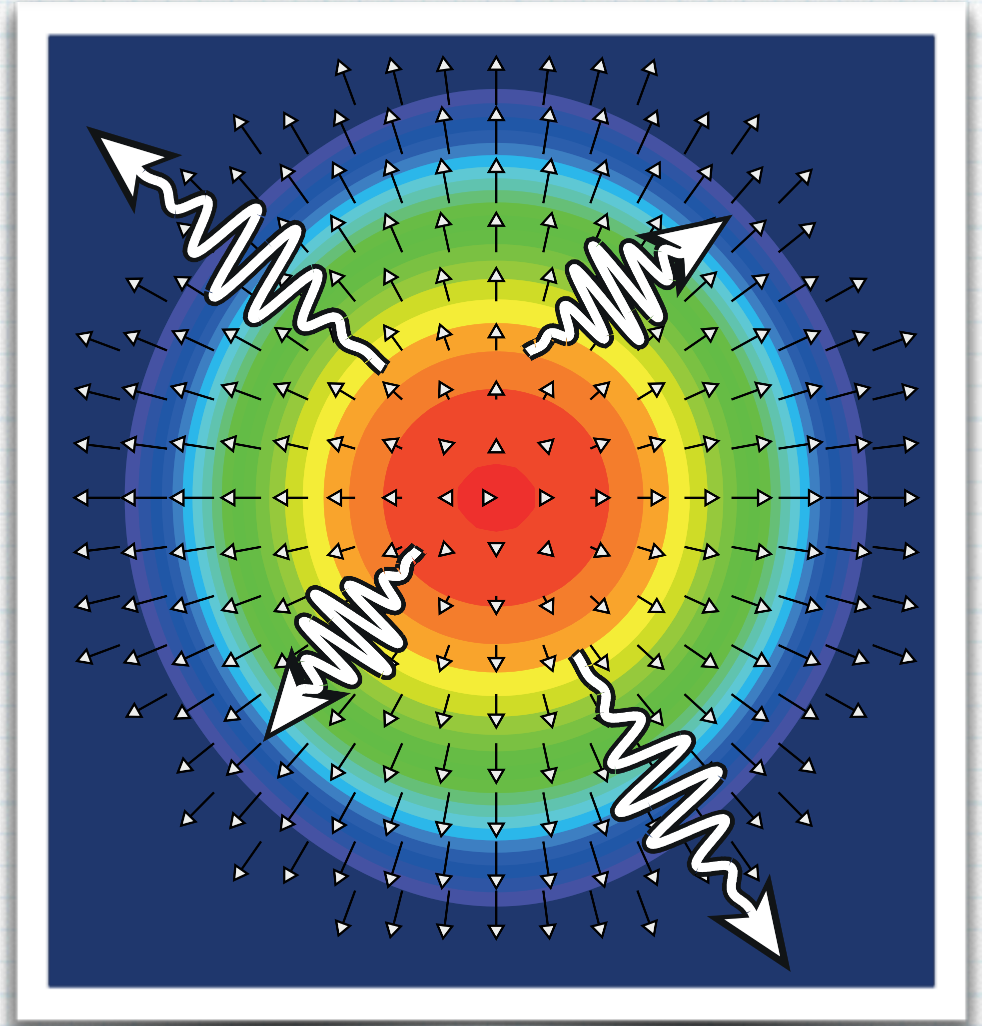
Photons and Dileptons in Relativistic Heavy-Ion Collisions: Light from the hydro



Charles Gale

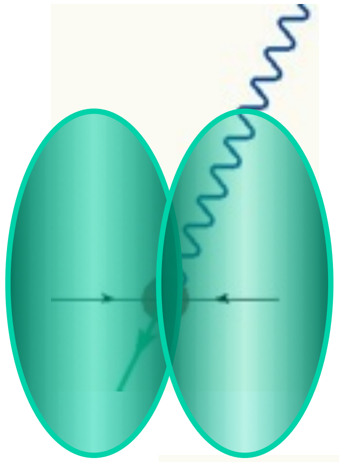
McGill University
FIAS

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

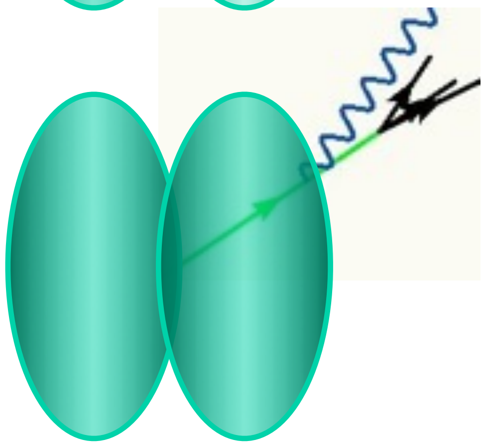
Why study photons and dileptons in relativistic nuclear collisions?

- 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

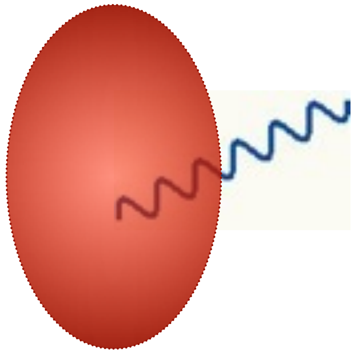
Sources of photons in a relativistic nuclear collision:



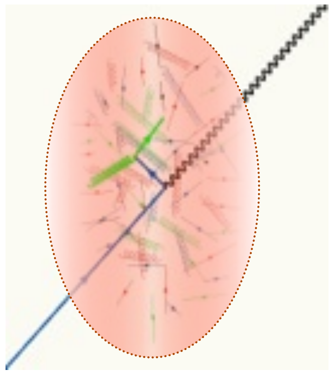
Hard direct photons. pQCD with shadowing
Non-thermal



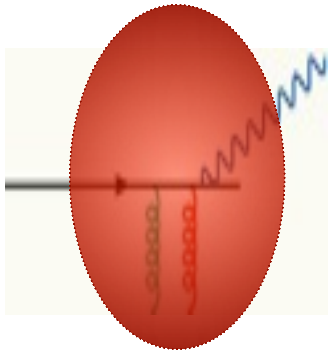
Fragmentation photons. pQCD with shadowing
Non-thermal



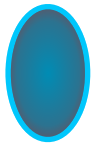
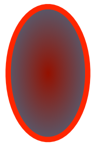
Thermal photons
Thermal



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:

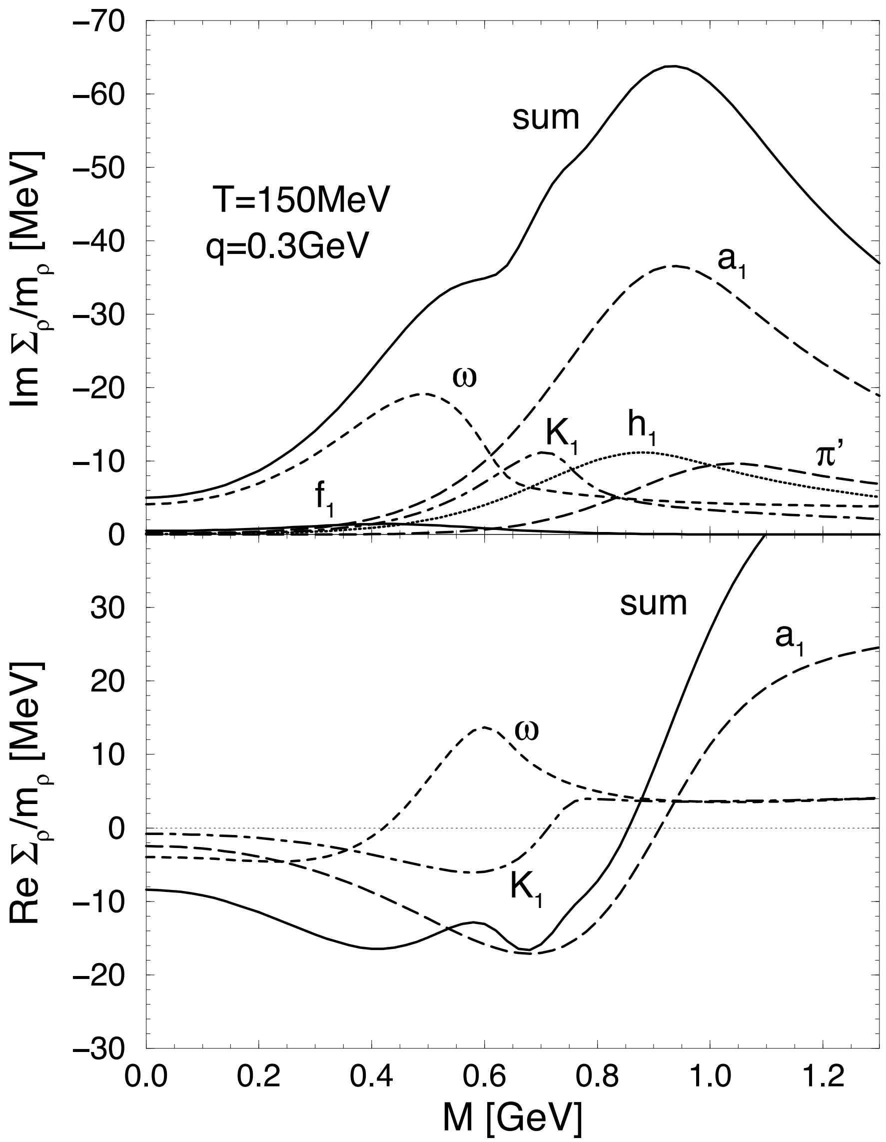
$$\omega \frac{d^3R}{d^3k} = -\frac{g^{\mu\nu}}{(2\pi)^3}\,\mathrm{Im}\Pi^R_{\mu\nu}(\omega,k)\frac{1}{e^{\beta\omega}-1} \qquad \text{(photons)}$$

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

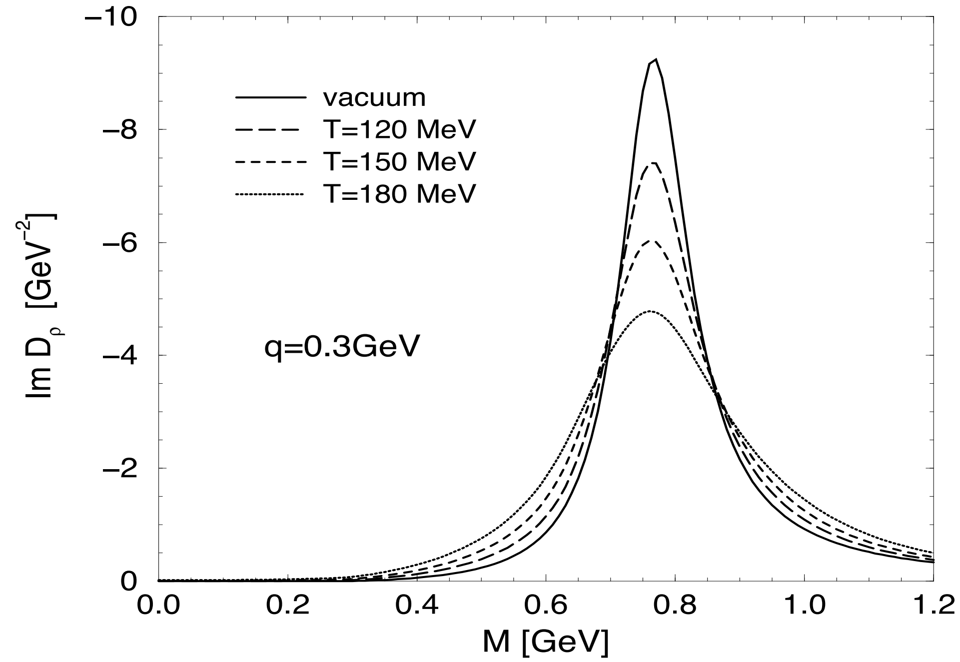
Feinberg (76), McLerran, Toimela (85)
Weldon (90), Gale, Kapusta (91)

For dileptons:

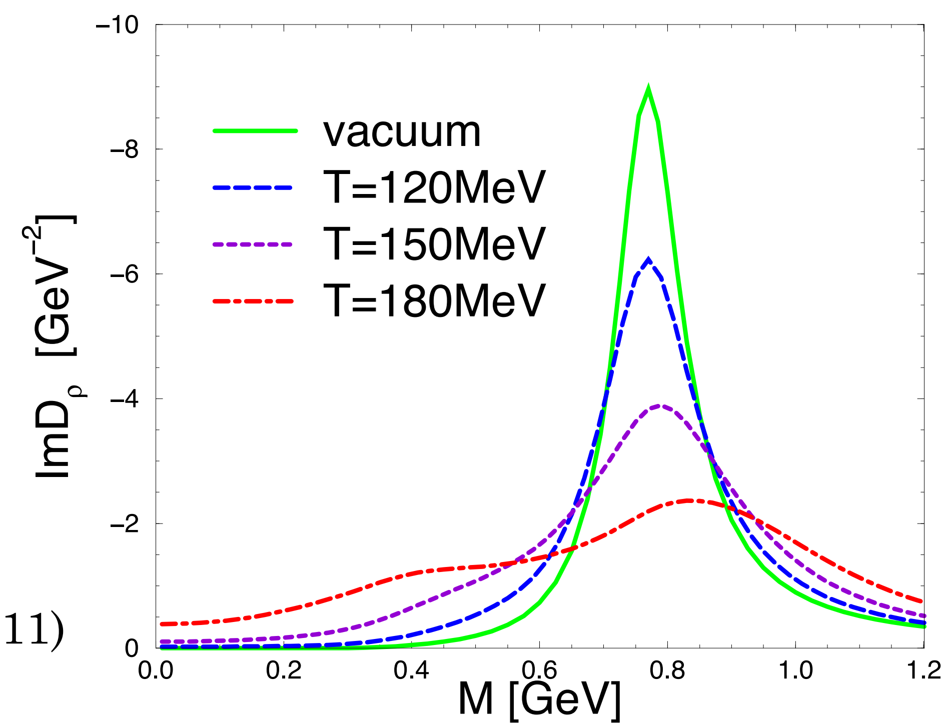
$$\mathrm{Im} < J_\mu J_\nu >_T \overset{\text{VMD}}{\Rightarrow} \mathrm{Im} < \rho_\mu \rho_\nu >_T \Rightarrow \mathrm{Im}\, D^T_{\mu\nu} \Rightarrow \text{Vector spectral density}$$



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

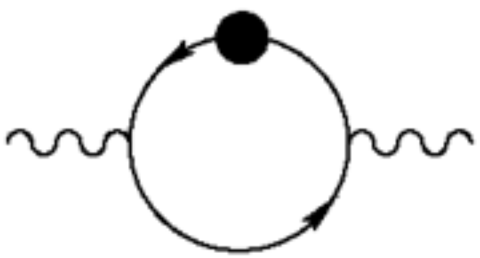


Rapp and Gale, PRC (1999)



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

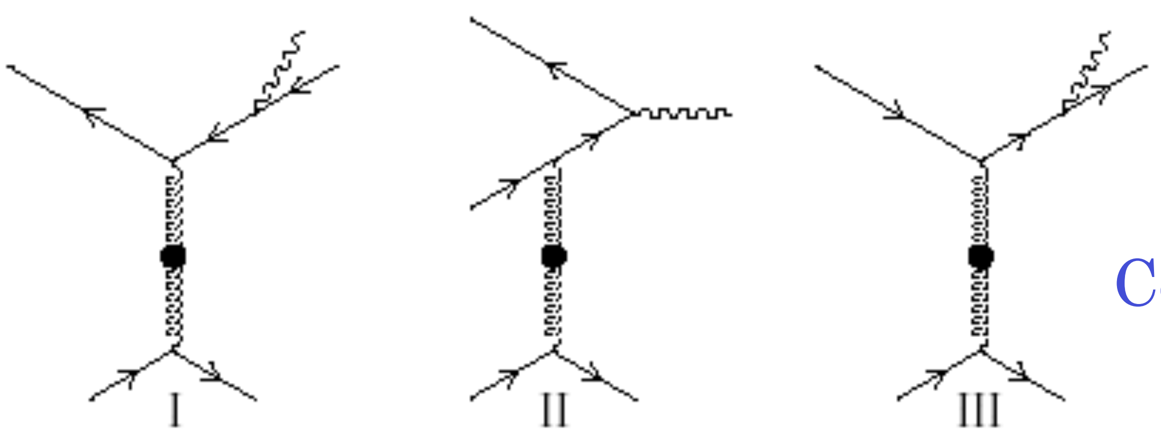
Thermal Photons from hot QCD: HTL program (Klimov (1981), Weldon (1982), Braaten & Pisarski (1990); Frenkel & Taylor (1990))



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

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 $O(\alpha_s)$

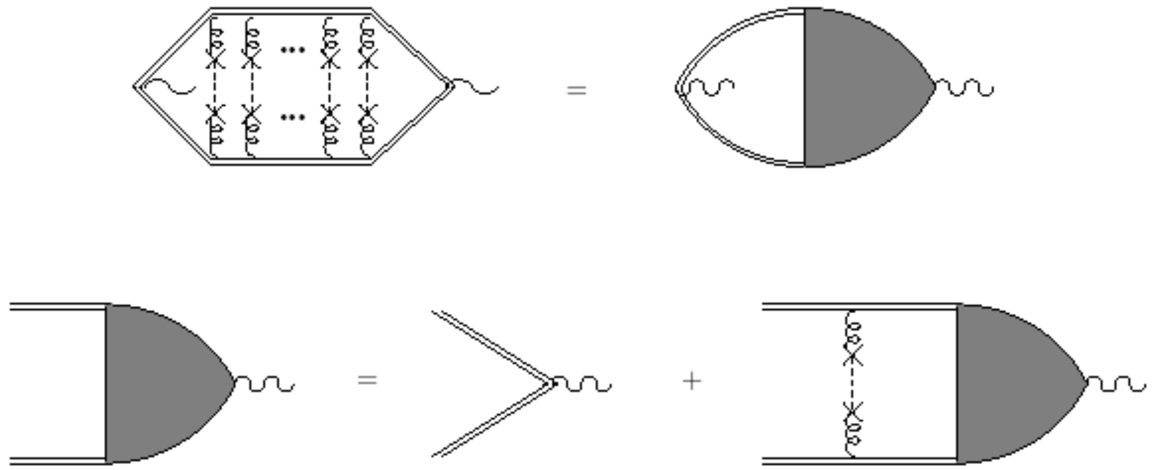
Arnold, Moore, and Yaffe JHEP **12**, 009 (2001); JHEP **11**, 057 (2001)
Incorporate LPM; Inclusive treatment of collinear enhancement, photon and gluon emission

Going beyond LO AMY rates?

- Approach is LO, but

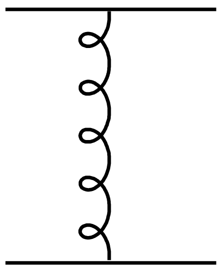
$$\alpha_s \sim 0.2 - 0.3$$

- 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:

$$gT \ll T$$

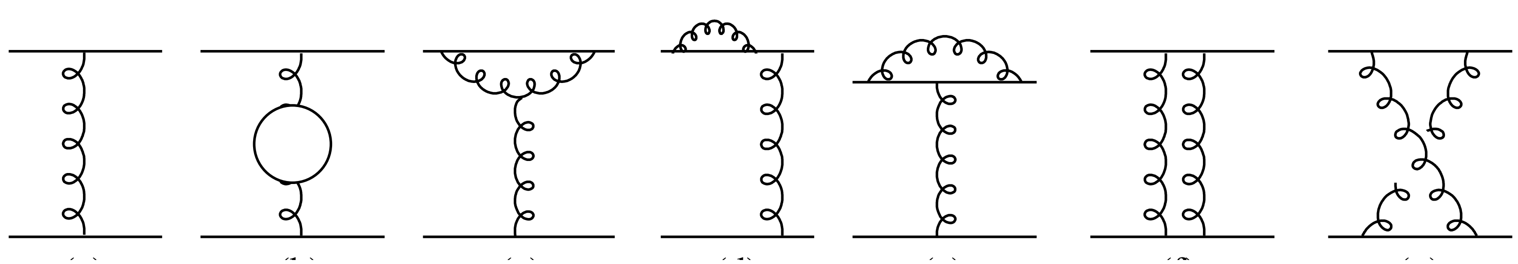
$$\text{soft} \ll \text{hard}$$

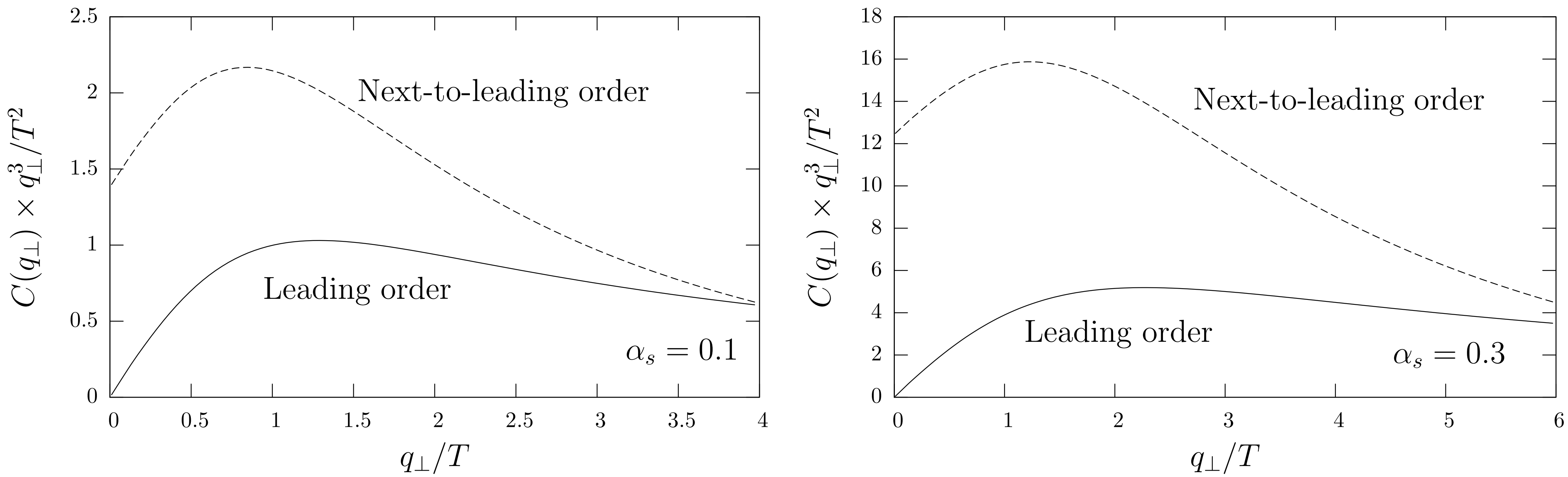
The LO-NLO scattering kernel(s)

Clue that NLO effects might be important: Heavy quark diffusion

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

Simon Caron-Huot PRD (2009)



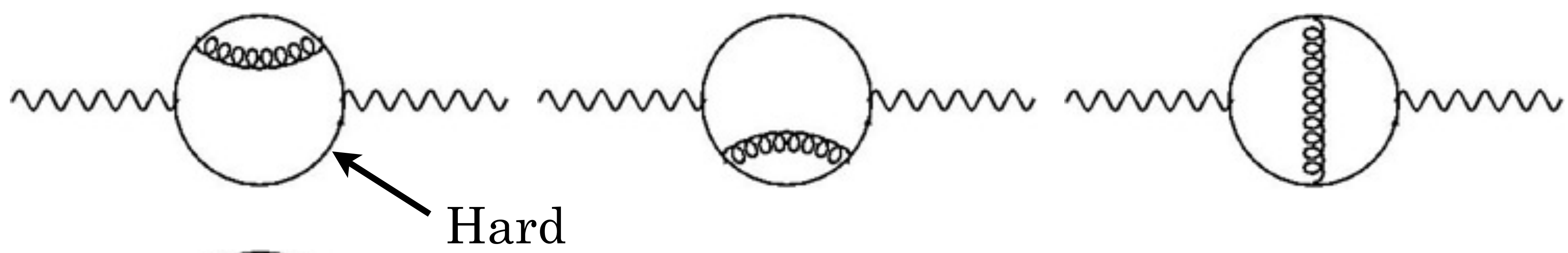


Possible large effects on photon production!?

