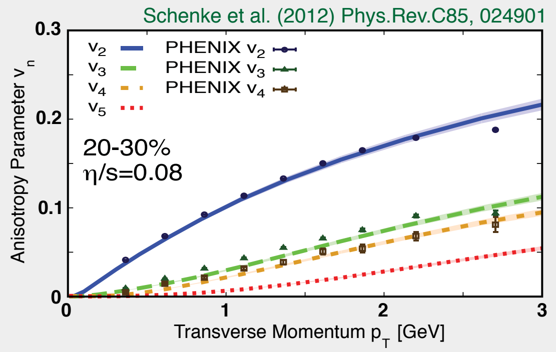
Important experimental and theoretical developments



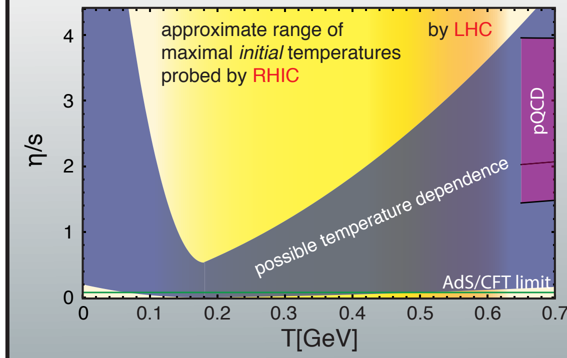
Early success of hydrodynamics missing physics of lattice QCD equation of state and viscosity.



Bounds on shear viscosity but large uncertainties from initial conditions.



Higher moments constrain viscosity and fluctuating initial conditions better, but temperature dependence of η/s is not yet determined.



To determine (η/s)(T) different initial temperatures need to be accessible. Only possible with combined data from LHC and RHIC beam energy scan.

2000

- experimental techniques developed
- v_2 systematics developed
  - p_T dependence
  - identified particle flow
  - rapidity dependence
  - analysis improved errors reduced

2002

2004

2006

- fluctuations important for v_2 analysis in small systems
- first flow results from viscous fluid-dynamics

2008

- reliable QCD equation of state from the lattice included

2010

- v_3
- v_n
- v_n correlations

2012

- $P(v_n)$

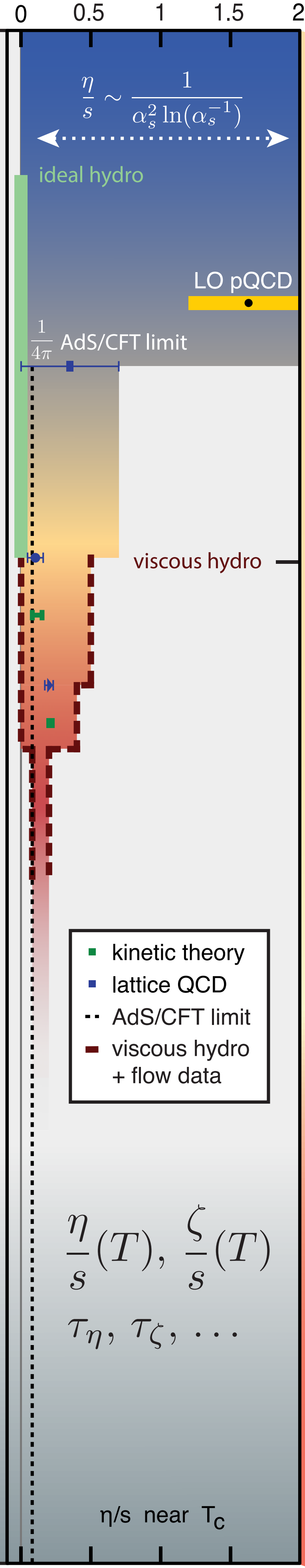
2014

RHIC BES-II upgrade required to

- measure lower bound to ~10%
- determine (η/s)(T) dependence
- measure bulk viscosity and relaxation times
- constrain initial state and its fluctuations

2022

Increasing precision of key observable



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

A general form for the dissipative terms:

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

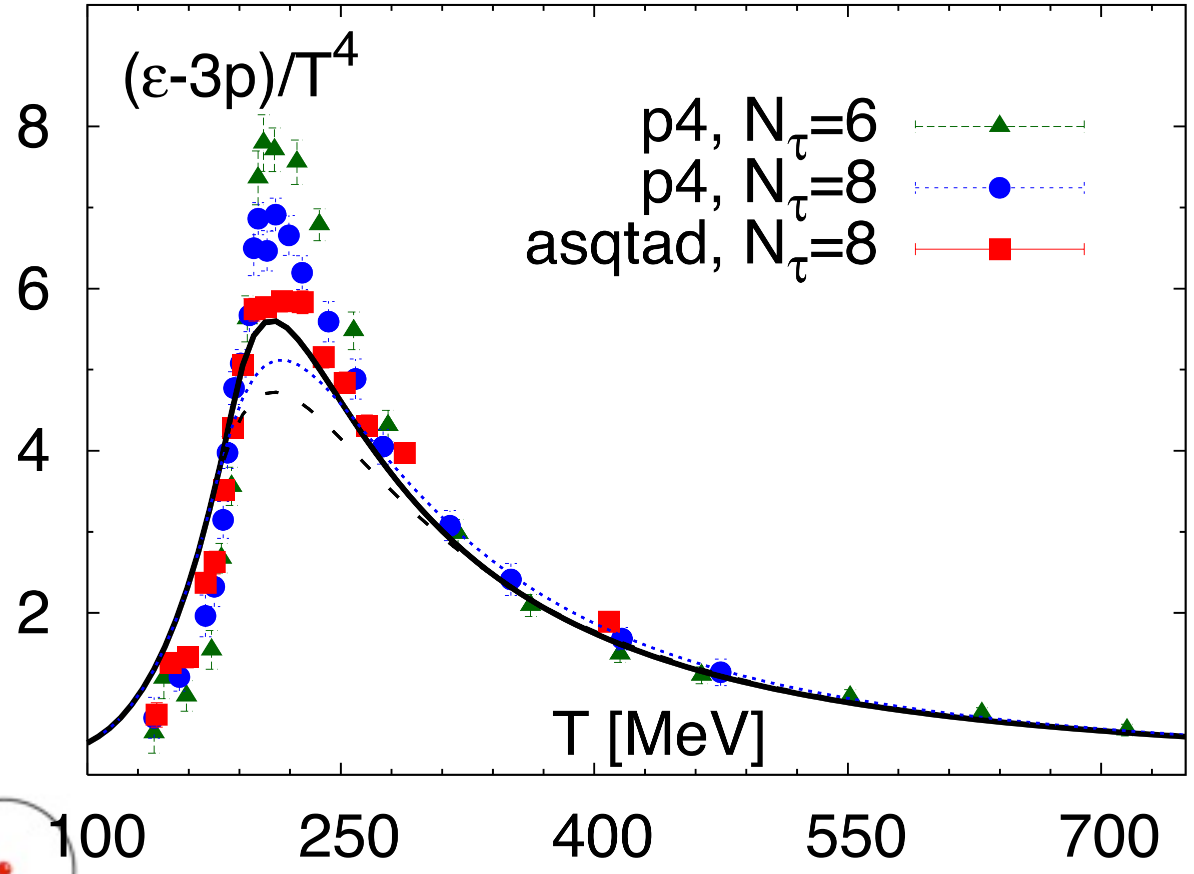
No simulation incorporates all of these

BULK VISCOSITY?