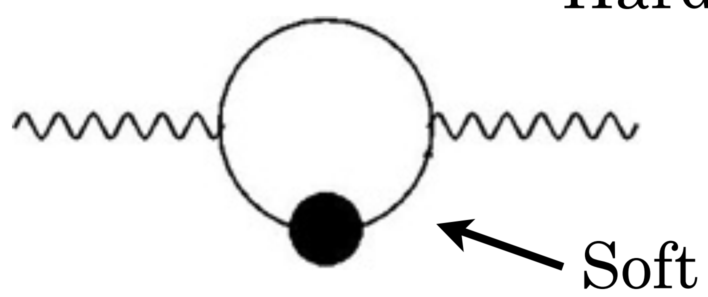
Photon emission at LO

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

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

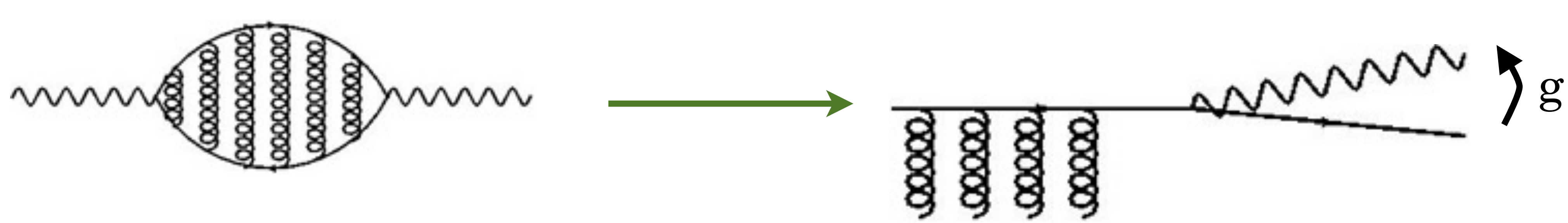


$$\left.\frac{d\Gamma_\gamma}{d^3k}\right|_{\mathrm{soft}} \rightarrow$$



(Conversion)

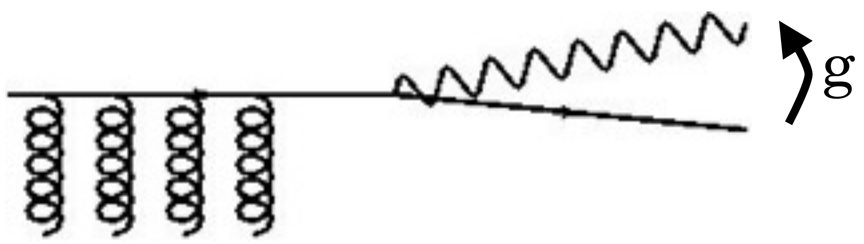
$$\left.\frac{d\Gamma_\gamma}{d^3k}\right|_{\mathrm{coll}} \rightarrow$$



The LO-NLO scattering kernels

Ghiglieri, Hong, et al., JHEP (2013)

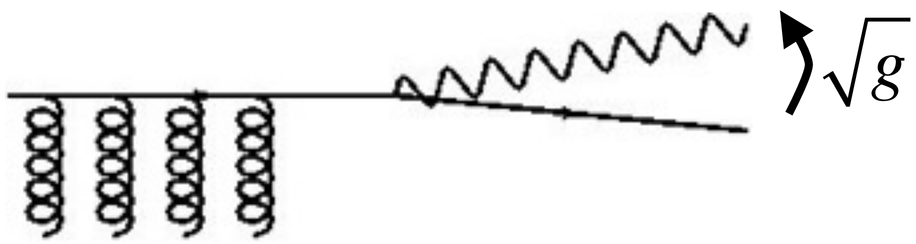
The two main contributions:



$$C(q_\perp)_{\rm LO} = g^2 T C_R \frac{m_D^2}{q_\perp^2\left(q_\perp^2 + m_D^2\right)} \Rightarrow \text{NLO}$$

Simon Caron-Huot PRD (2009)

Enhanced at NLO



Larger angle bremmstrahlung

Suppressed at NLO

The LO-NLO scattering kernels

Ghiglieri, Hong, et al., JHEP (2013)

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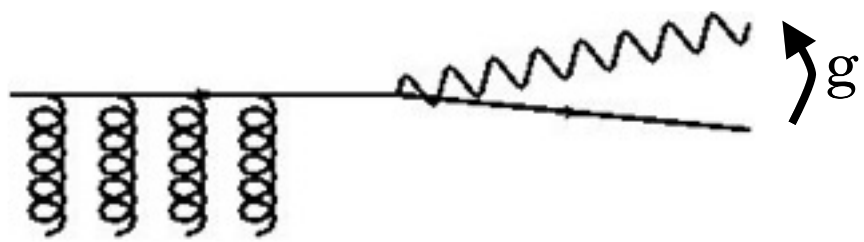

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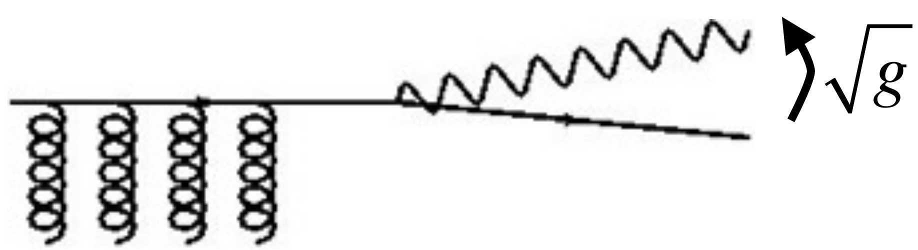

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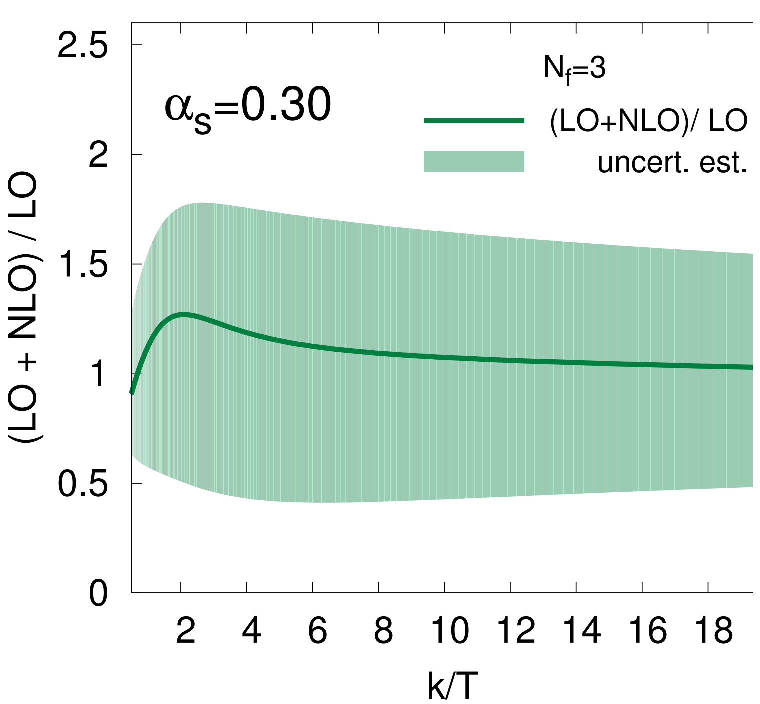
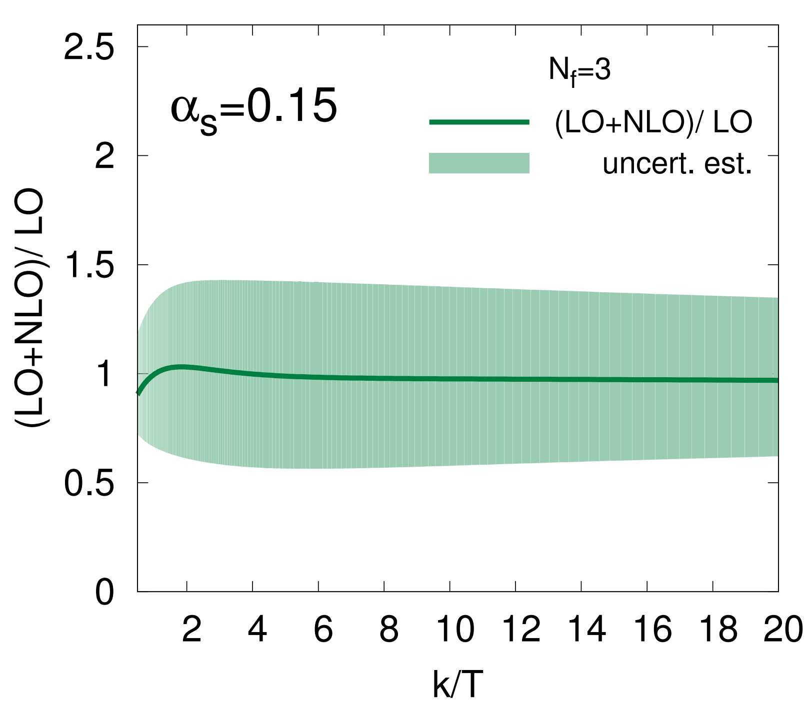




- Net correction to photon production rate is modest up to high k/T
- Techniques developed here have many more applications in FTFT
- Perturbative

Electromagnetic radiation from hadrons

Chiral, Massive Yang-Mills:

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

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

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

+ non-minimal terms

Parameters and form factors are constrained by hadronic phenomenology:

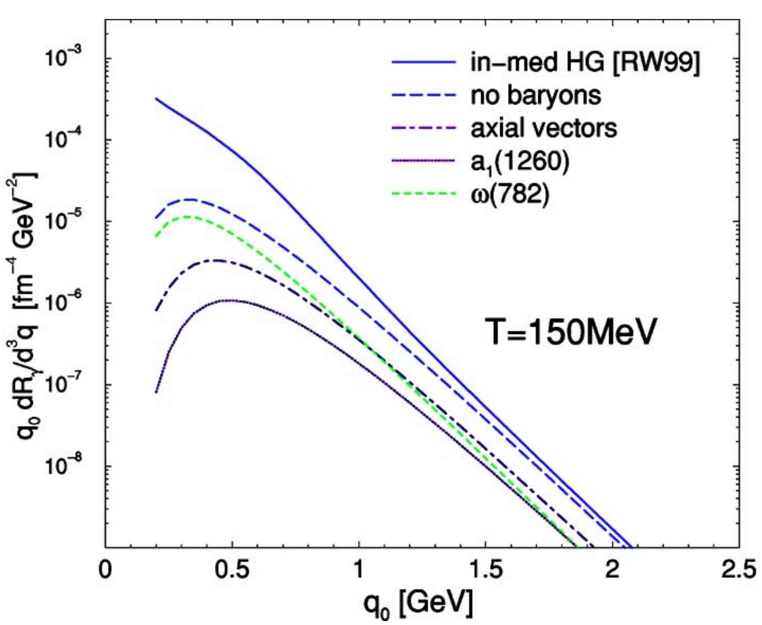
- Masses & strong decay widths
- Electromagnetic decay widths
- Other hadronic observables:
  - *e.g.* $a_1 \to \pi\rho \quad D/S$ (See also, Lichard and Vojik, Nucl. Phys. (2010); Lichard and Juran, PRD (2008))

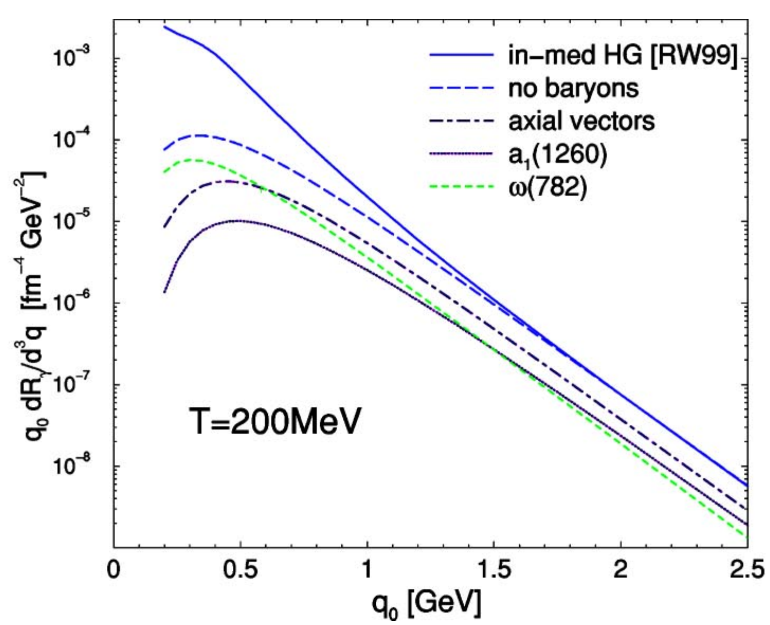
EM emissivities computed: Turbide, Rapp, Gale, PRC (2004); Turbide, McGill PhD (2006)

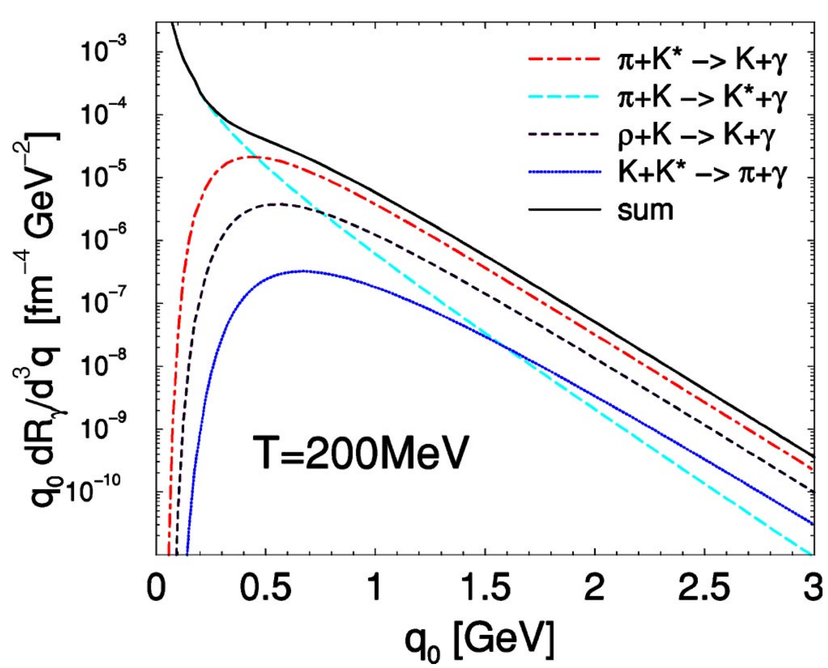
Electromagnetic radiation from hadrons

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

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

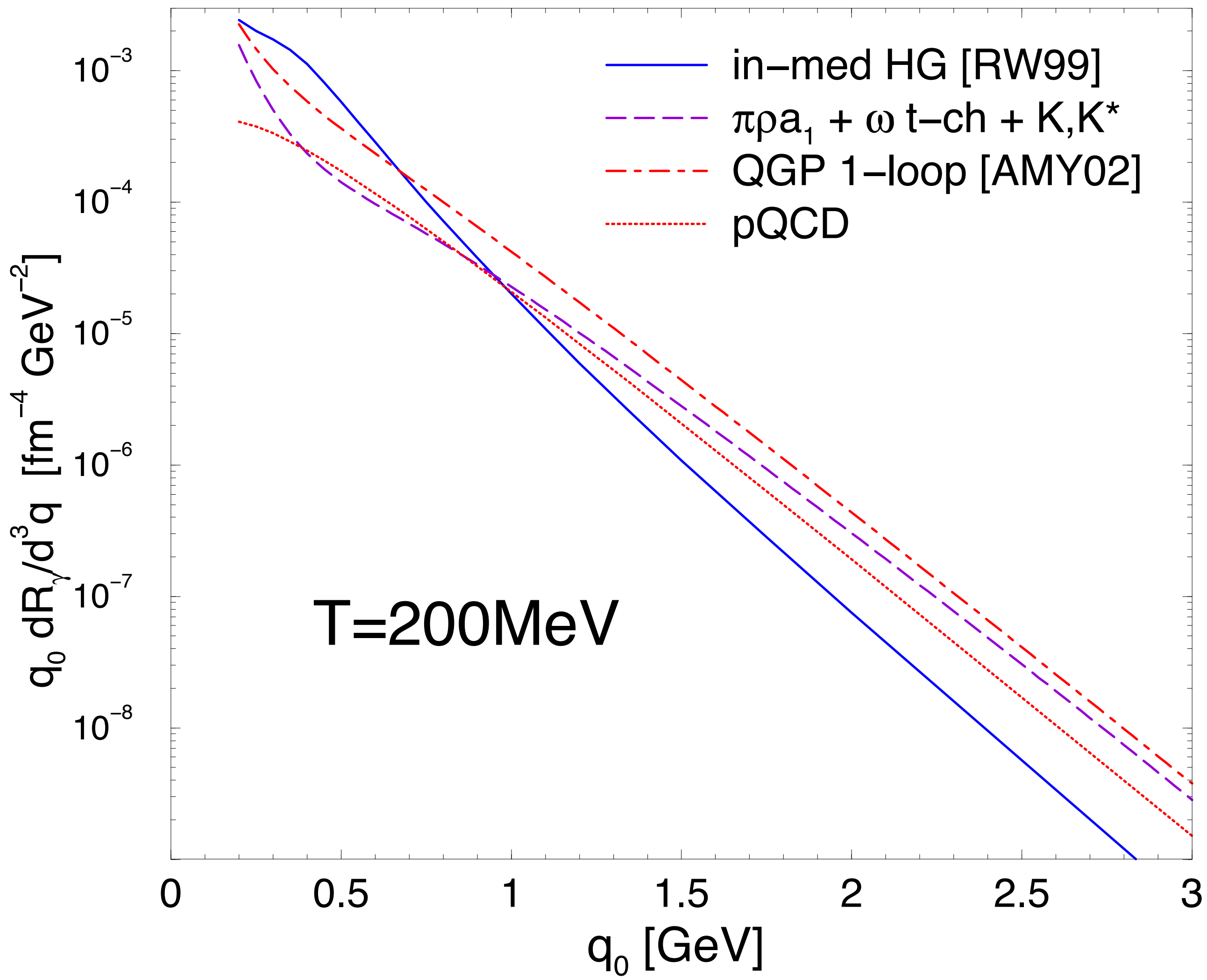






Turbide, Rapp, and Gale, PRC (2004)

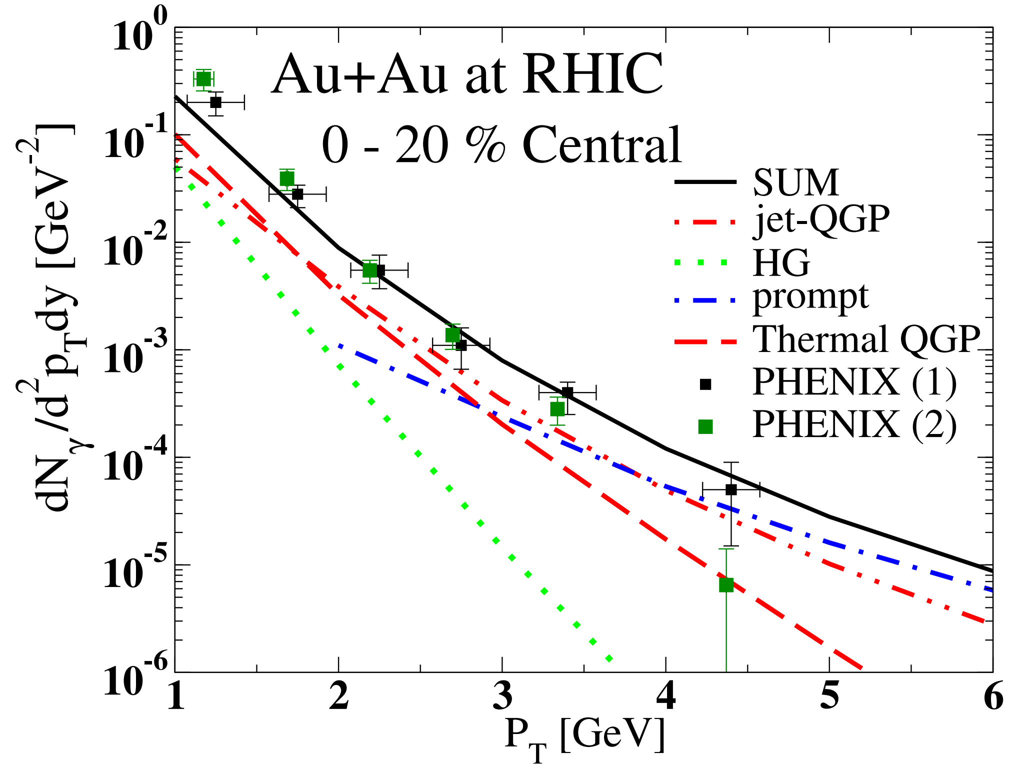
COMPARING RATES



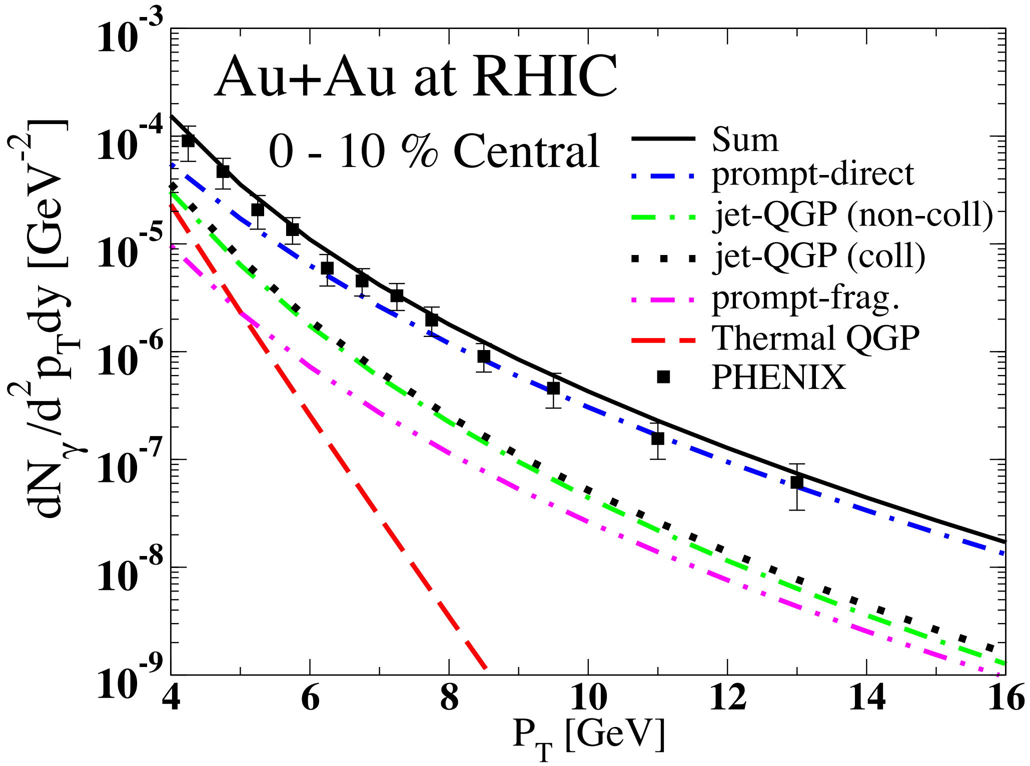
Integrate rates with hydro evolution

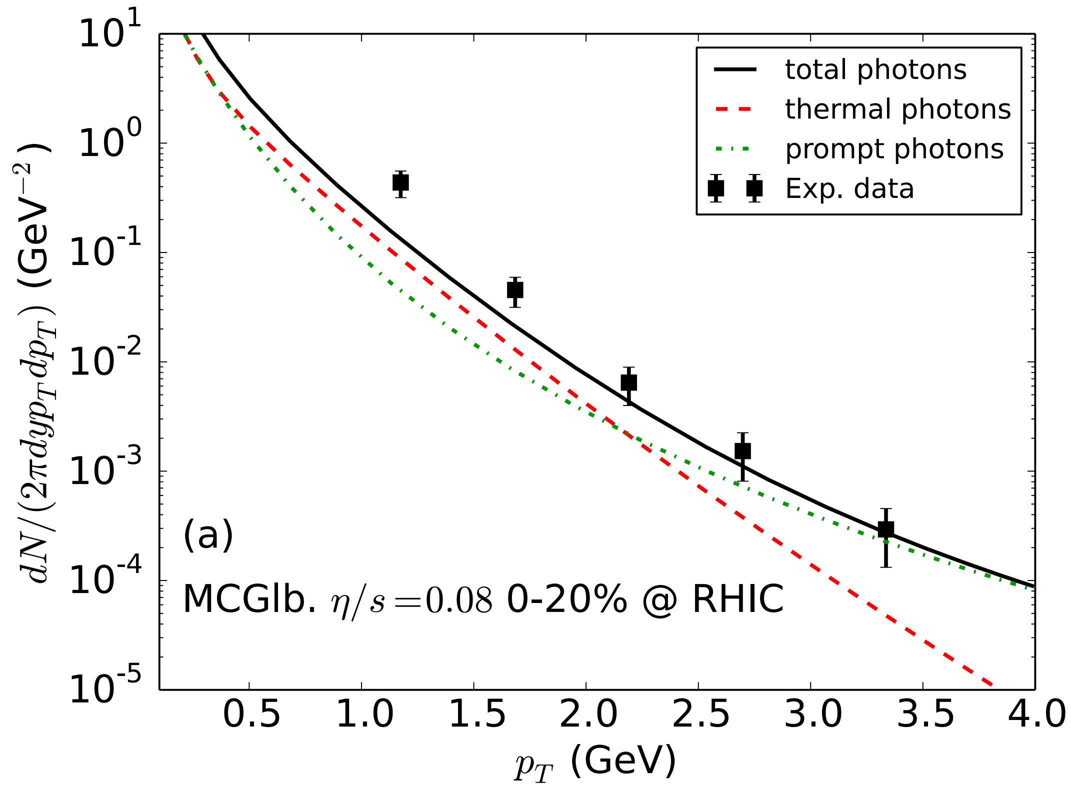
Turbide, Rapp, and Gale, PRC (2004)

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-QPG contributions at mid-p_T?

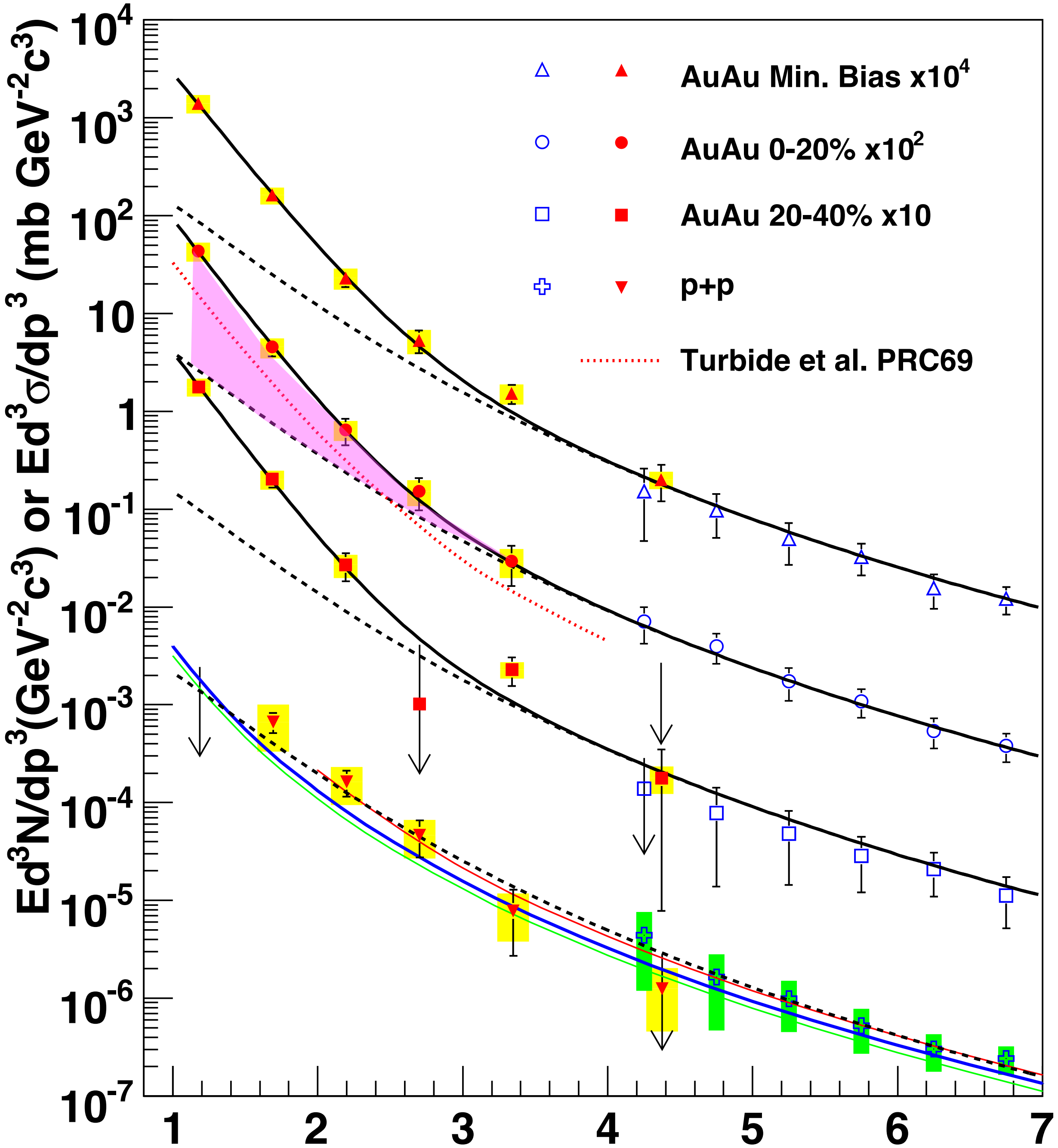




Turbide, Gale, Frodermann, Heinz, PRC (2008);
Higher p_T: G. Qin et al., PRC (2009)

Shen, Heinz, Paquet, Gale, PRC (2014)

One of the uses of photons: Characterizing the hot matter created at RHIC



PHENIX, PRL 104 (2010)

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

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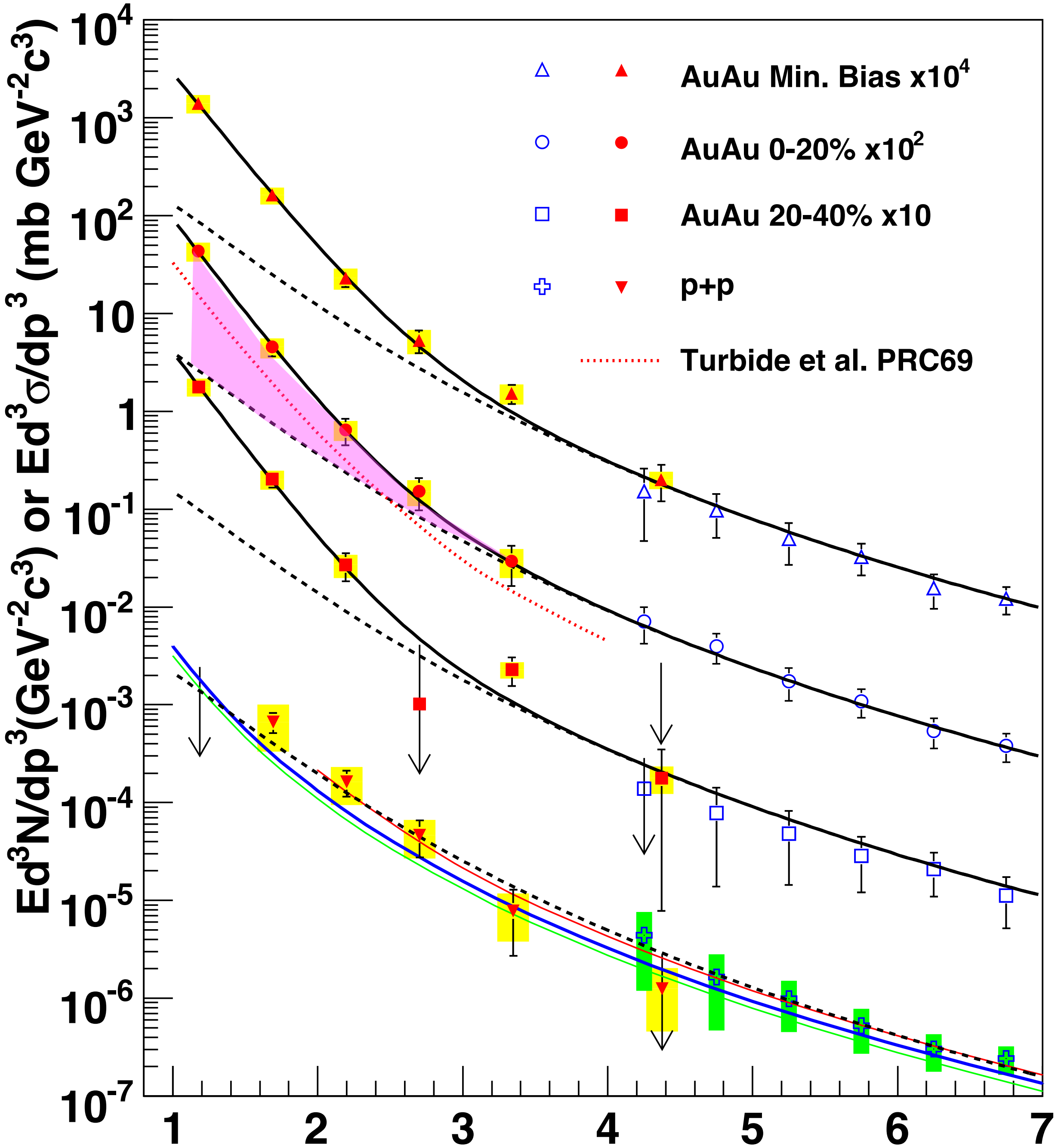


PHENIX, PRL 104 (2010)

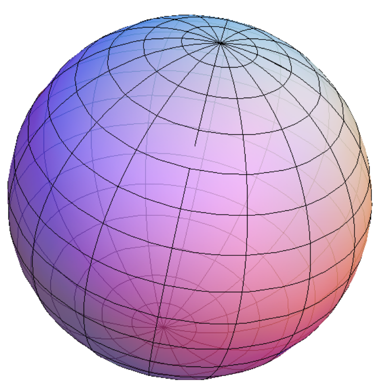
$$T_{\text{excess}} = 221 \pm 19 \pm 19\,\text{MeV}$$

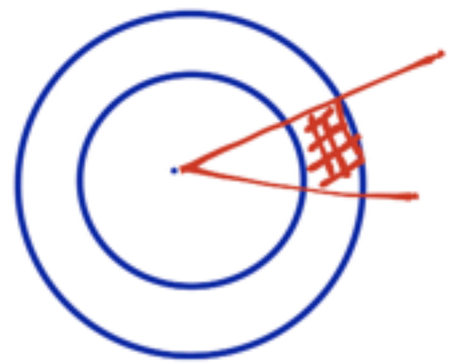
Flow effects will be important

- van Hees, Gale Rapp,PRC (2011)
- Shen, Heinz, Paquet, Gale, PRC (2014)

Thermal Photons as a thermometer

Suppose a static source at temperature T:



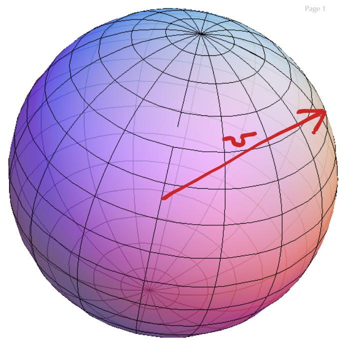


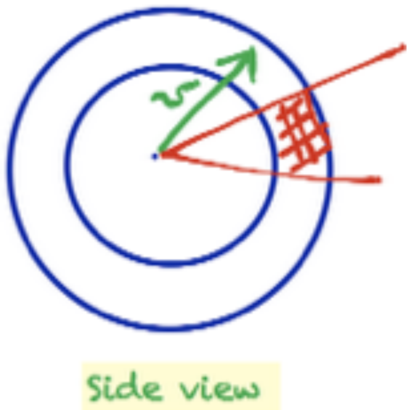
Side view

$$E\frac{d^3n}{d^3p} = E\,e^{-\beta E}$$

Read off the temperature from the exponent

Suppose an expanding source at local temperature T:





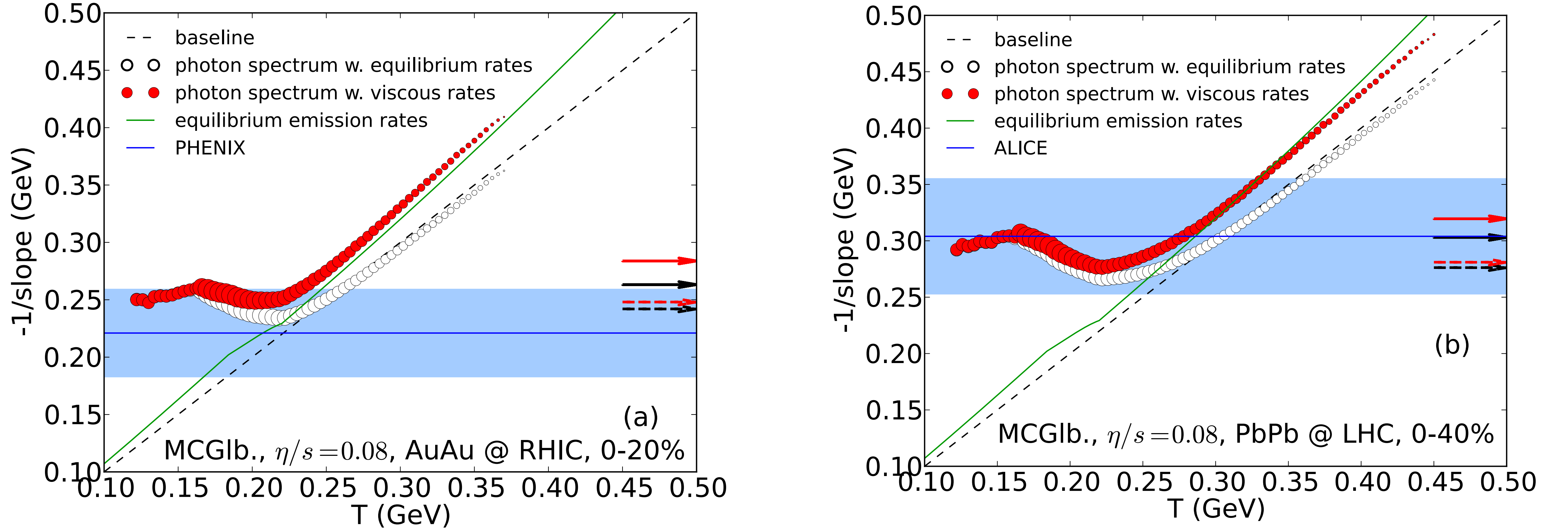
$$E\frac{d^3n}{d^3p} \approx E\, e^{-\beta\gamma E + \beta\gamma v E}$$

$$\boxed{T_e = \sqrt{\frac{1+v}{1-v}}\, T}$$

Doppler shift

The effective temperature (deduced from the slope) is not the true temperature

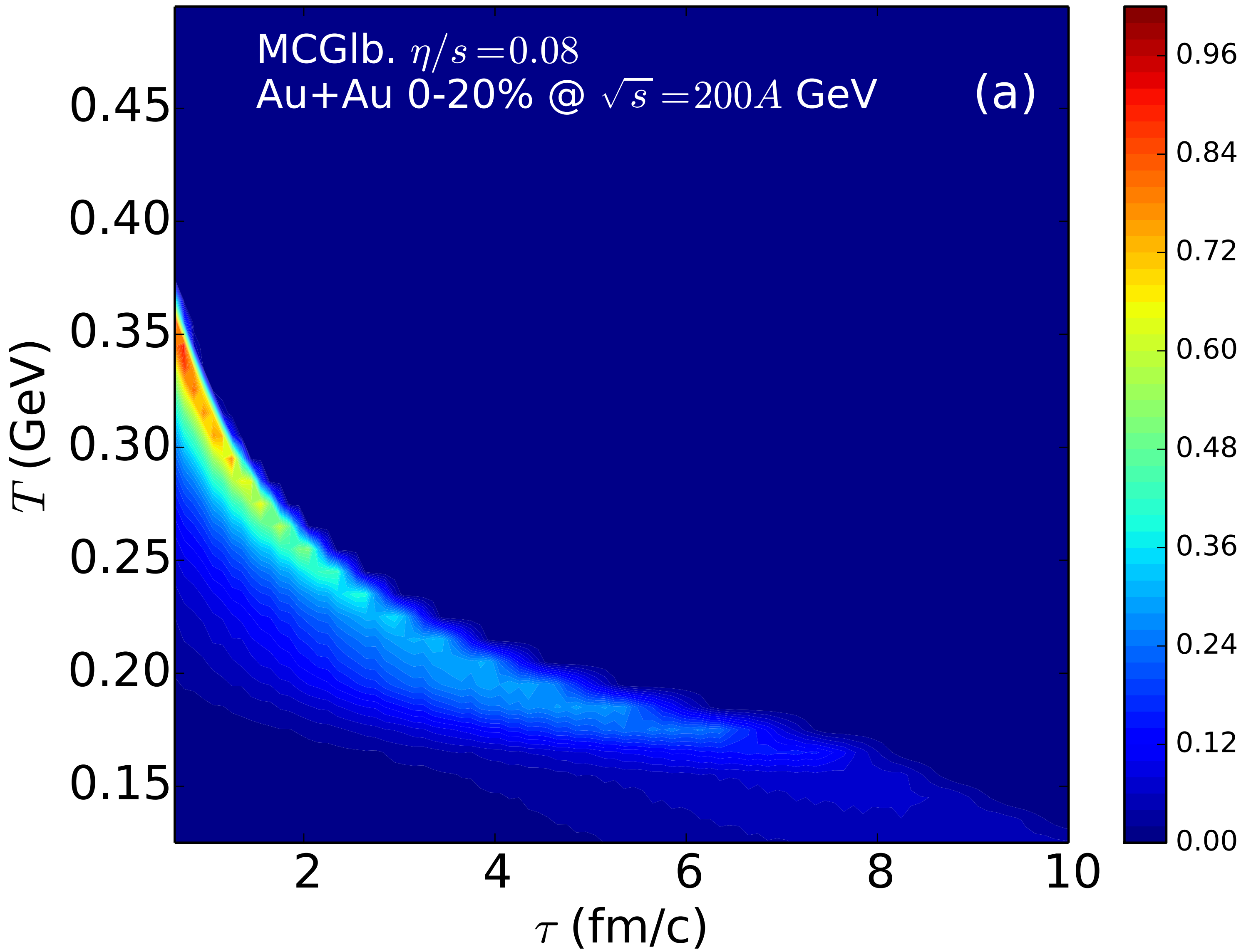
Using a hydro simulation



Shen, Heinz, Paquet, Gale, PRC (2014)
van Hees, Gale, Rapp, PRC (2011)

* The apparent temperature deviates from the true temperature: flow contamination
* The system does go through regions with $T \gg T_c$, but a model is needed to extract T

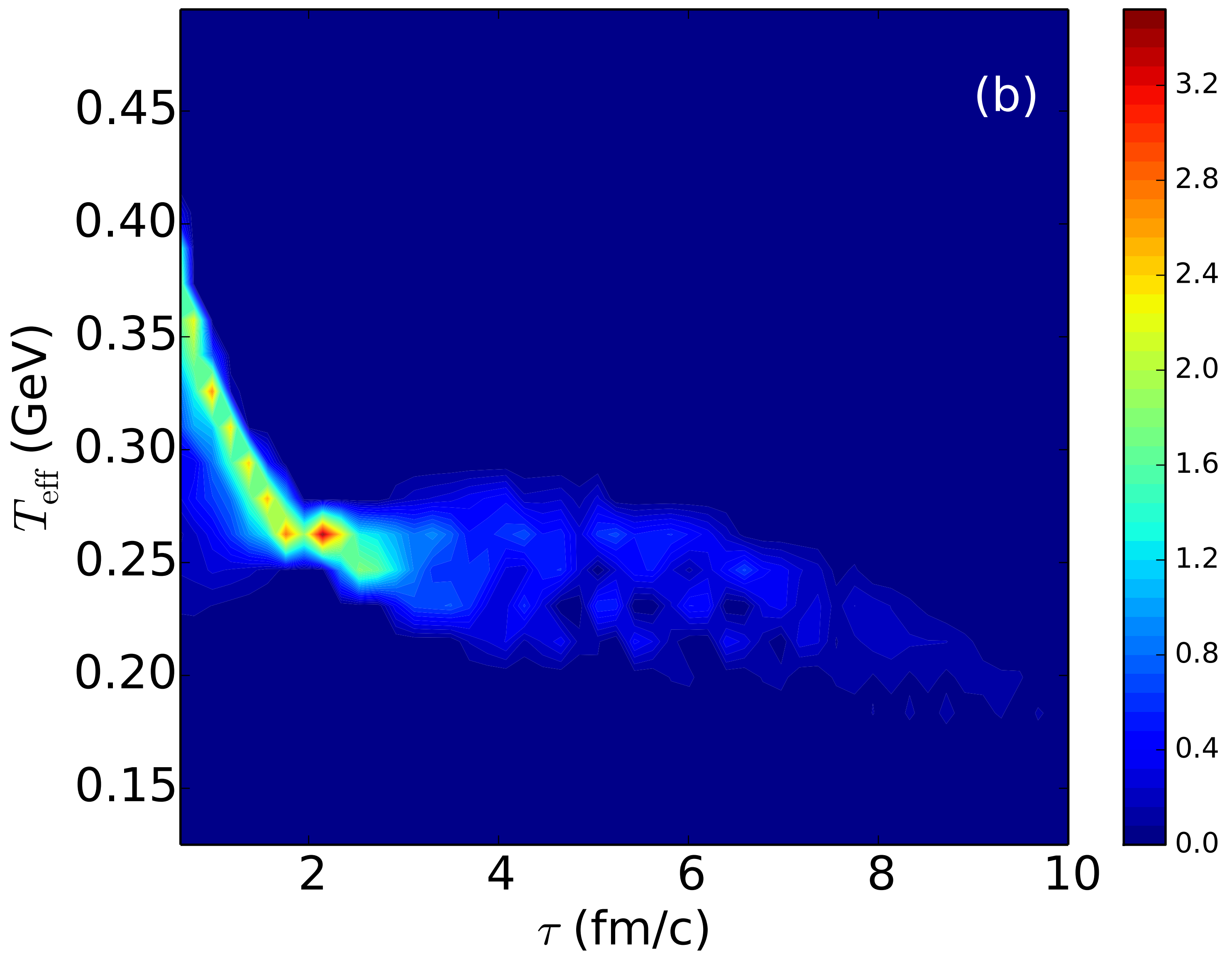
Studying the differential temperature distribution



RHIC

The 3rd dimension is $\dfrac{dN^{\gamma} / dydTd\tau}{dN^{\gamma} / dy}$

Studying the differential temperature distribution



RHIC

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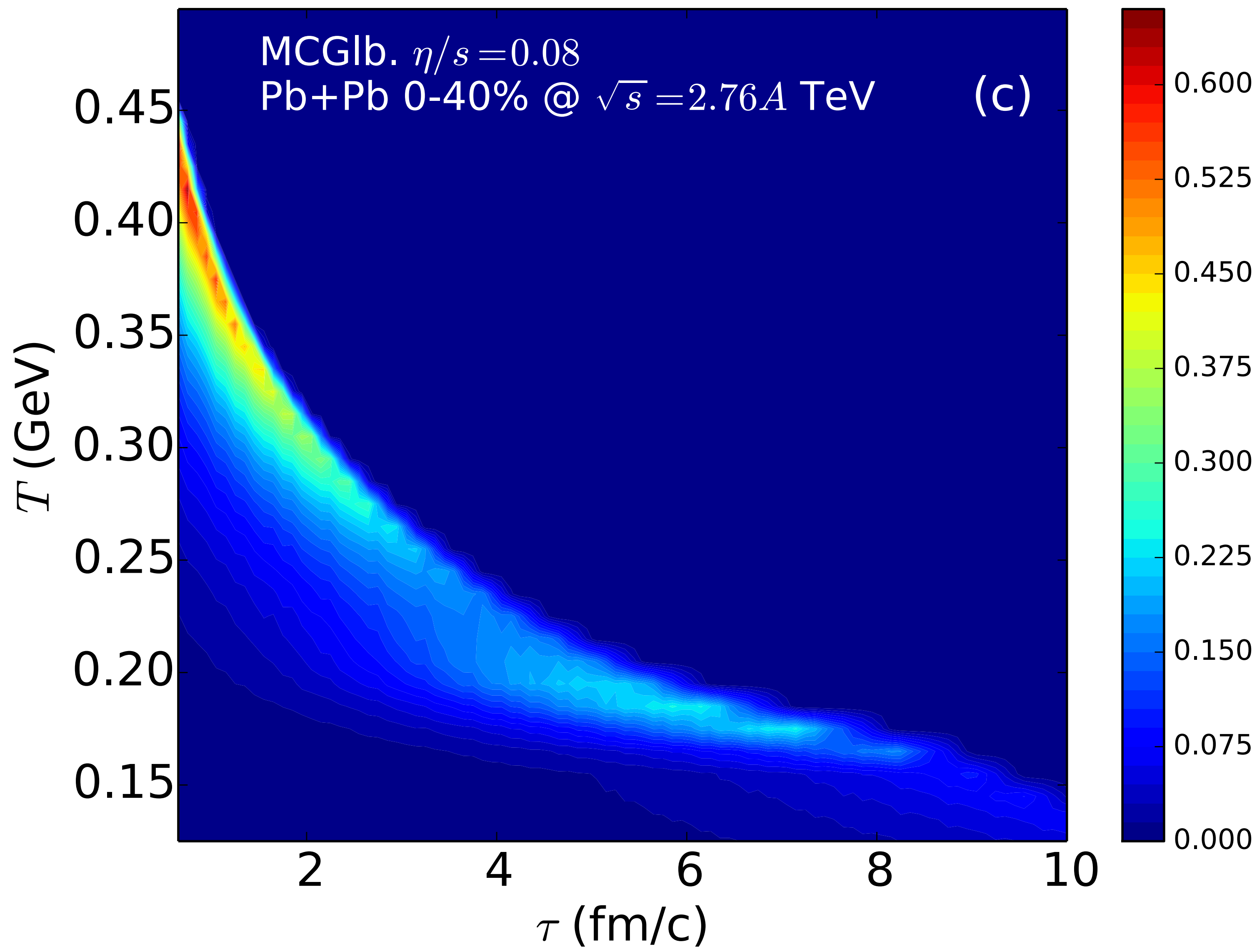
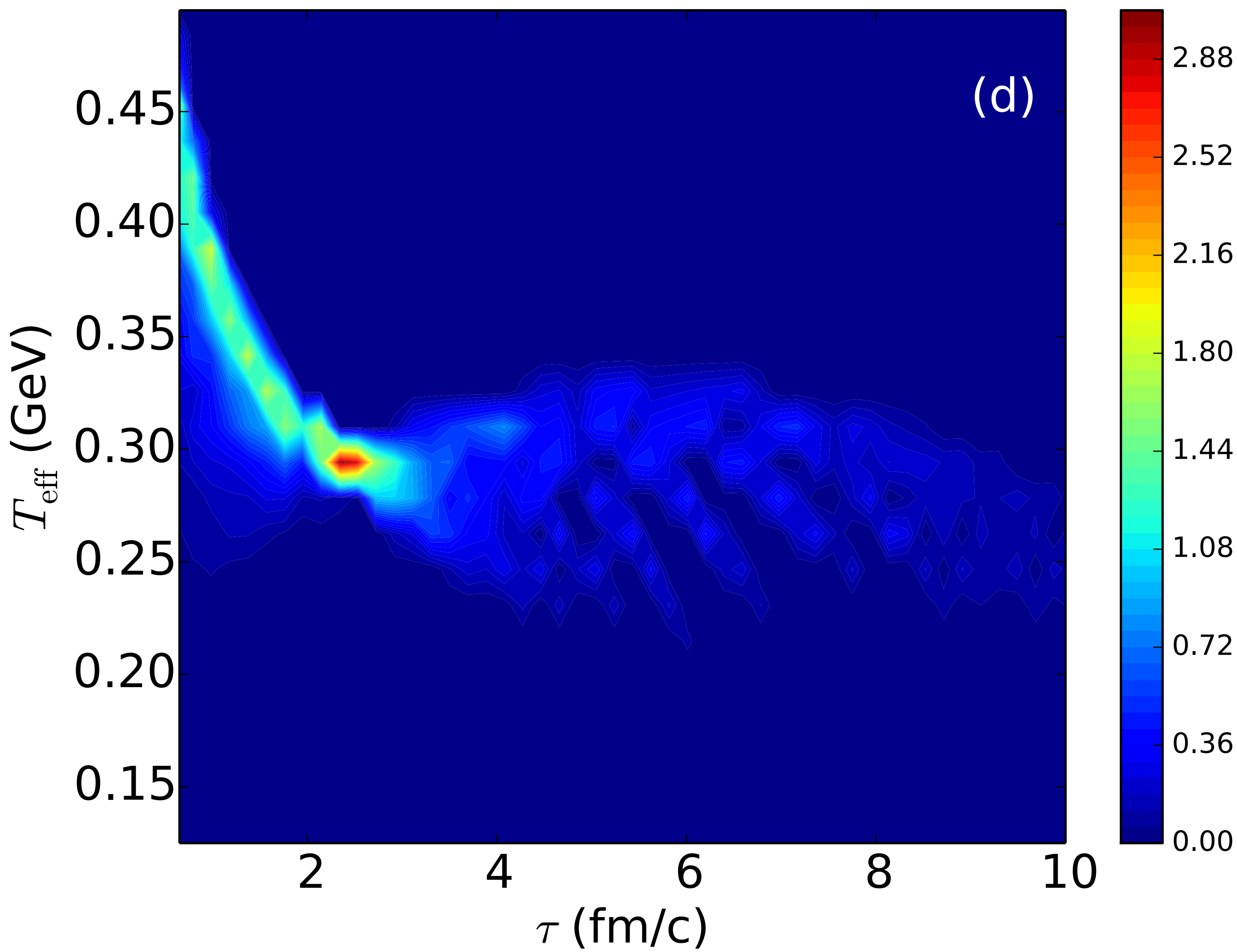