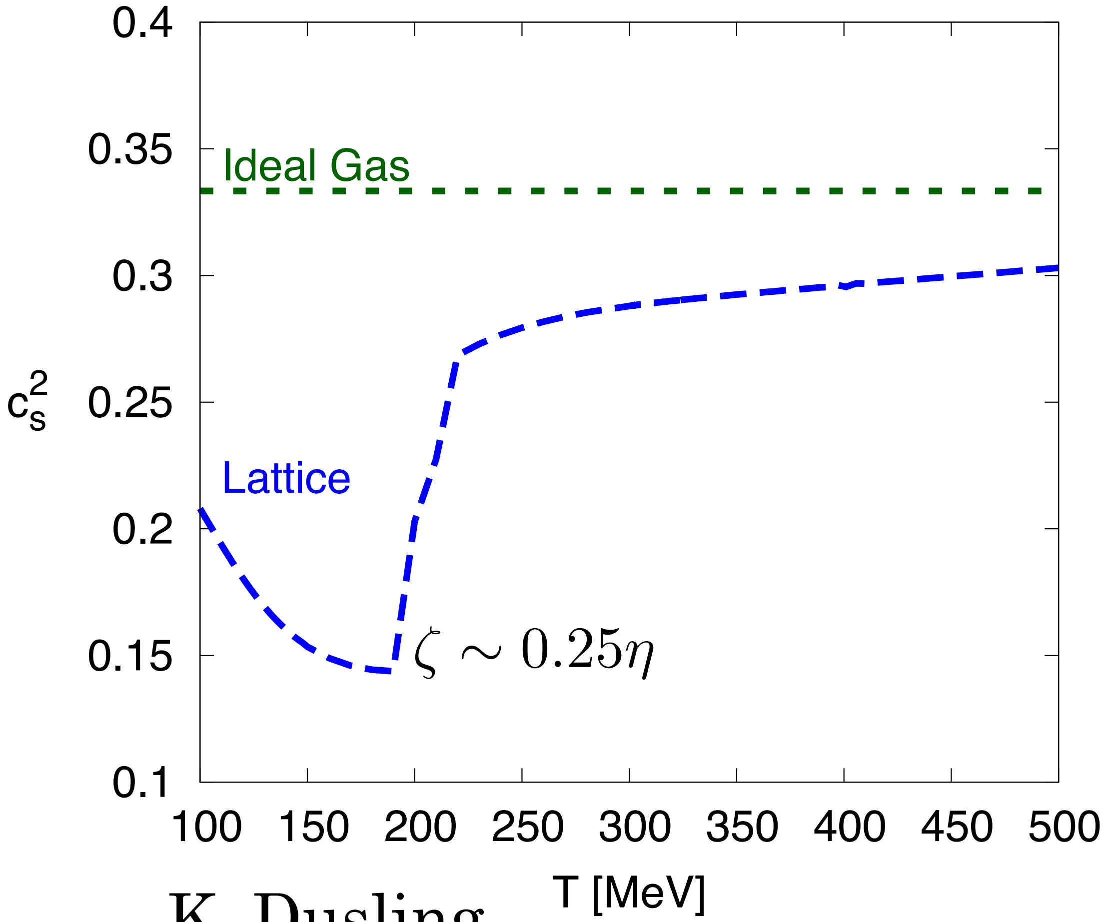
$$\zeta \approx 15\eta\left(\frac{1}{3}-c_s^2\right)^2$$ S. Weinberg, Ap. J (1971)

$$\zeta \gtrsim 2\eta\left(\frac{1}{3}-c_s^2\right)$$ A. Buchel, Phys. Lett. (2008)

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



Huovinen & Petreczky



K. Dusling

BULK VISCOSITY?

- Quantifies deviations from equilibrium, when the fluids expands or contracts more quickly than the time needed to relax back to equilibrium

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

$$\frac{\delta f}{f_0} \sim p_T^2\left(\frac{1}{3} - c_s^2\right)^2 (\partial_{\mu}u^{\mu})$$

Relaxation Time Approximation, Dusling & Schäfer (2012)