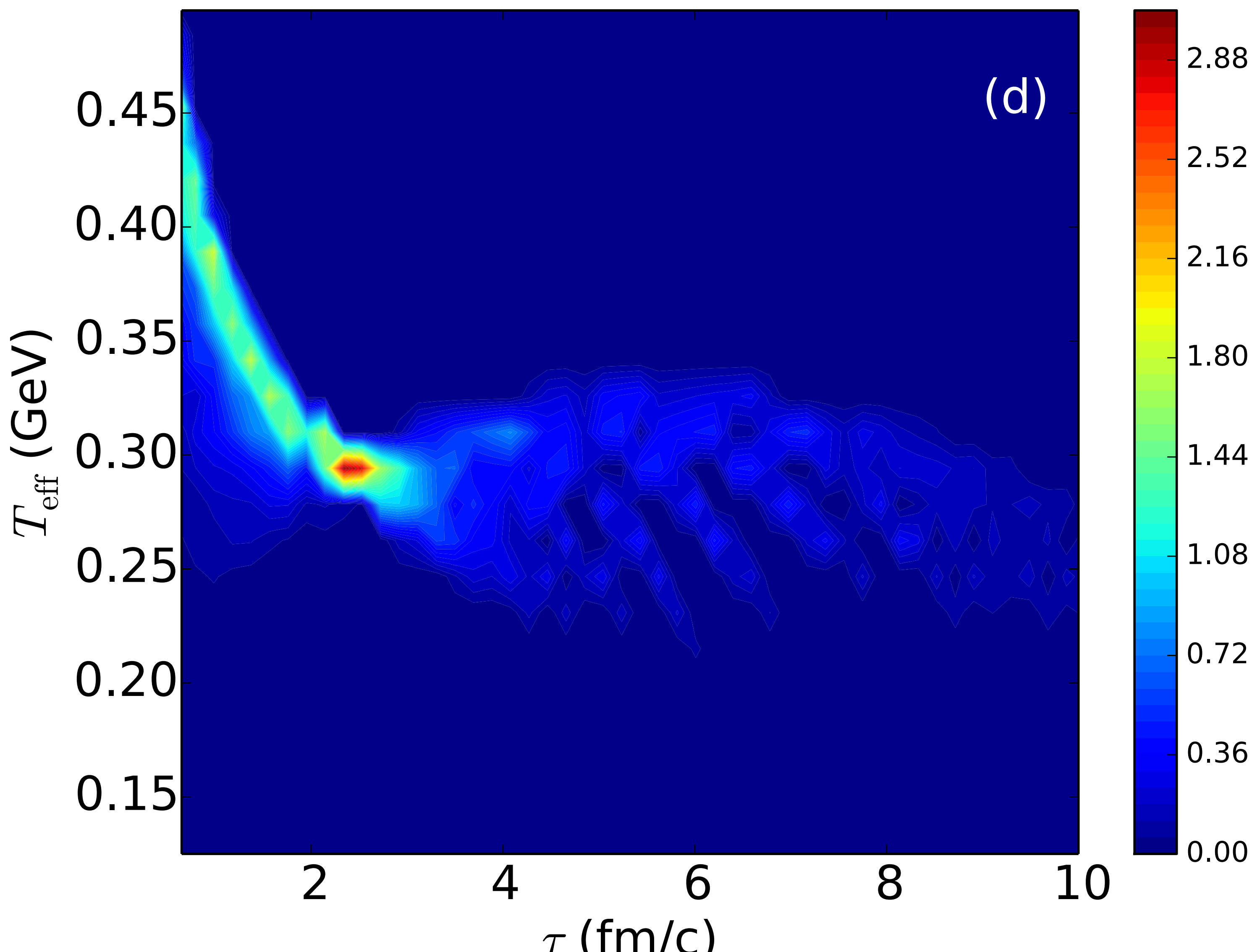
LHC

Studying the differential temperature distribution



LHC

Studying the differential temperature distribution



LHC

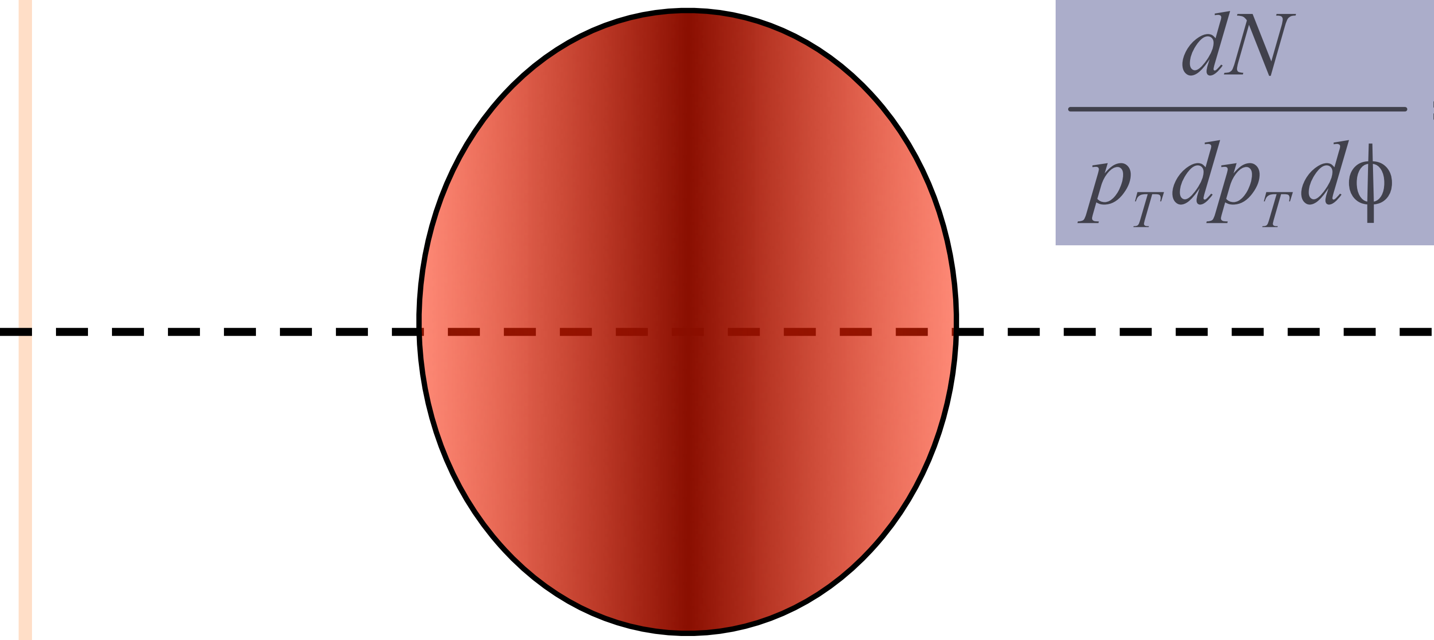
A summary:

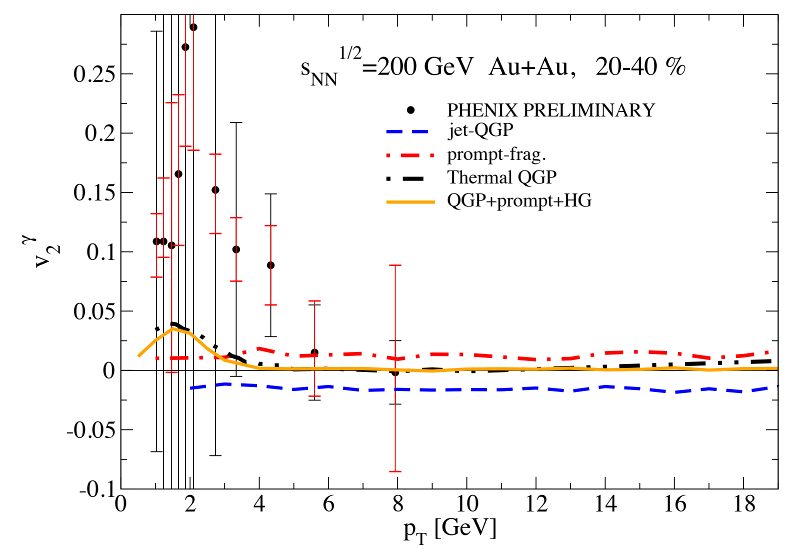
range of photon emission	fraction of total photon yield AuAu@RHIC 0-20% centr.	PbPb@LHC 0-40% centr.
$T = 120\text{-}165$ MeV	17%	15%
$T = 165\text{-}250$ MeV	62%	53%
$T > 250$ MeV	21%	32%
$\tau = 0.6 - 2.0$ fm/c	28.5%	26%
$\tau > 2.0$ fm/c	71.5%	74%

Charles Gale

Beyond simple spectra: Flow and correlations

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



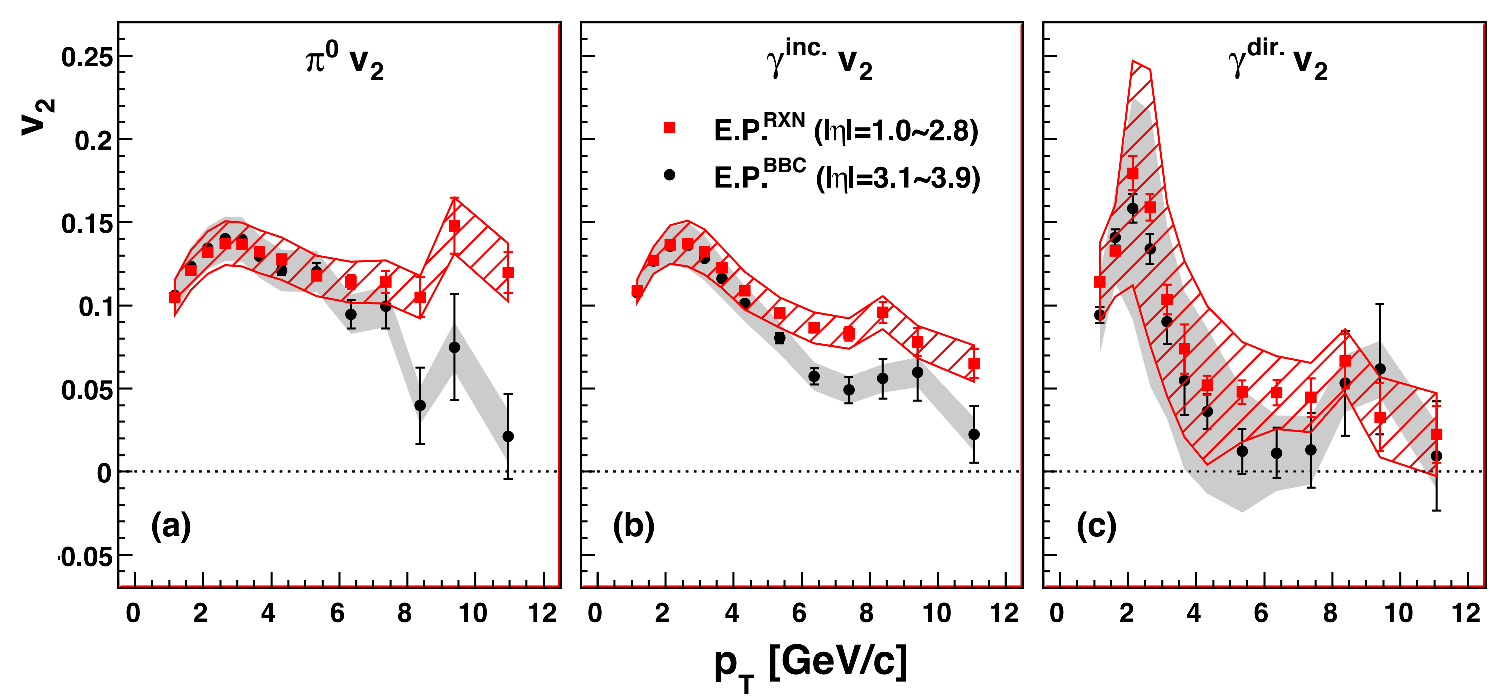


(2008)

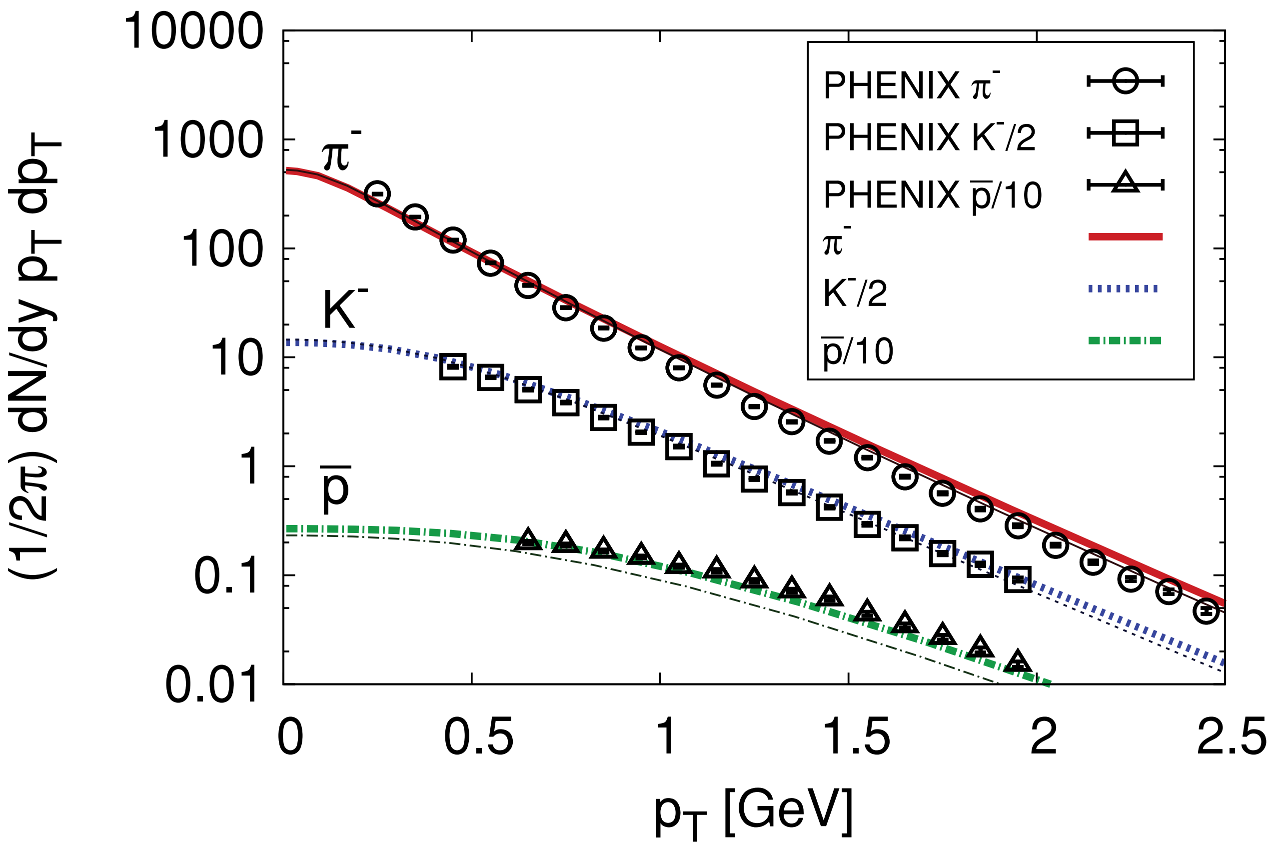
- Soft photons will go with the flow
- Jet-plasma photons: a negative v_2
- <u>Details will matter</u>: flow, T(t). . .

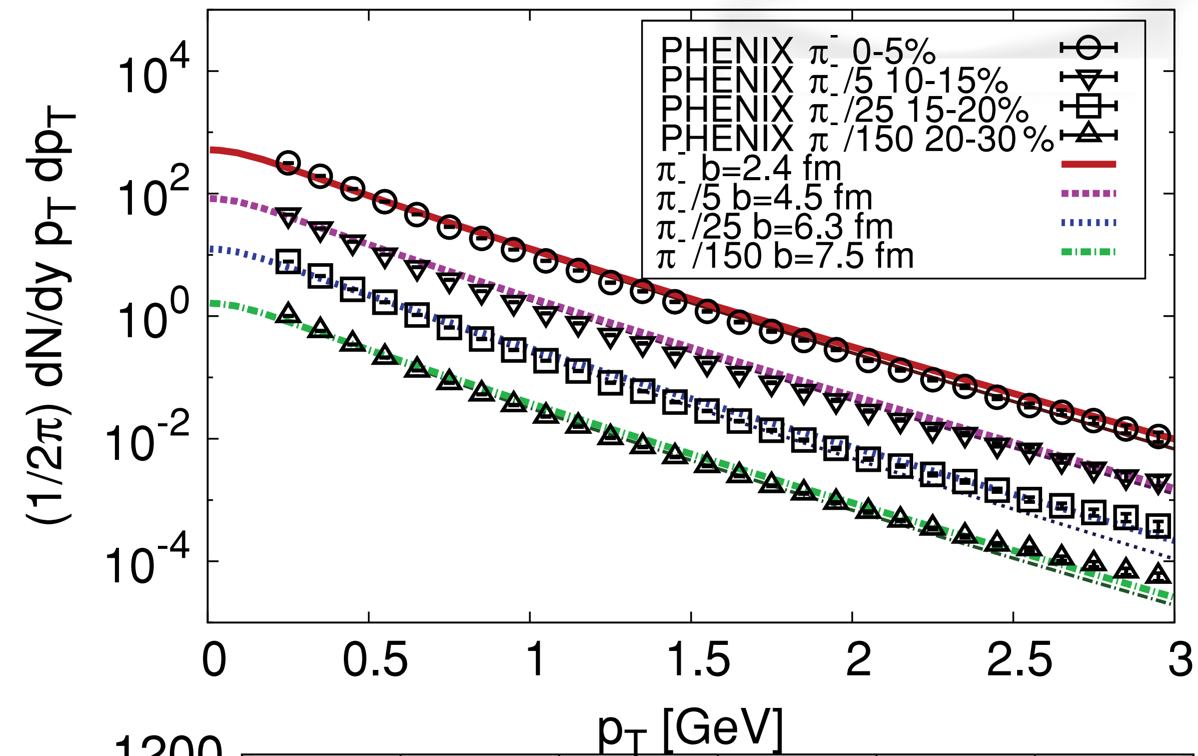
Turbide, Gale, Fries PRL (2006)
Low p_T: Chatterjee *et al.,* PRL (2006)
All p_T: Turbide *et al.,* PRC (2008)

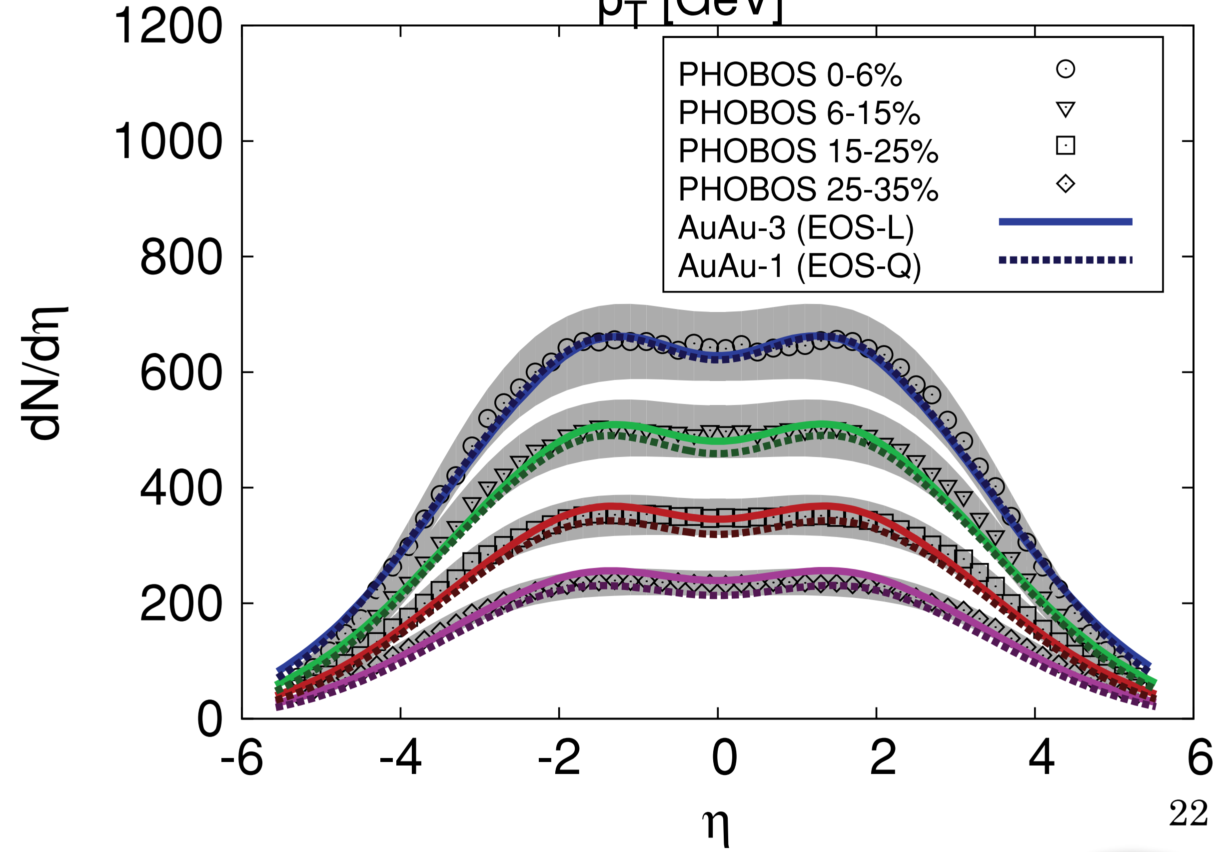
(2011)



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 & FIC effects on EM observables?

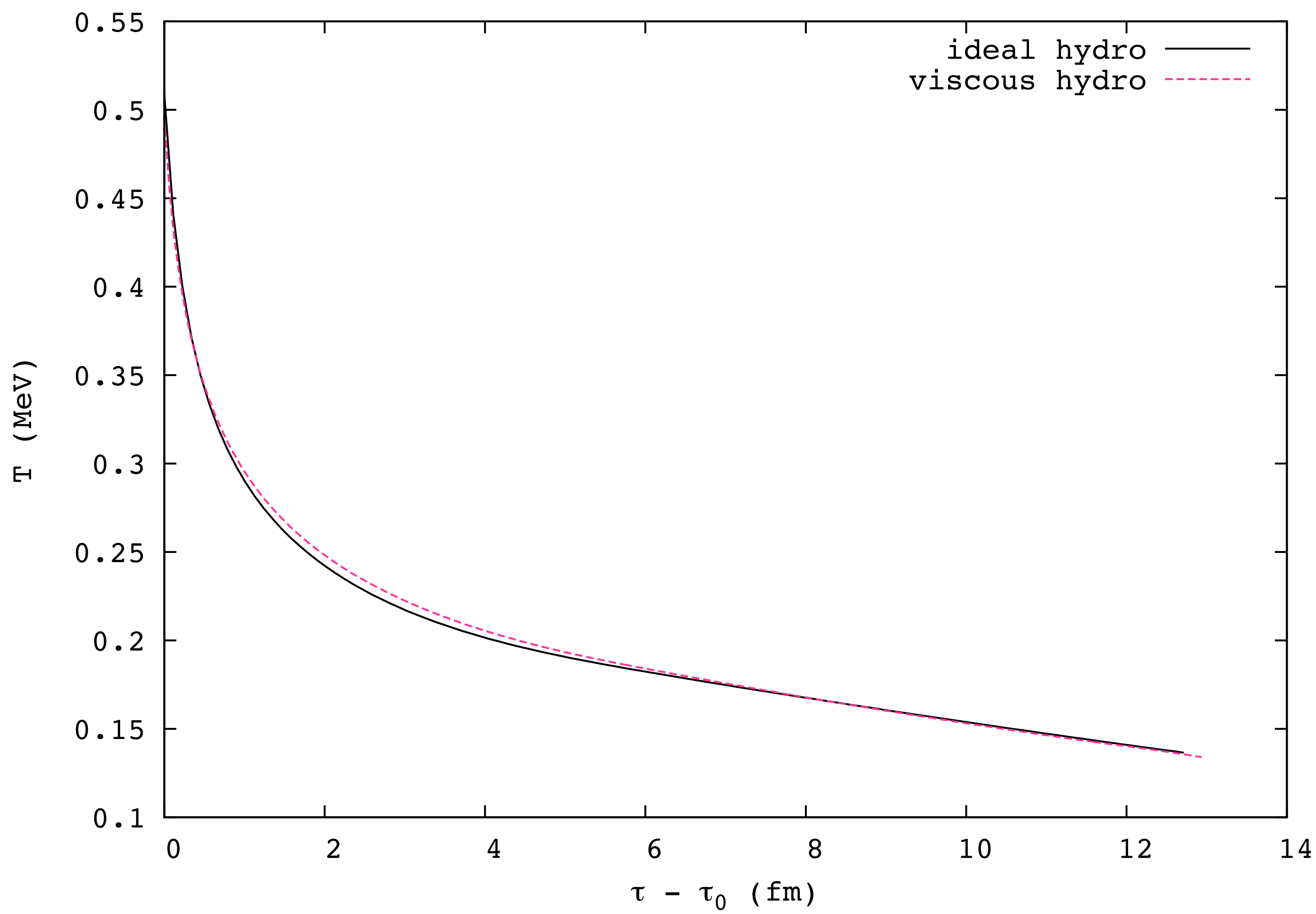
The effects of shear viscosity on bulk dynamics

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

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

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

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



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

The effects of shear viscosity on bulk dynamics

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

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

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

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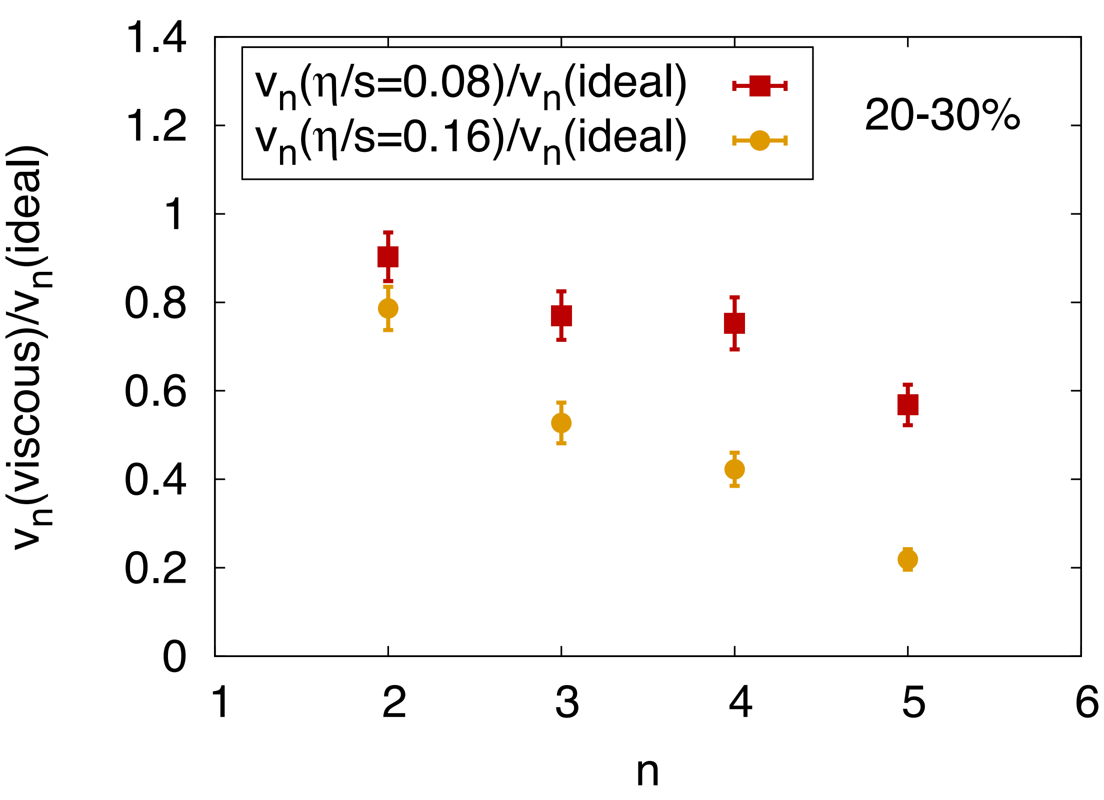
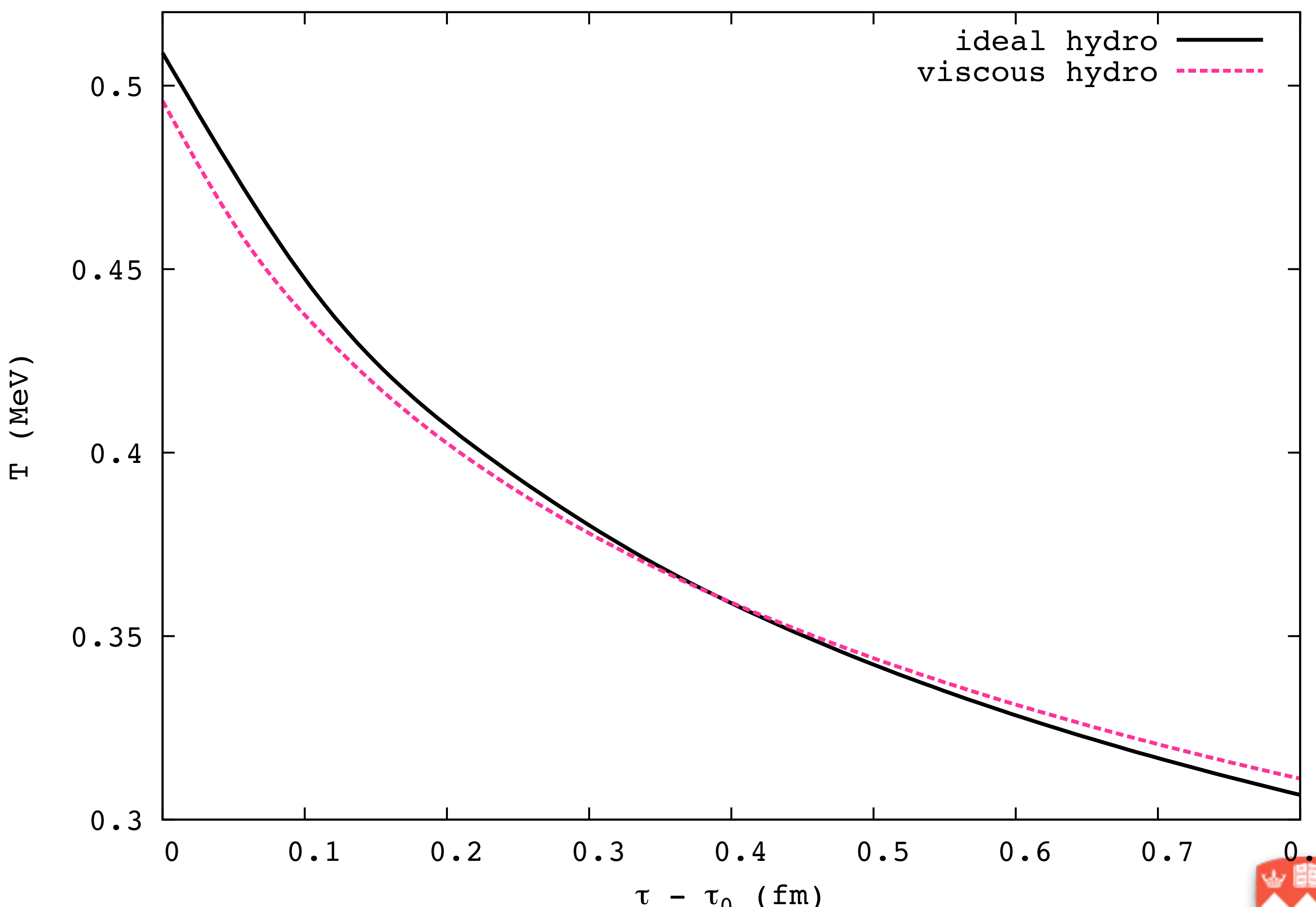




Schenke, Jeon, Gale, PRC (2012)

Charles Gale

The effects of shear viscosity on the photon distribution

In-medium **hadrons**:

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

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

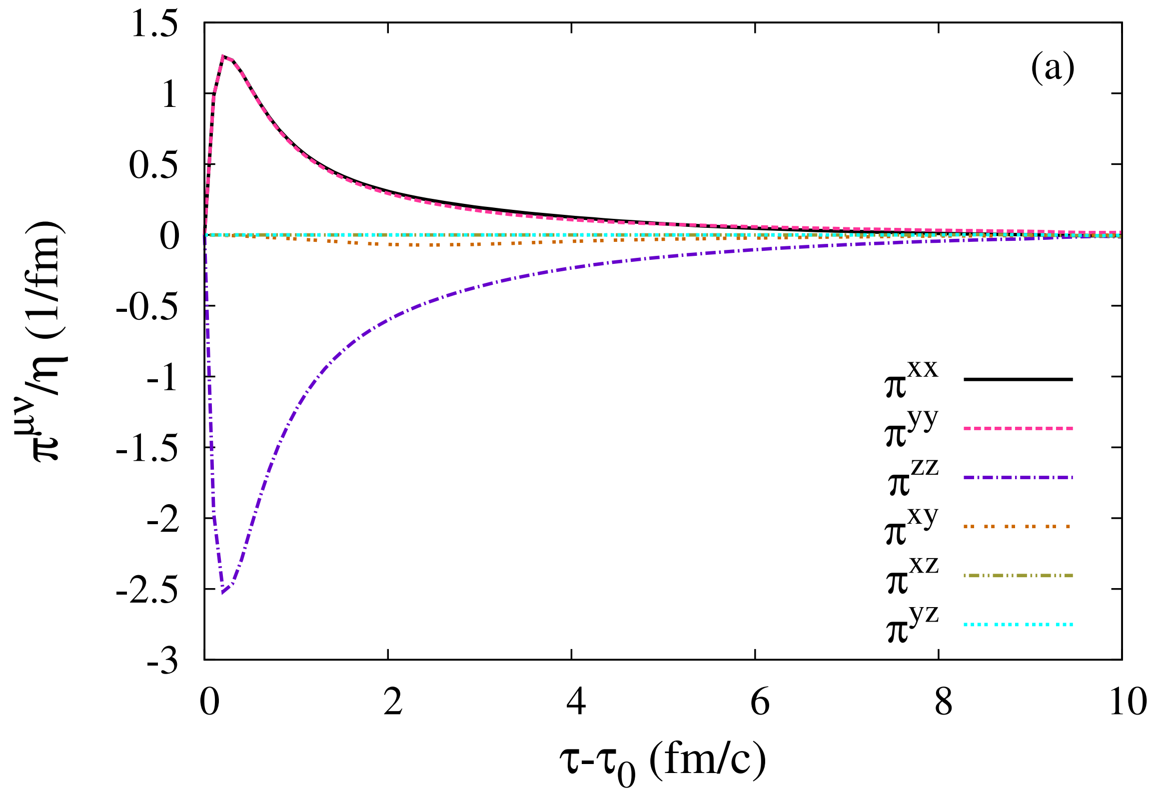
$$q_0 \frac{d^3R}{d^3q} = \int \frac{d^3p_1}{2(2\pi)^3 E_1}\frac{d^3p_2}{2(2\pi)^3 E_2}\frac{d^3p_3}{2(2\pi)^3 E_3}(2\pi)^4 |M|^2 \delta^4(\ldots)\frac{f(E_1)f(E_2)\left[1 \pm f(E_3)\right]}{2(2\pi)^3}$$

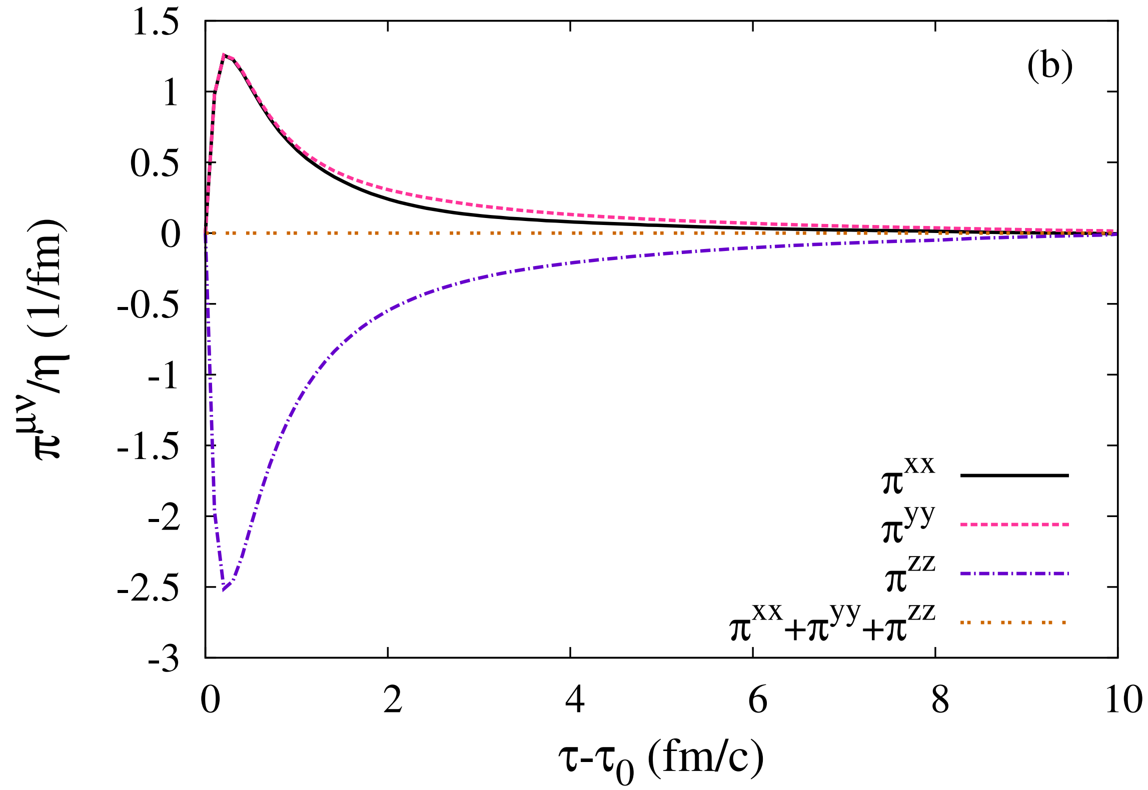
One considers all the reaction and radiative decay channels of external state combinations of:

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

QGP photons (viscous 2 to 2 for the moment)

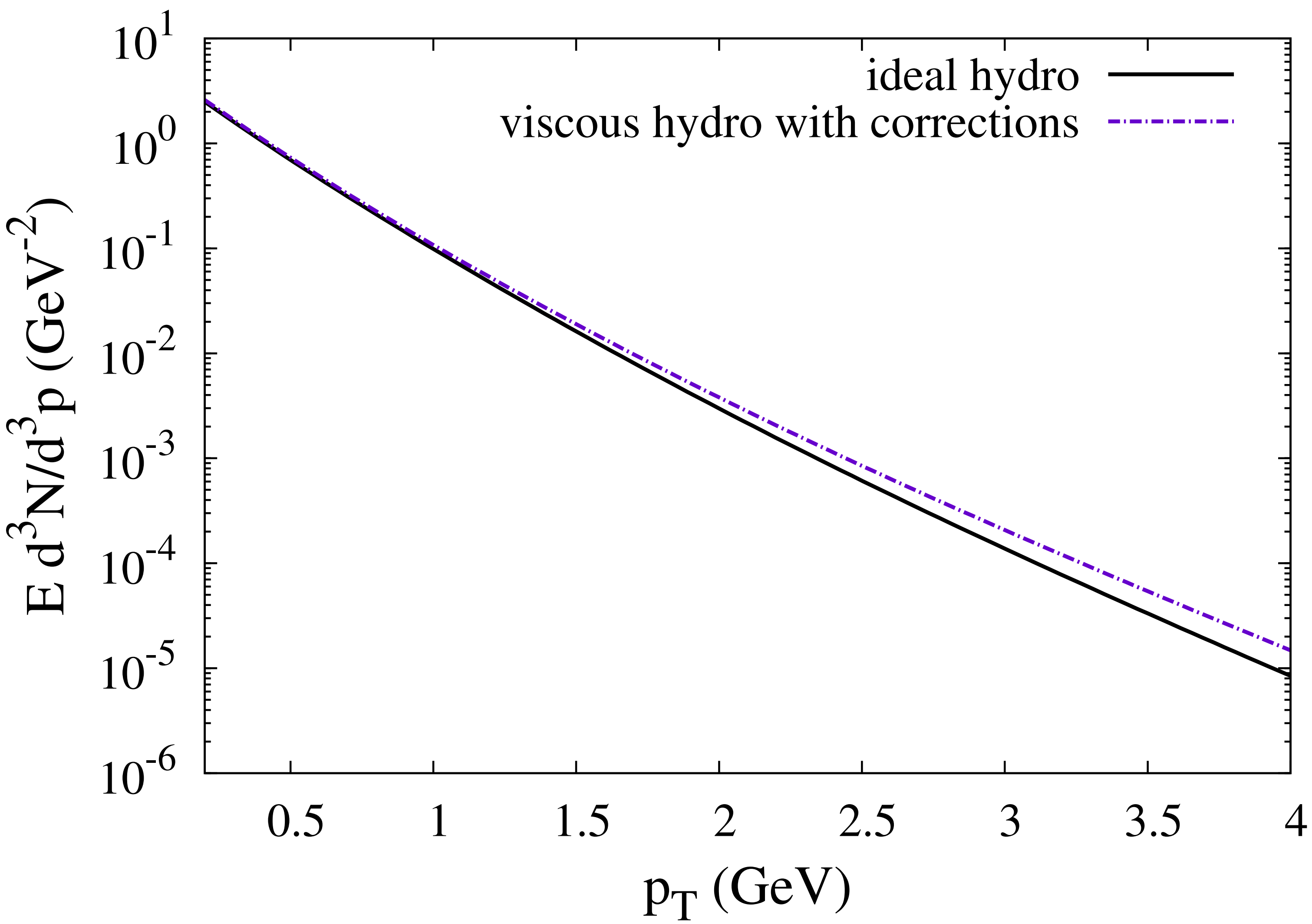
THE EFFECTS OF SHEAR VISCOSITY ON THE BULK DYNAMICS





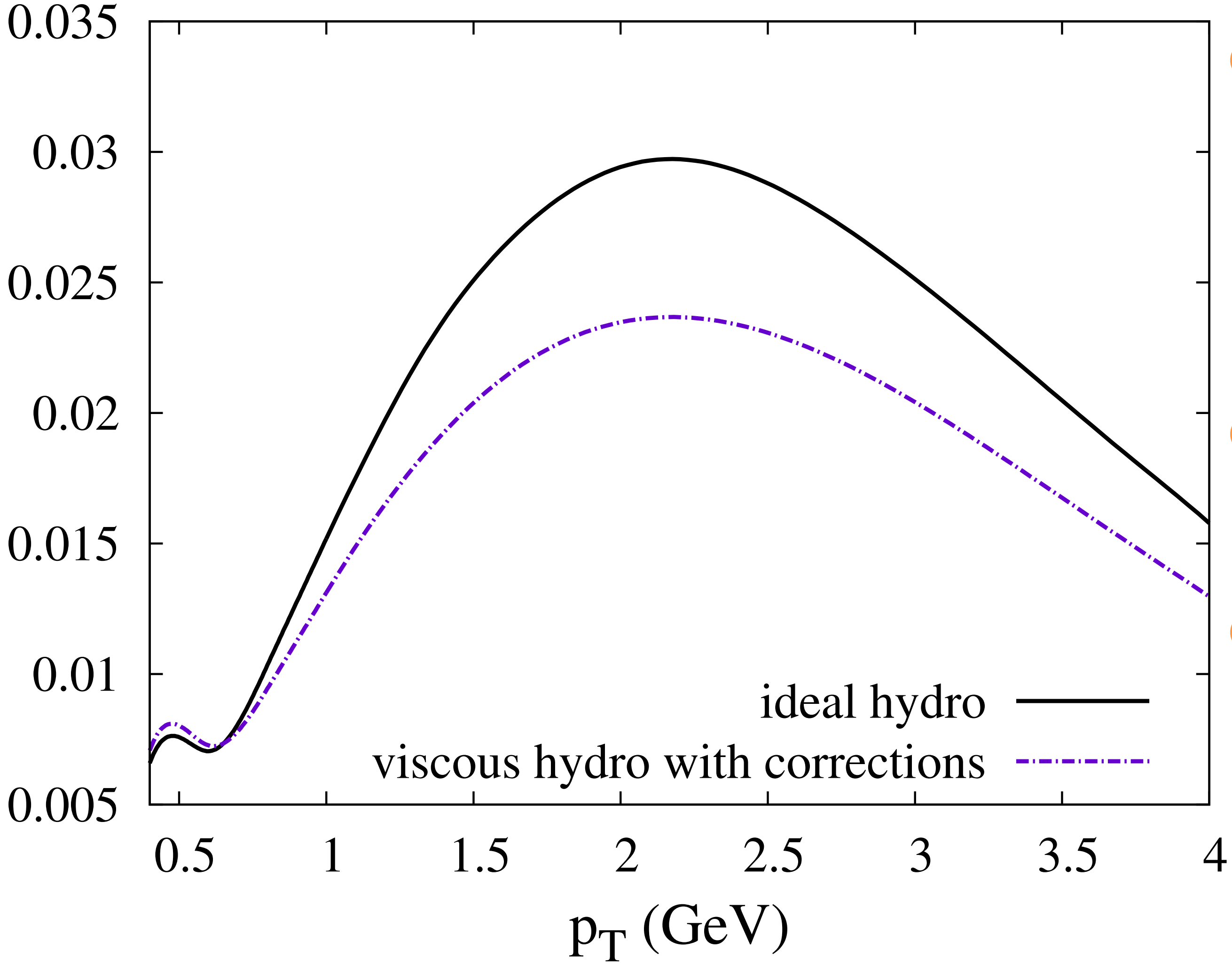
- Large at early times
- Small at later times: viscosity corrections to the distribution functions will also vanish

The net thermal photon yield



- Viscous corrections make the spectrum harder, ≈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

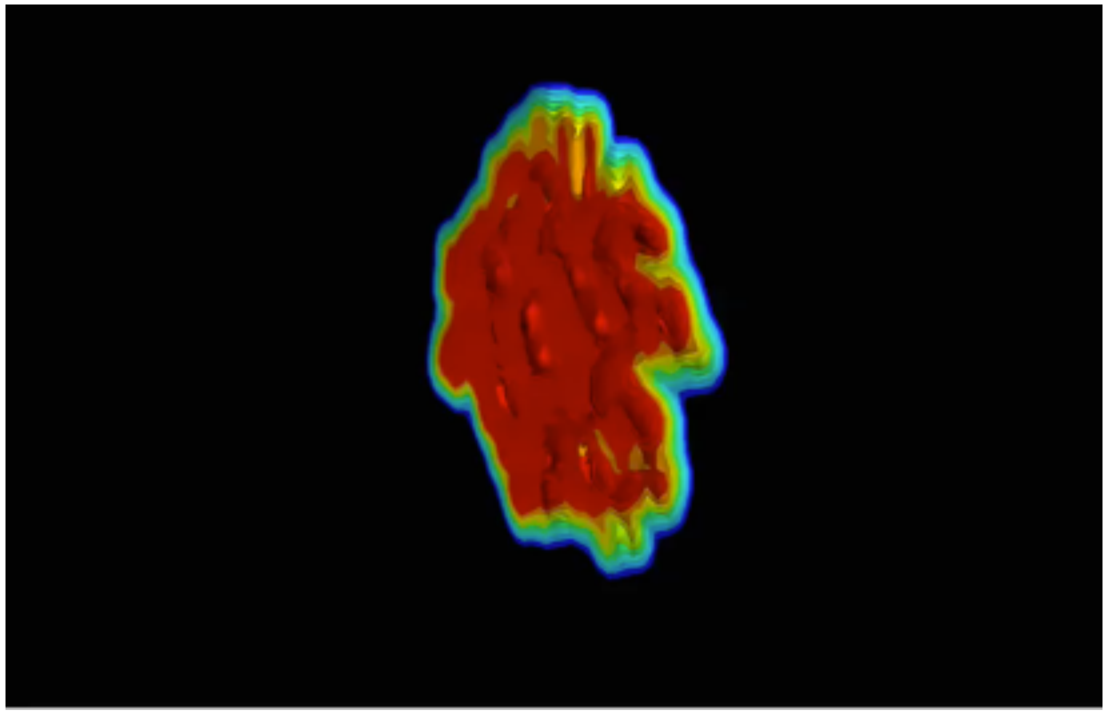


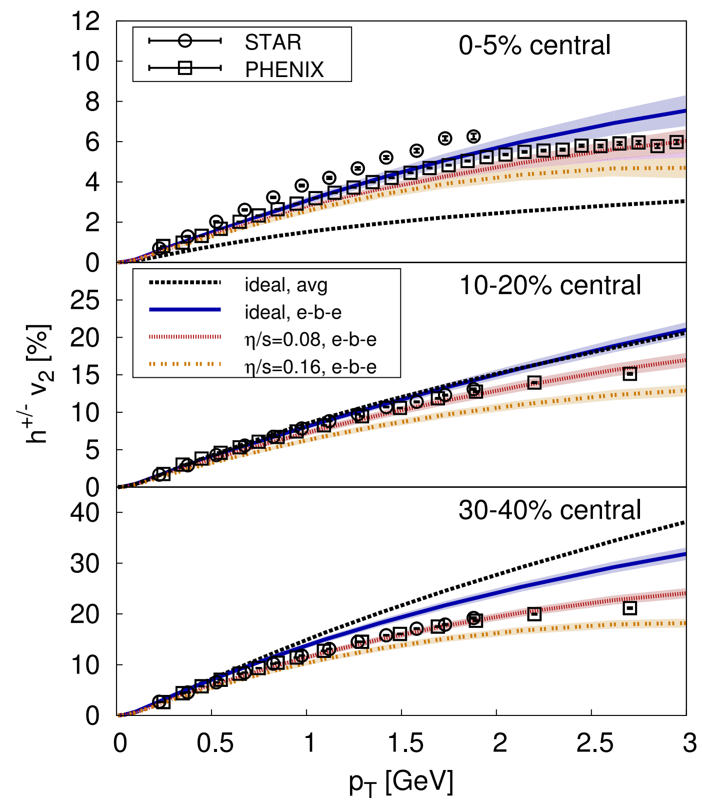
- The net elliptic flow is a *weighted average*. A larger QGP yield will yield a smaller v_2. Same story - *mutatis mutandis* -for the HG
- The turnover at $p_T \approx 2$ GeV could be QGP-driven and/or pQCD-driven
- The net effect of viscous corrections makes the photon elliptic flow *smaller*, as it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