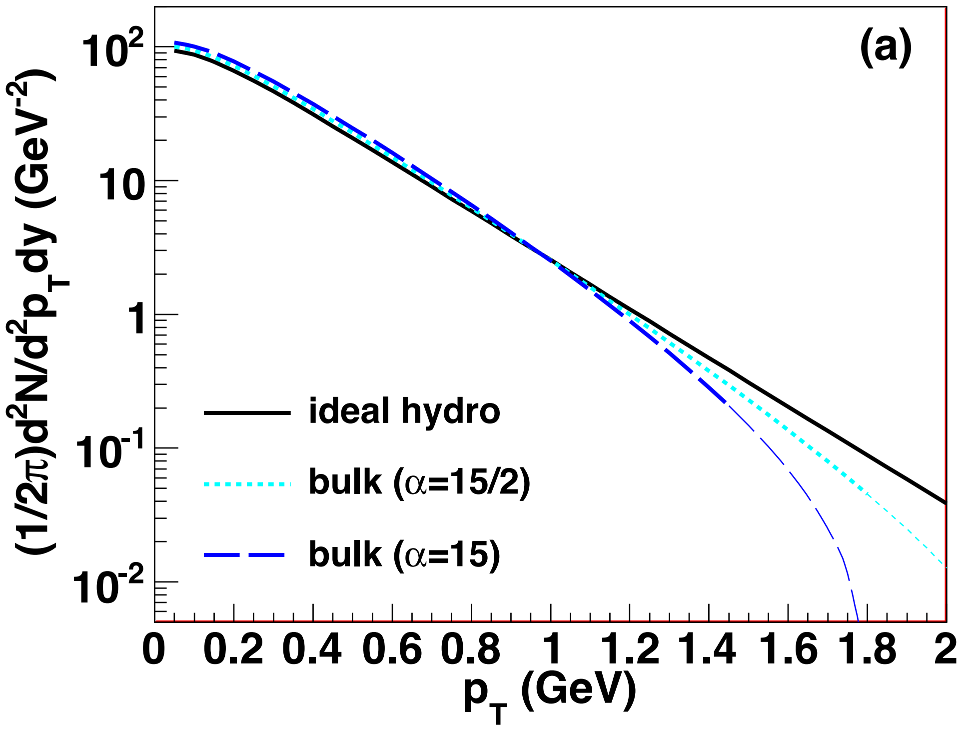
$$\frac{\delta f}{f_0} \sim \zeta\left(\partial_{\mu}u^{\mu}\right)\left[\alpha + \beta\, u\cdot k + \gamma\,(u\cdot k)^2\right]$$

Modified Moment Expansion Noronha-Hostler, Denicol, et al., (2013)

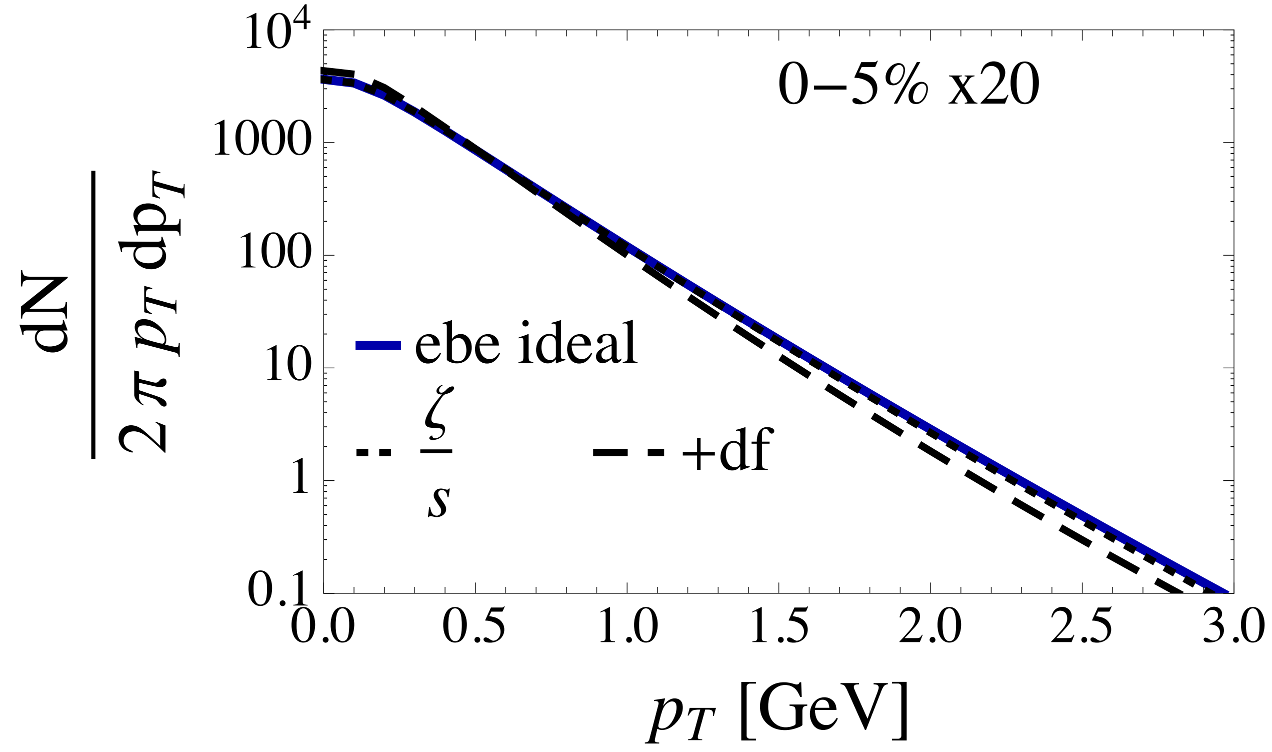
- Acts as a “negative pressure”