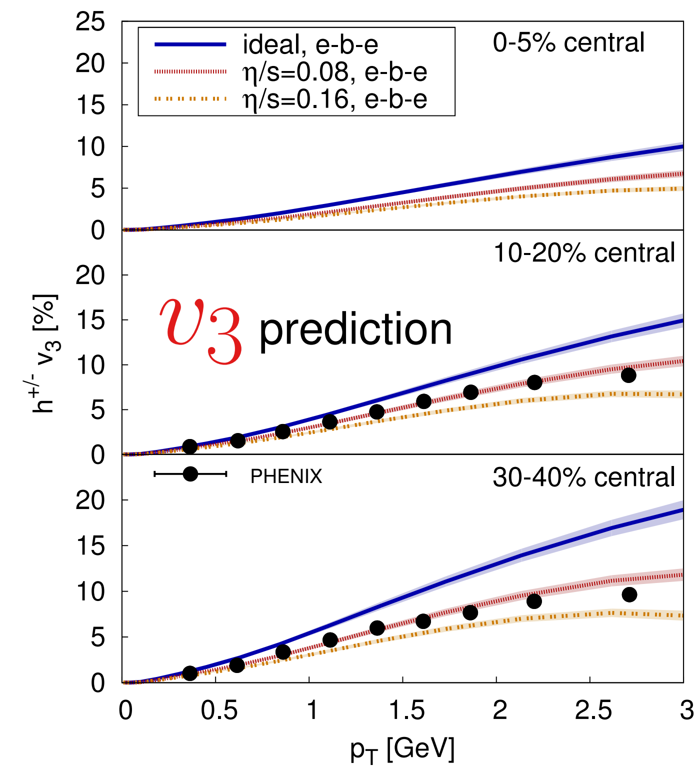
M. Dion *et al.*, PRC 2011

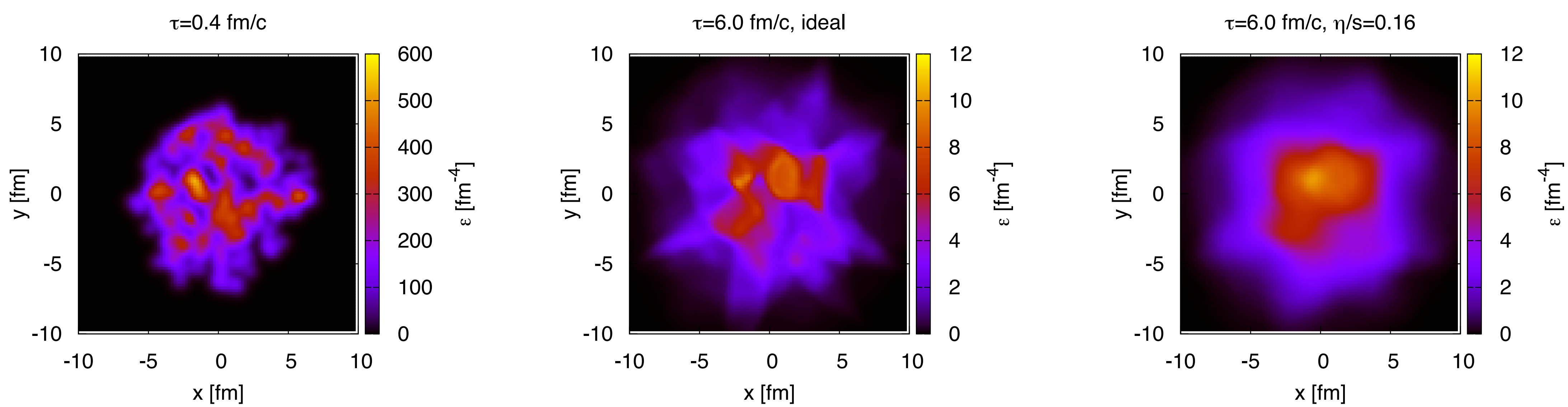
INITIAL STATE FLUCTUATIONS: A PARADIGM SHIFT IN HEAVY ION ANALYSES

Lumpy MUSIC





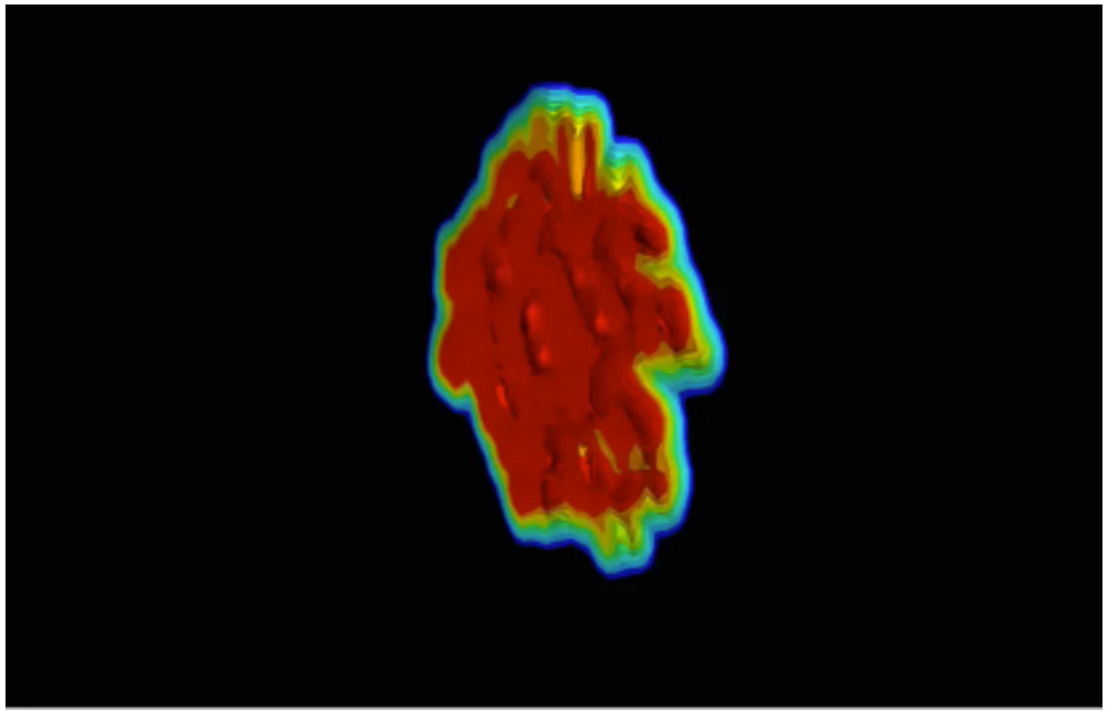


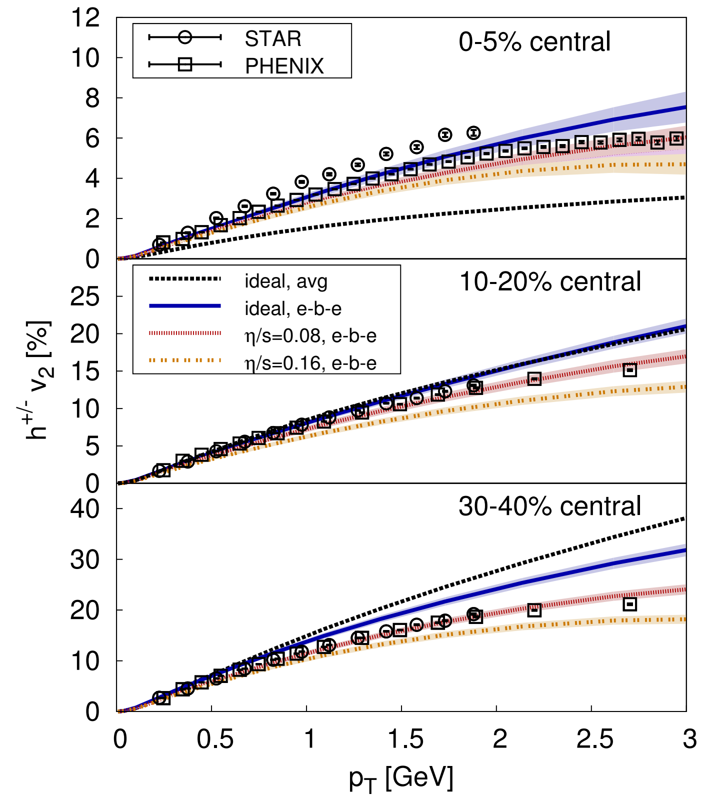


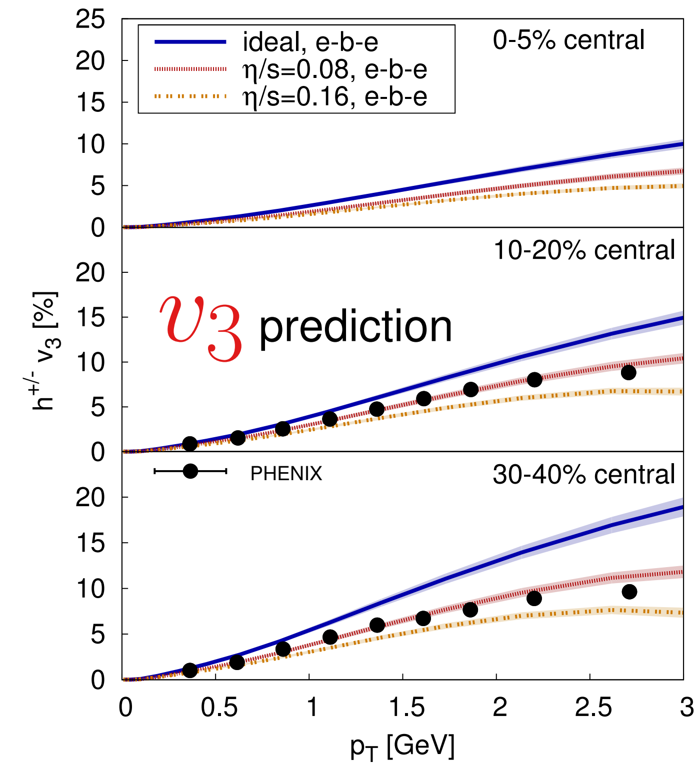
Schenke, Jeon, Gale, PRL (2011)

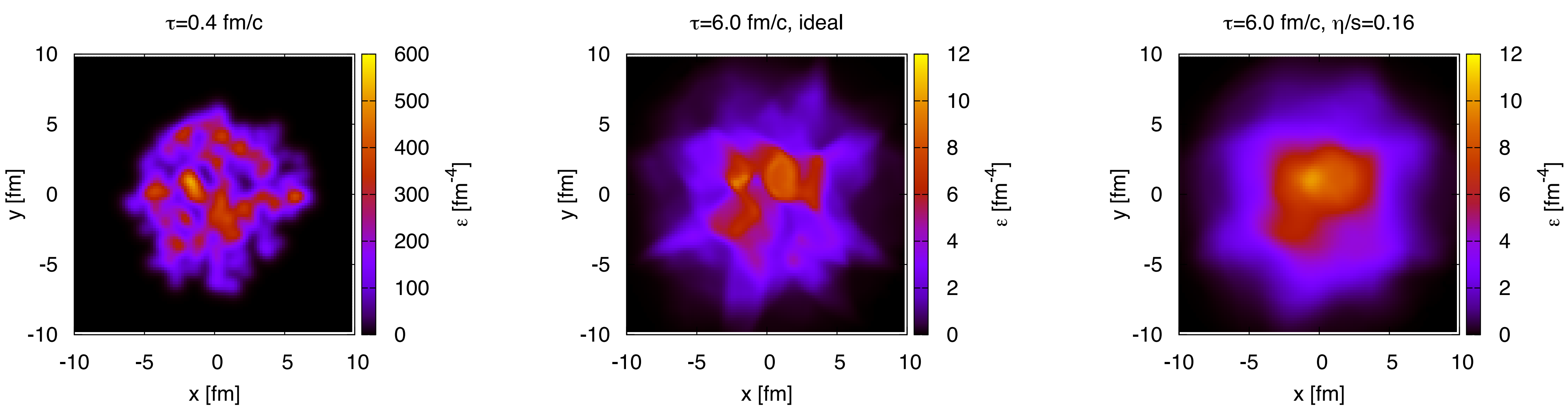
Initial state fluctuations: a paradigm shift in heavy ion analyses

Lumpy MUSIC



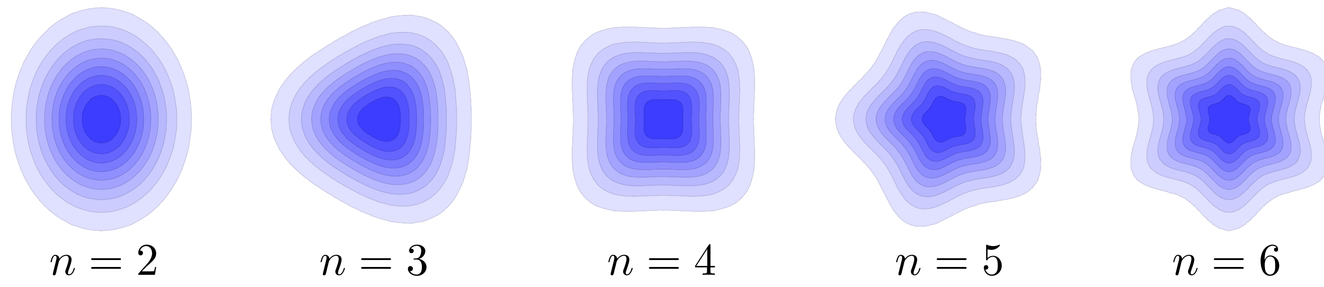


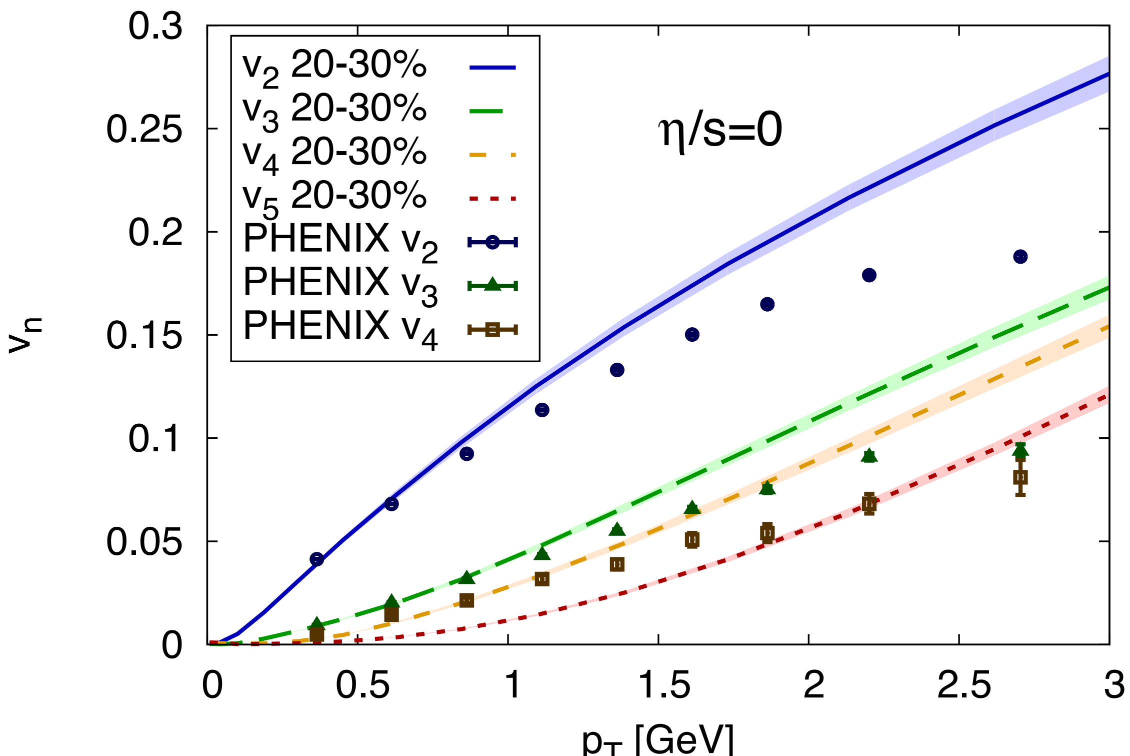


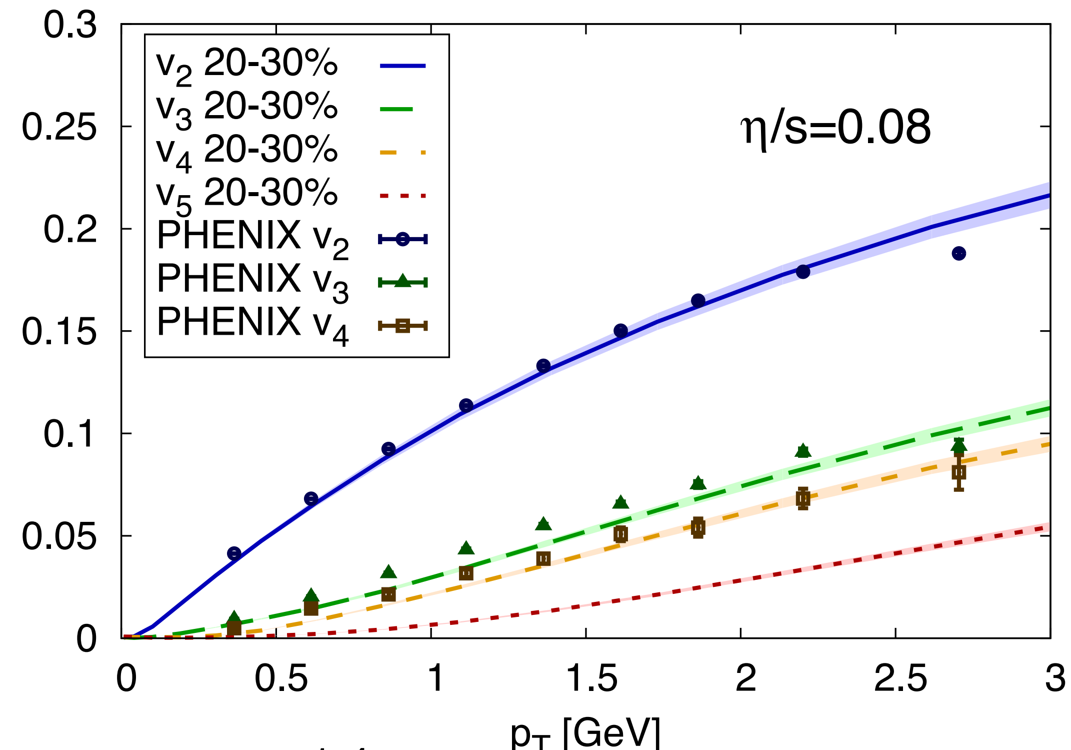


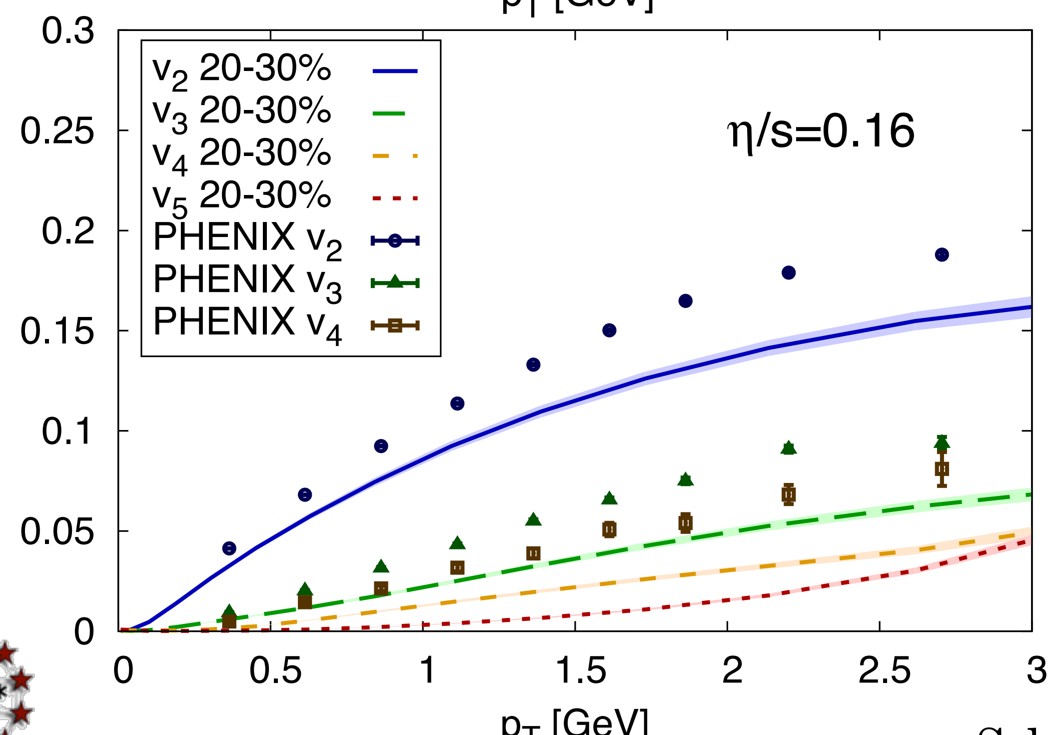
Schenke, Jeon, Gale, PRL (2011)

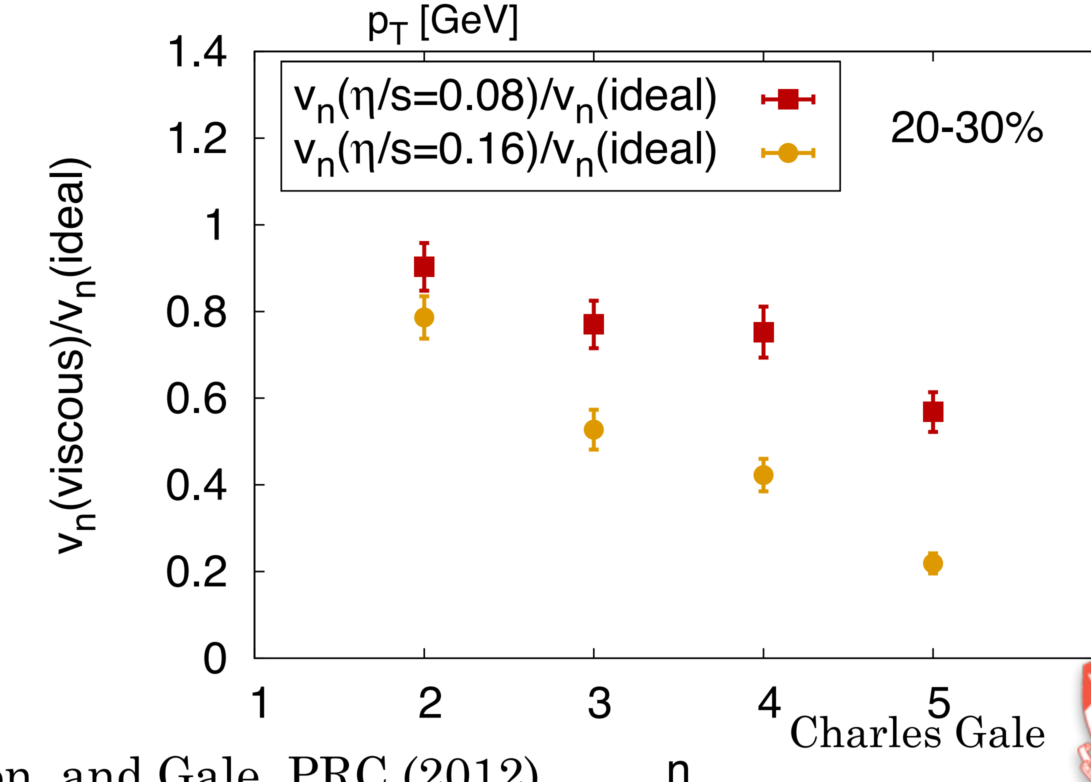
Moving into the "characterization" phase…





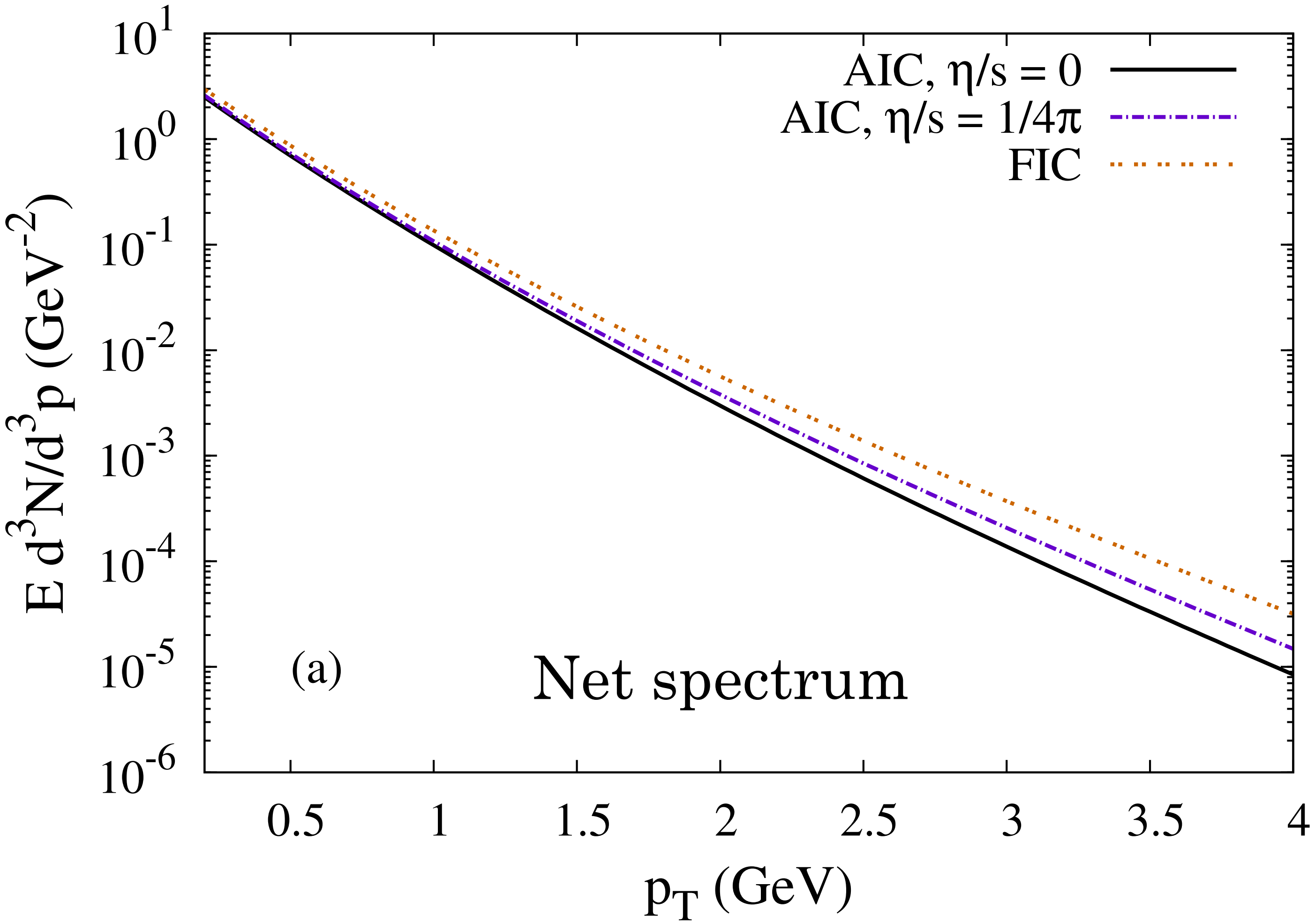






Schenke, Jeon, and Gale, PRC (2012)

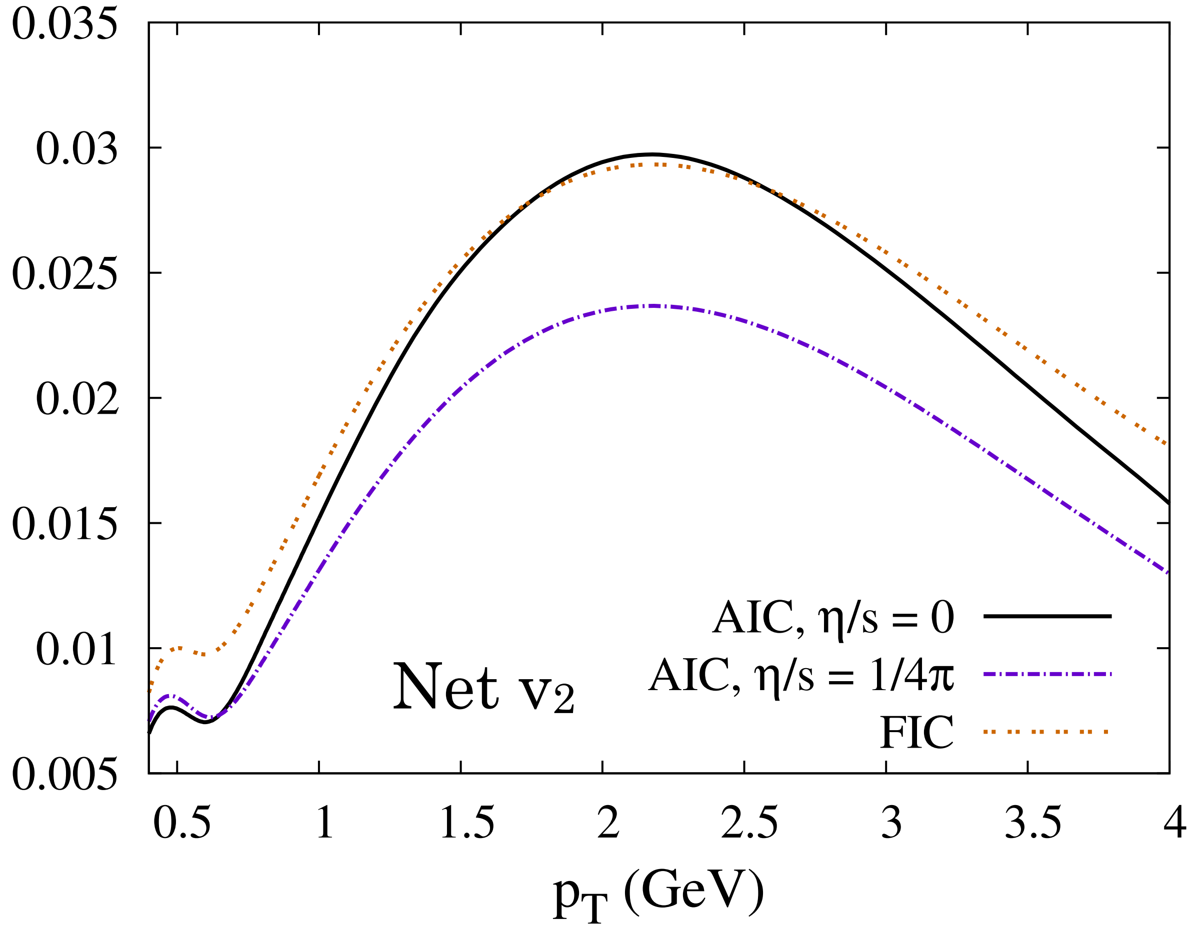
ALL TOGETHER: FICS + VISCOSITY



- 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

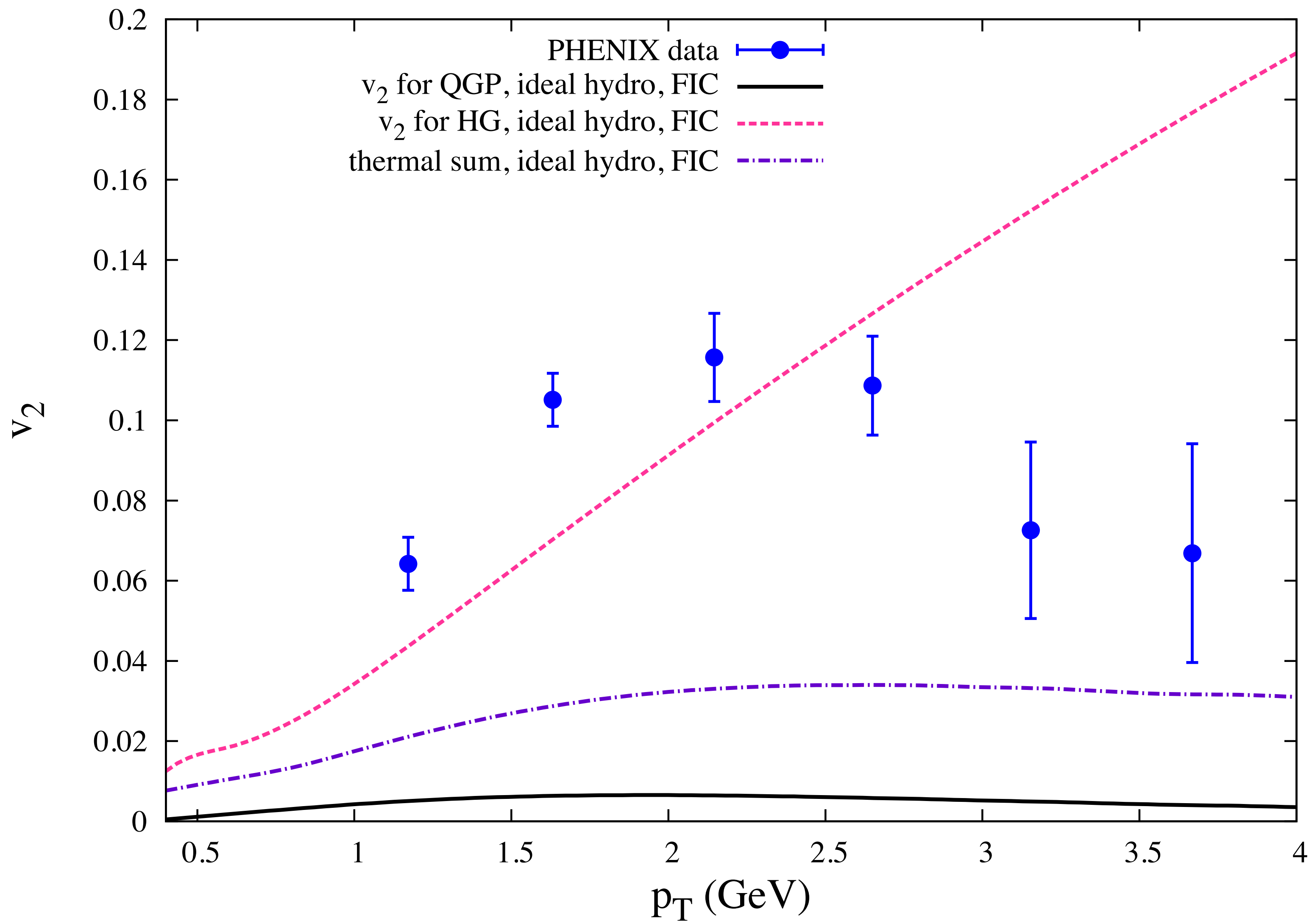
Dion et al., PRC (2011) [FIC+Visc.]
Chatterjee et al., PRC (2011) [FIC]

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?



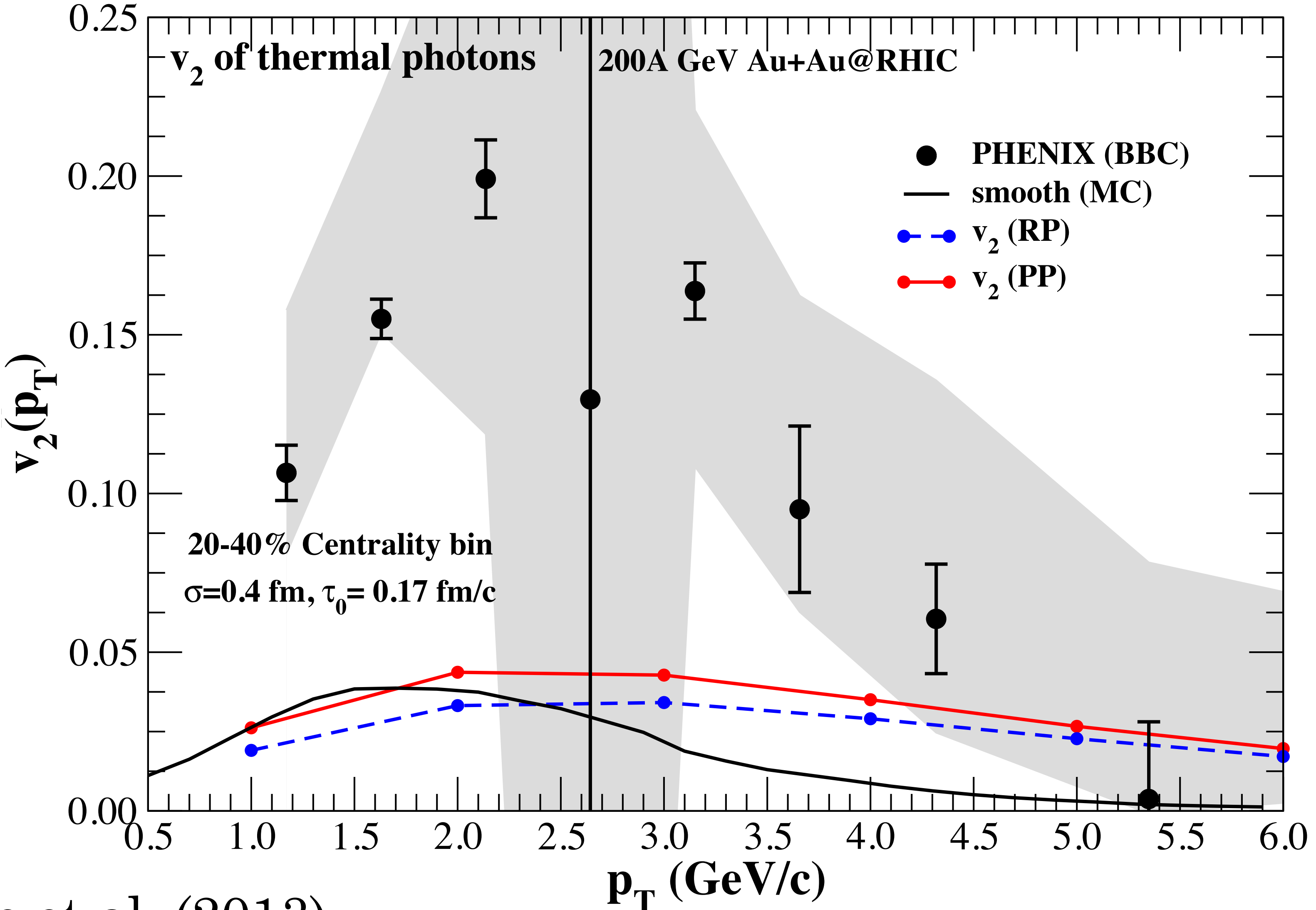
RHIC

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

* E. Bratkovskaya, plenary talk QM2014
* J. Ghiglieri, plenary talk QM2014
* C. Shen, parallel talk QM2014
* J.-F. Paquet, poster QM2014

Photon v_2 Data?



Chatterjee et al. (2013)

RHIC

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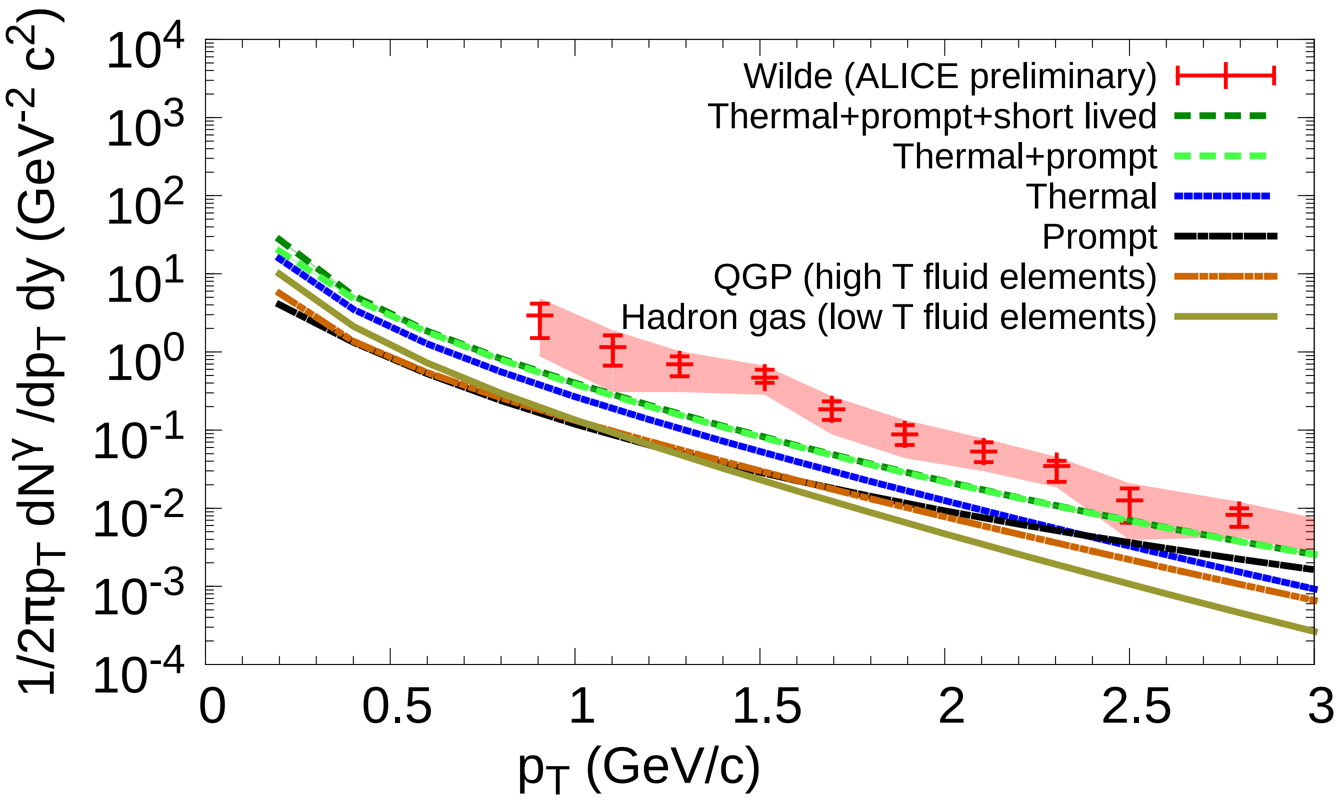
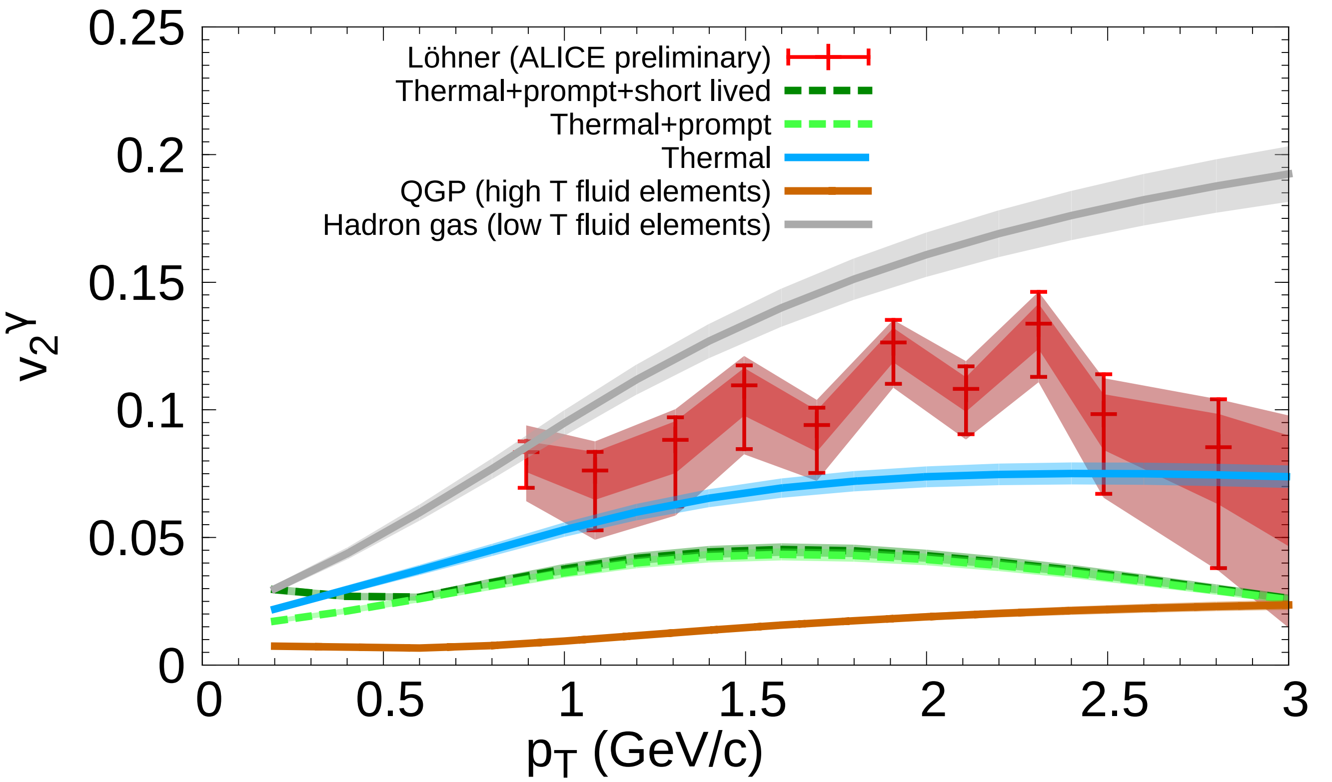
* E. Bratkovskaya, plenary talk QM2014
* J. Ghiglieri, plenary talk QM2014
* C. Shen, parallel talk QM2014
* J.-F. Paquet, poster QM2014

Photon v_2 Data?

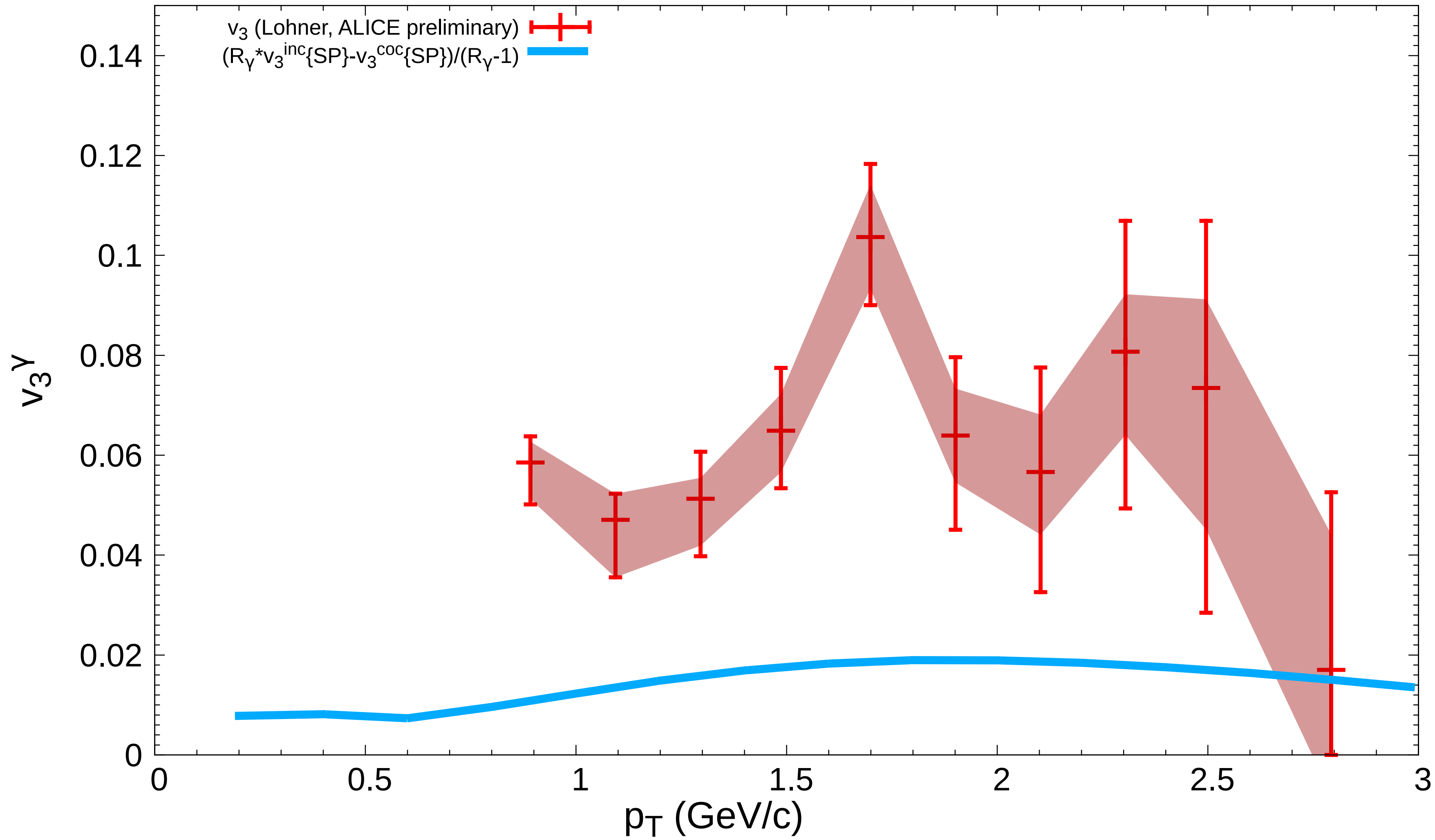
LHC Pb+Pb, 2.76 TeV 0-40%





- E. Bratkovskaya, plenary talk QM2014
- J. Ghiglieri, plenary talk QM2014
- C. Shen, parallel talk QM2014
- J.-F. Paquet, poster QM2014

Photon v_3 Data?



- Data: D. Lohner, PhD thesis (Heidelberg, 2013)
- Calc.: J.-F. Paquet

What about dileptons?