$$P \rightarrow P - \left|\Pi\right|$$

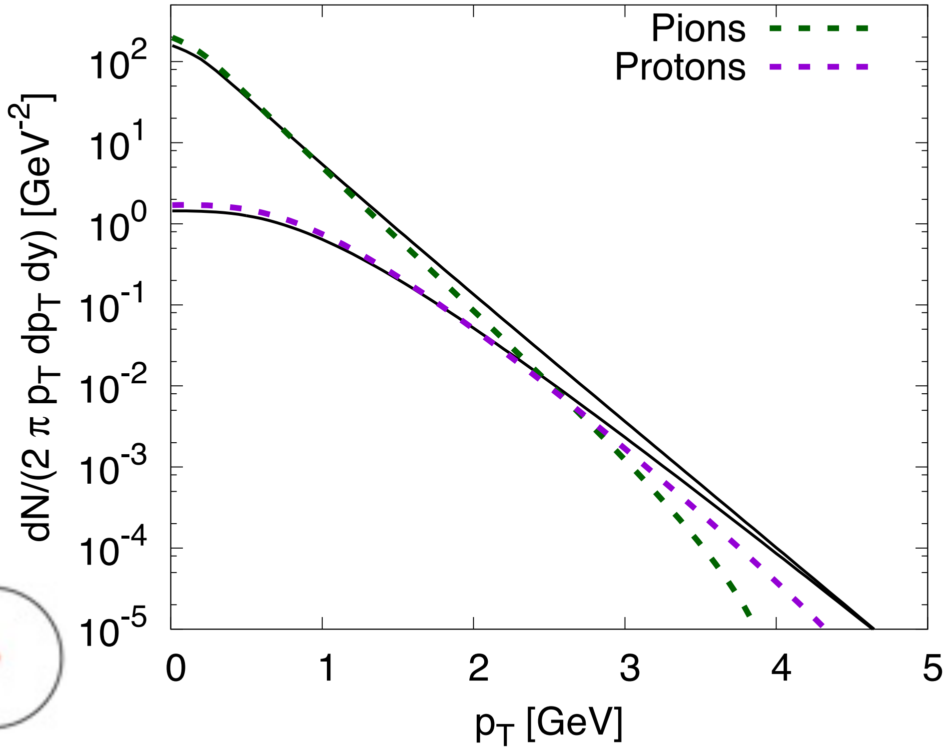
BULK VISCOSITY EFFECTS ON HADRON SPECTRA @ RHIC



Monnai and Hirano (2009)
3+1D Hydro



Noronha-Hostler, Denicol, Andrade, Grassi (2013), 2+1D Hydro

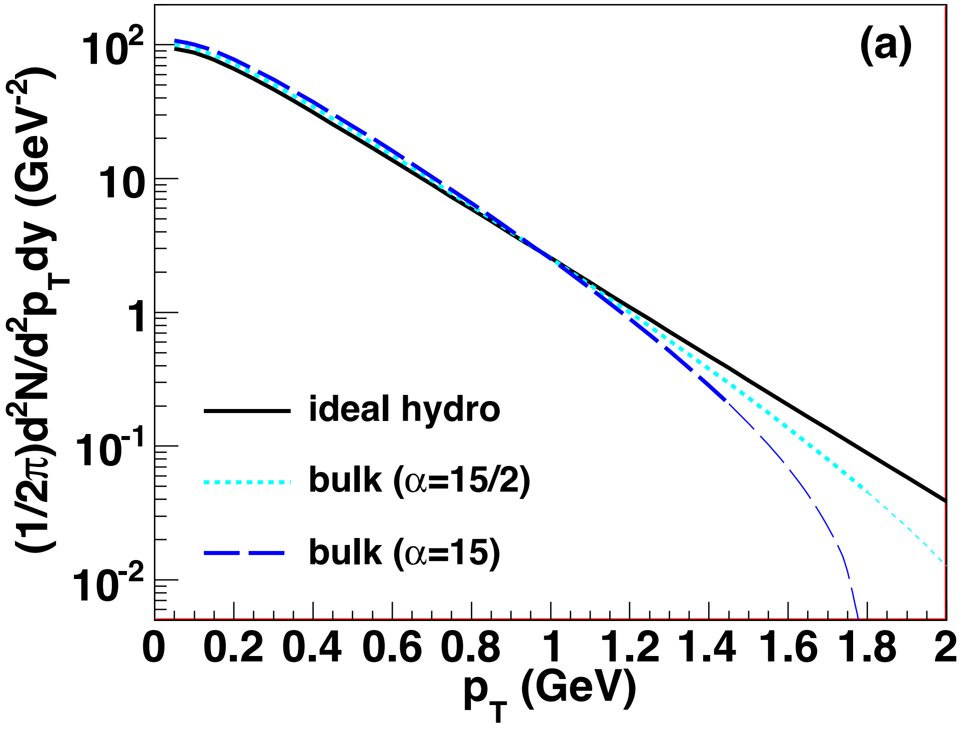


Dusling and Schäfer, (2012)
2+1D Hydro

— $\eta / s = 0.16$

__ $\eta / s = 0.16, \zeta / s = 0.005$

BULK VISCOSITY EFFECTS ON HADRON SPECTRA @ RHIC



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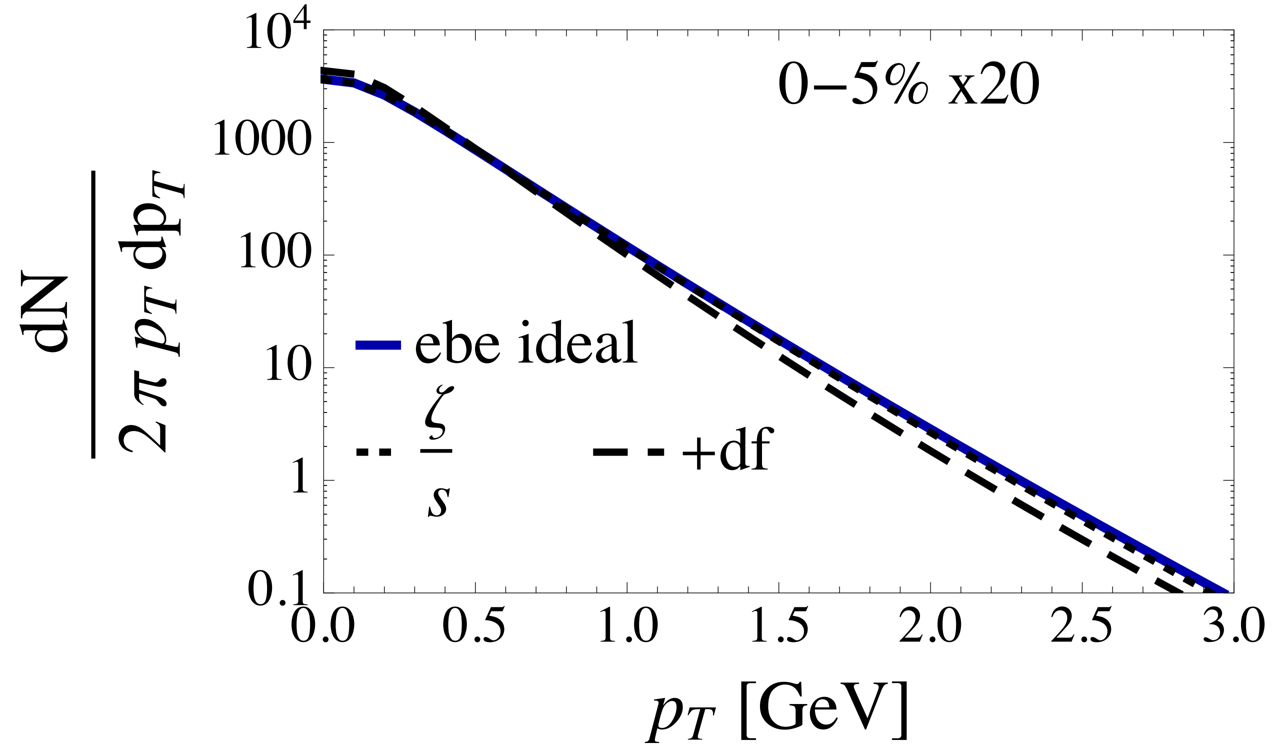
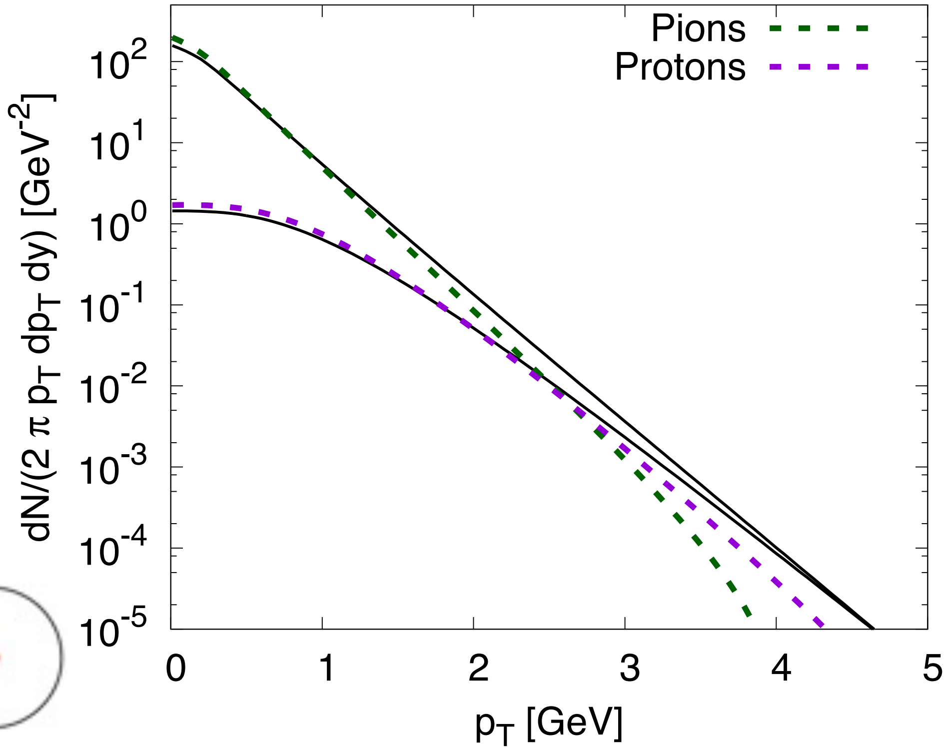


Noronha-Hostler, Denicol, Andrade, Grassi (2013), 2+1D Hydro



Dusling and Schäfer, (2012)
2+1D Hydro

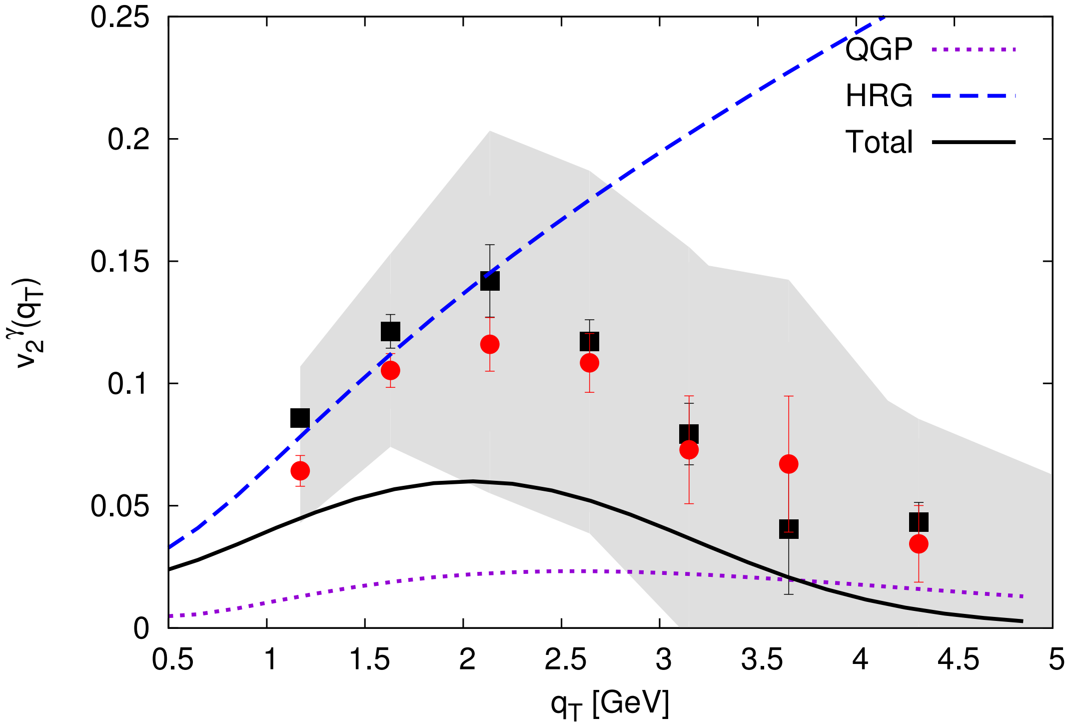
— $\eta/s = 0.16$

__ $\eta/s = 0.16, \zeta/s = 0.005$

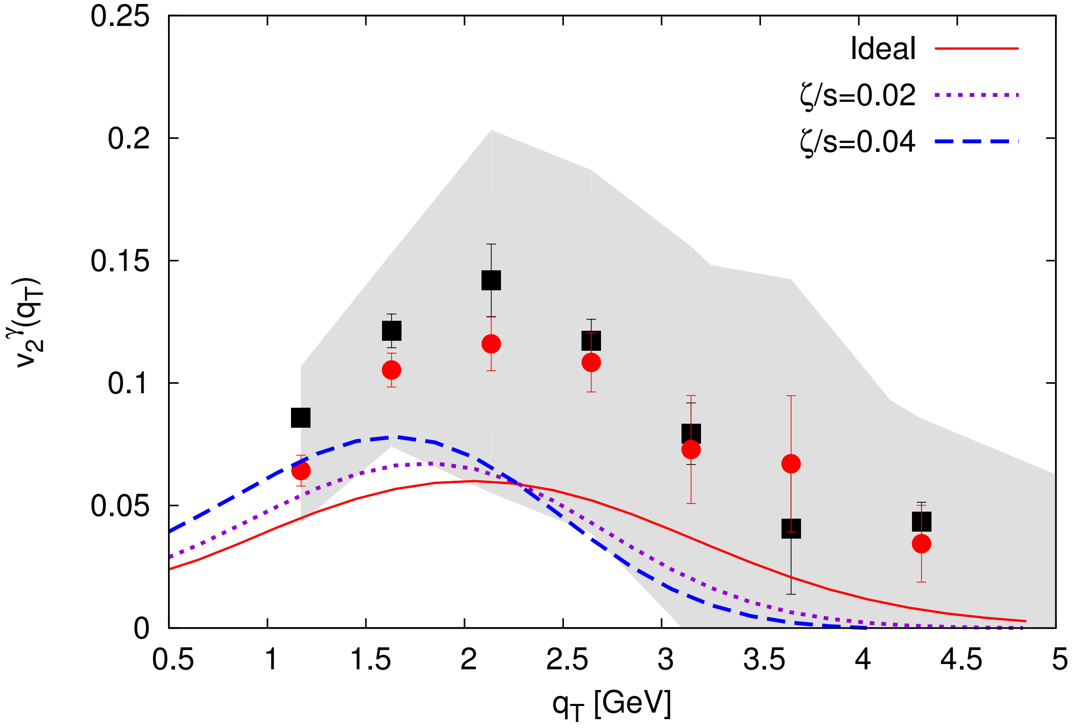
- Spectra are systematically softer
- Details depend on the scheme to implement the viscosity correction(s)
- Some cancellation between shear and bulk effects

BULK VISCOSITY EFFECTS ON PHOTONS?

Ideal photon $v_2(q_T)$



Viscous photon $v_2(q_T)$



K. Dusling

- Bulk viscosity seems to help, but perhaps not enough?
- Effects are however large enough: a <u>consistent</u> inclusion of bulk is warranted.
- $\frac{\zeta}{s}(T)$ etc...

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). Current v_2 data: new physics? Measuring photon $v_{3,}$ v_n at RHIC and LHC will help complete this picture
- FICs and viscosity(ies) make a difference in photon (and dilepton) characterization of the HICs: one must be consistent with hadronic data
- Jet-plasma photons need to be included: MARTINI
- Known unknowns: pre-equilibrium radiation

Thanks to

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