- Additional degree of freedom: M and p_T may be varied independently
- Same approach as for photons: integrate rates with hydro

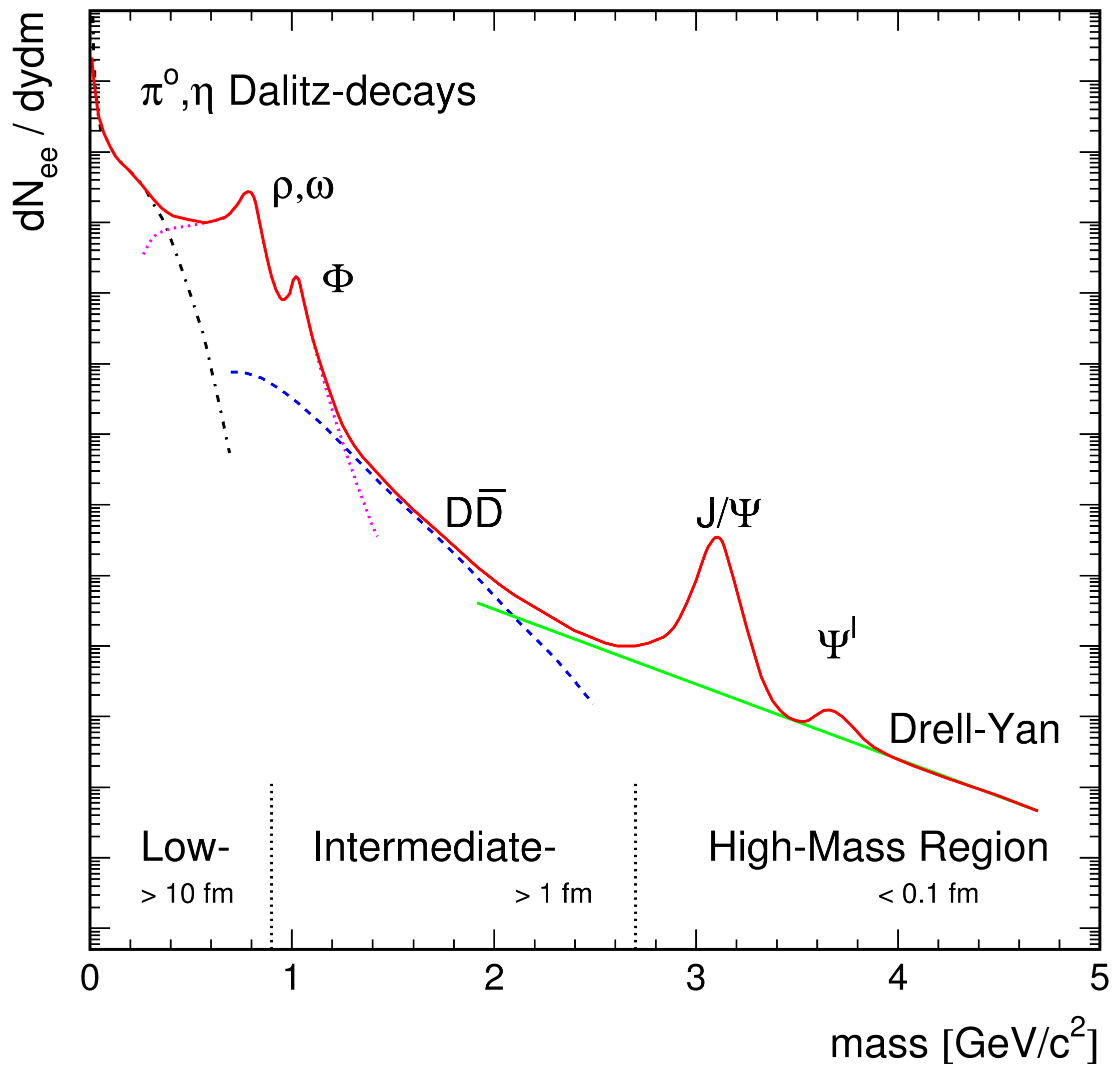
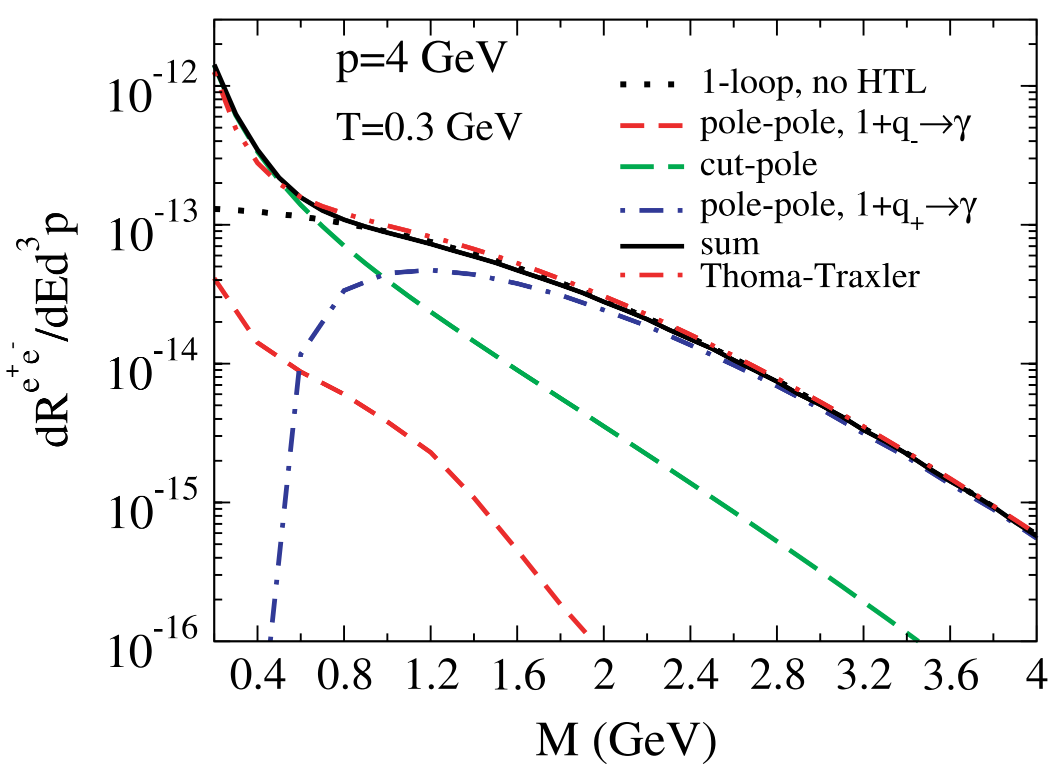


Figure: A. Drees

Thermal dilepton sources, QGP

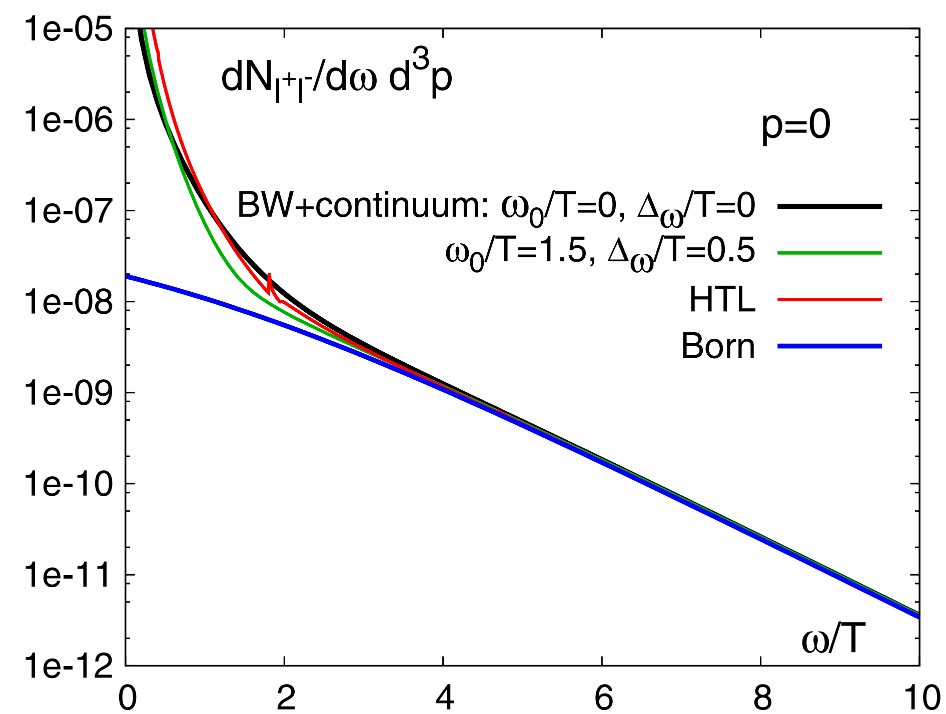
- HTL at zero momentum: Braaten, Pisarski and Yuan, PRL (1990)
  - Moore and Robert, hep-ph/0607172
- 2-loop, p=0, E>>T: Majumder and Gale, PRC (2002)
- HTL, *M~gT, E>T*: Aurenche, Gélis, Moore, Zaraket, JHEP (2008)

- HTL at finite momentum:



Turbide, Gale, Srivastava, Fries PRC (2006)

- Non-perturbative calculation:



Ding et al., PRD (2011)

No single calculation covers the entire dilepton kinematical phase space

M. Laine, arXiv:1310.0164

$$M^2 \gtrsim (\pi T)^2,\ p \neq 0$$

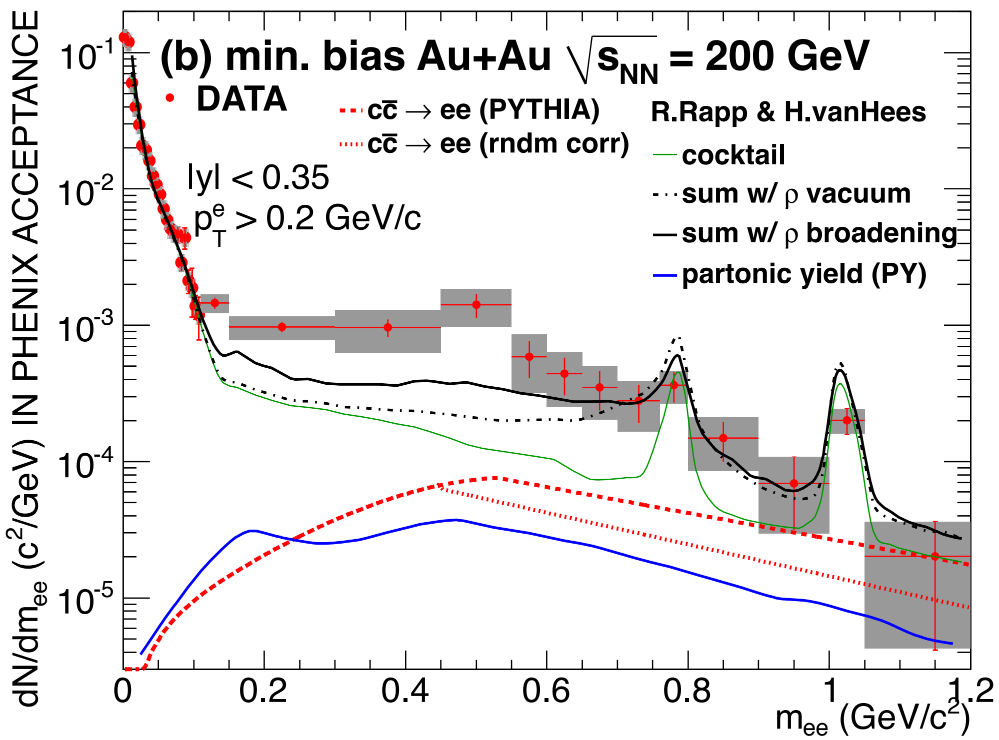
Thermal dilepton sources, HG

- HG contribution: calculate the in-medium vector spectral density:
  - Many-Body approach with hadronic effective Lagrangians
    - Rapp and Wambach, ANP (2000)
  - Empirical evaluation of the vector mesons forward-scattering amplitudes

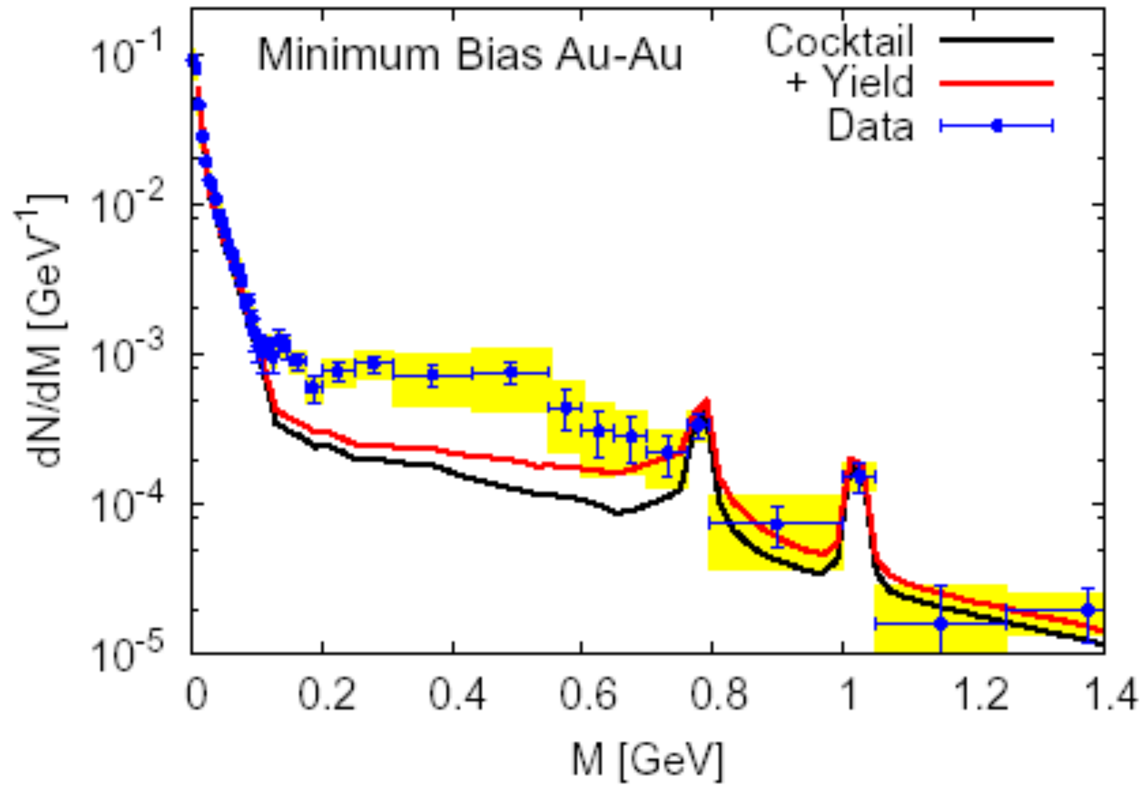
$$\Pi_{ab}(E,p) = -4\pi \int \frac{d^3k}{(2\pi)^3} n_b(\omega) \frac{\sqrt{s}}{\omega} f_{ab}^{\text{c.m.}}(s)$$

    - E. Shuryak, NPA (1991)
    - Eletsky, Ioffe, Kapusta (1999)
    - Vujanovic, Gale (2009)
  - Chiral Reduction formulae
    - Yamagishi, Zahed (1996)

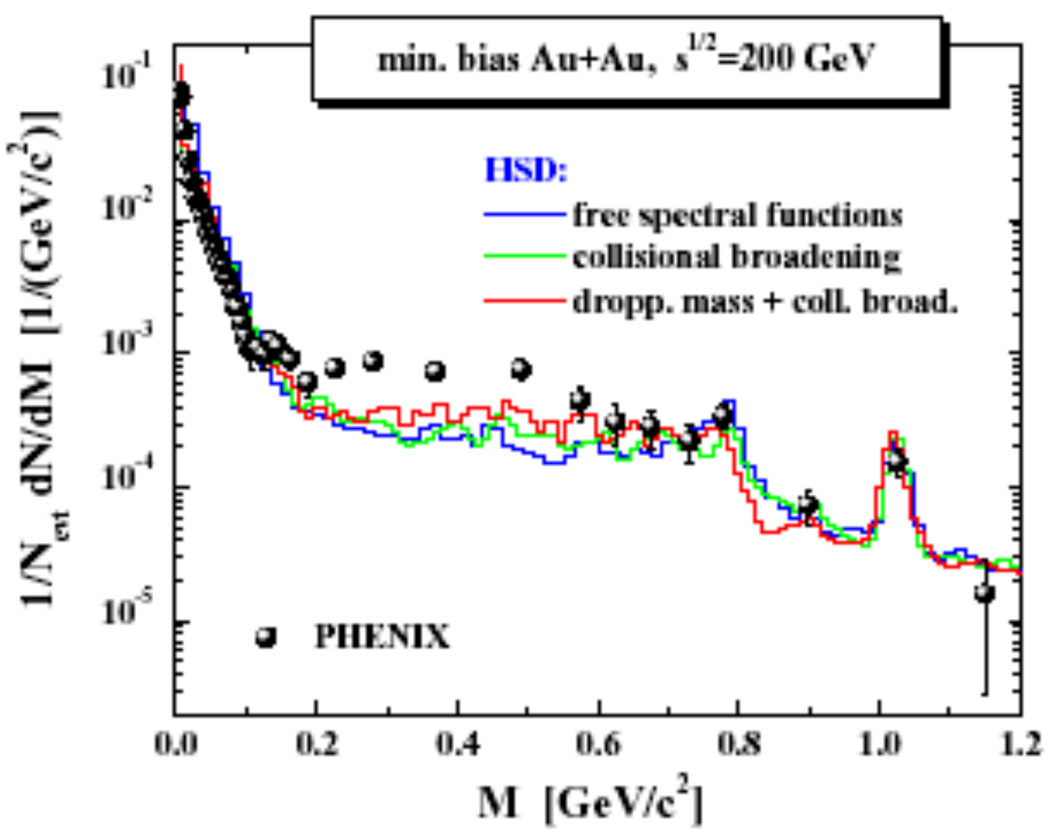
DILEPTONS, THE STORY AS OF TWO YEARS AGO



van Hees, Rapp (2010)

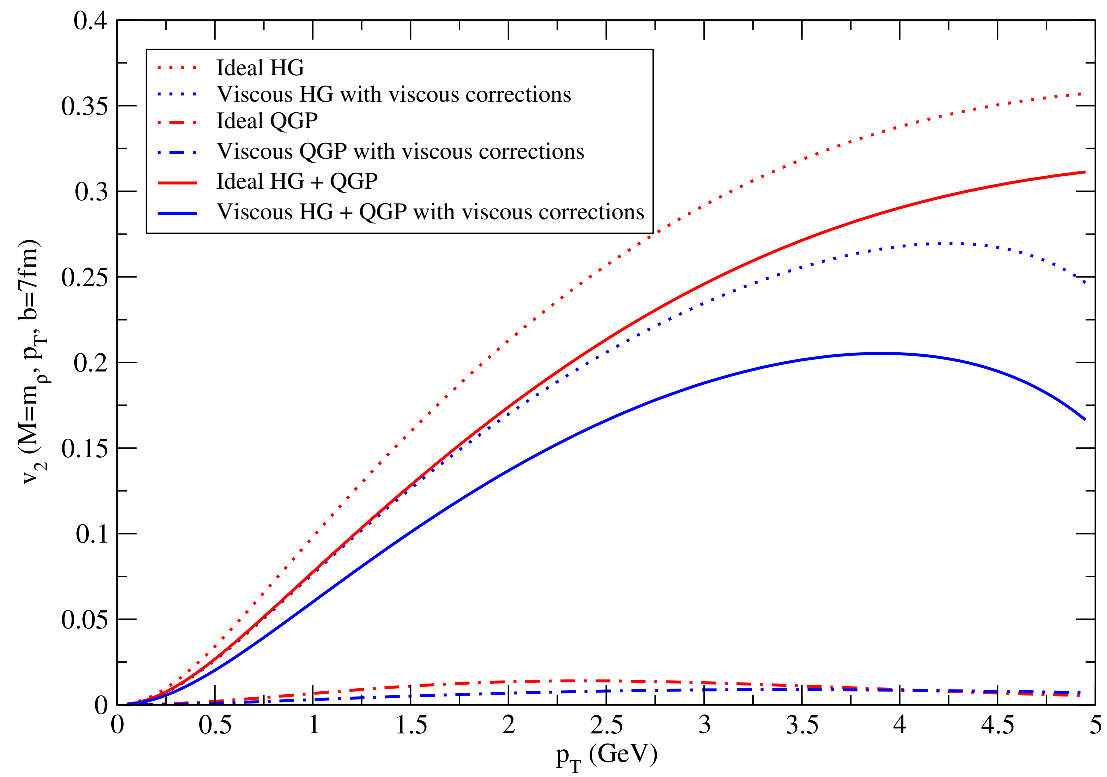


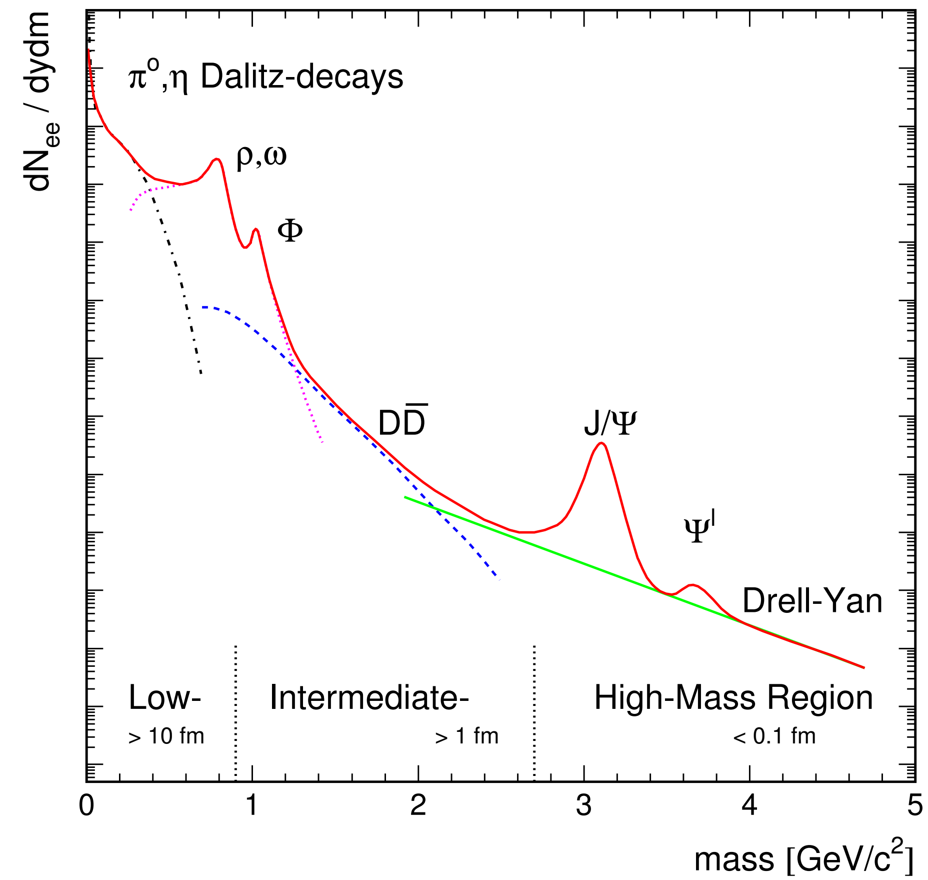
Dusling, Zahed (2009)

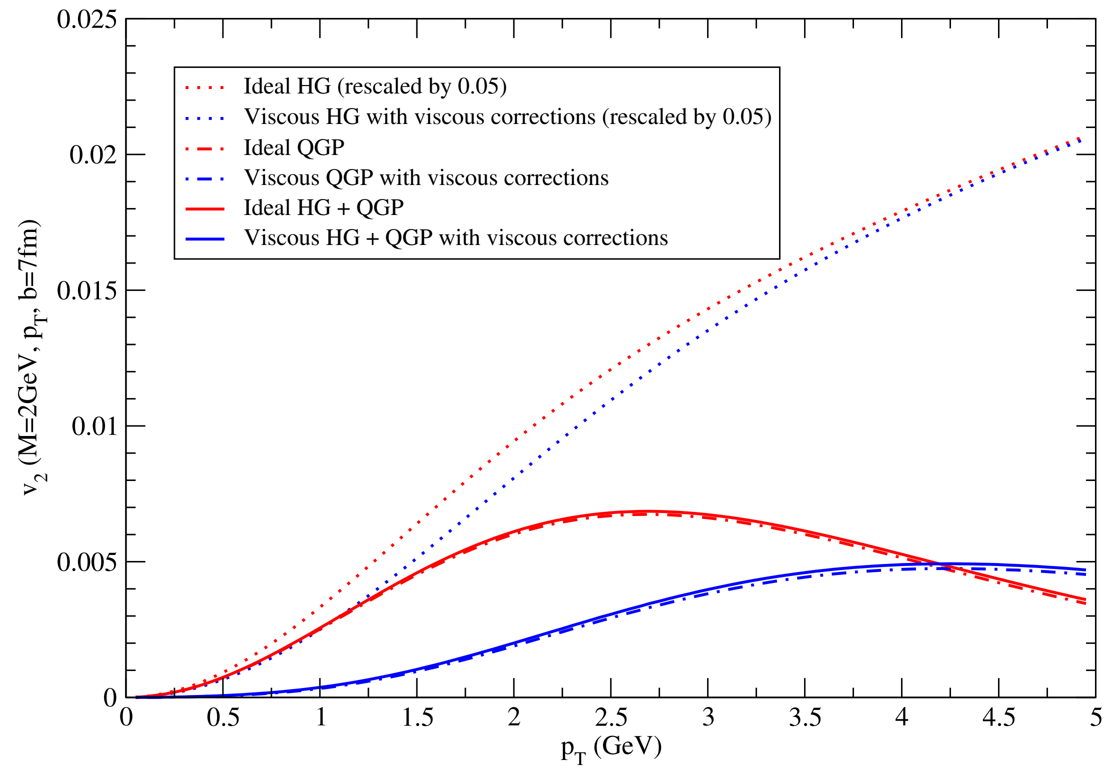


Bratkovskaya, Cassing, Linnyk (2012)

THERMAL DILEPTON V2 WITH VISCOUS EFFECTS
DILEPTON V2? [R. CHATTERJEE ET AL., PRC (2007)]





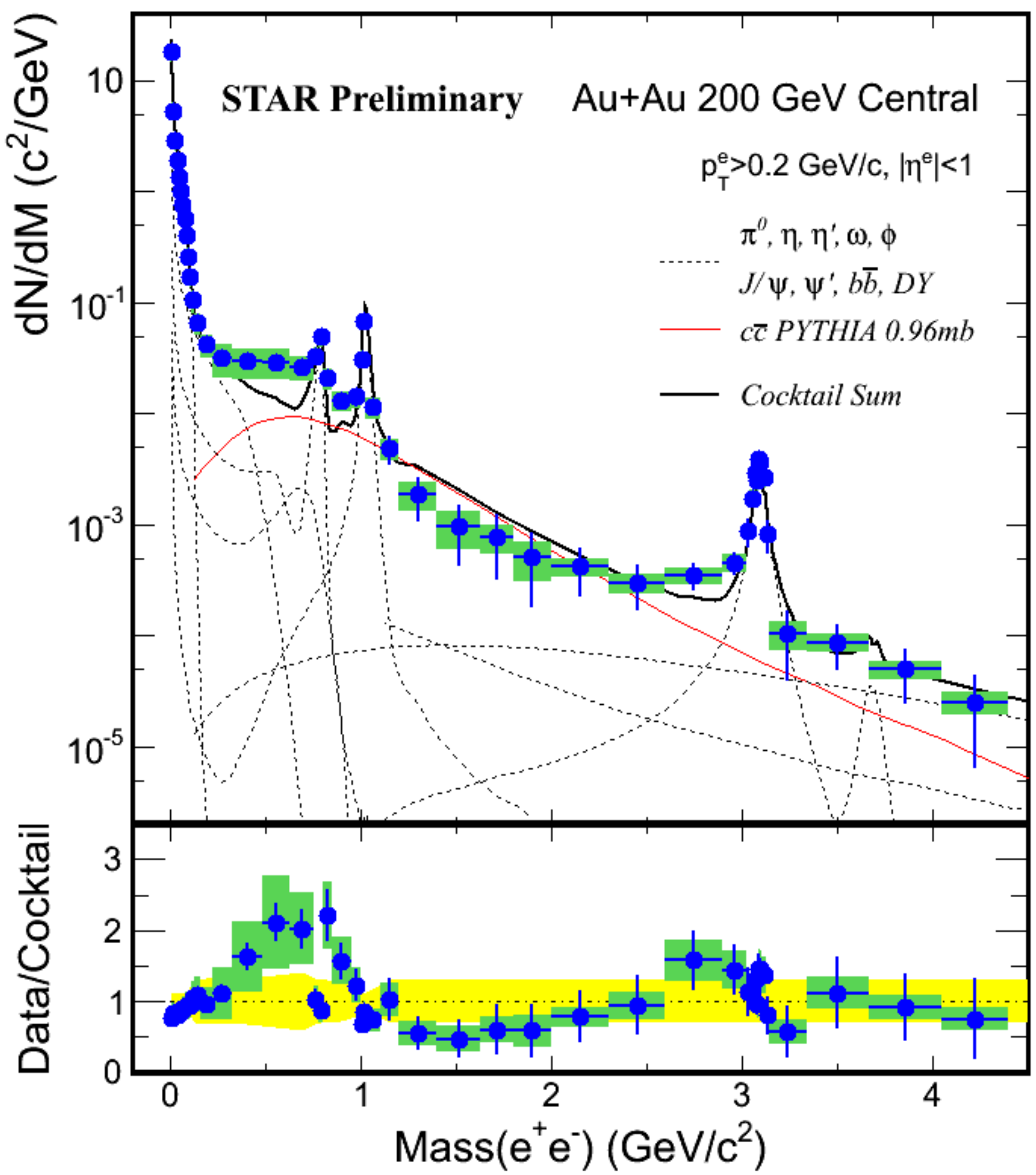


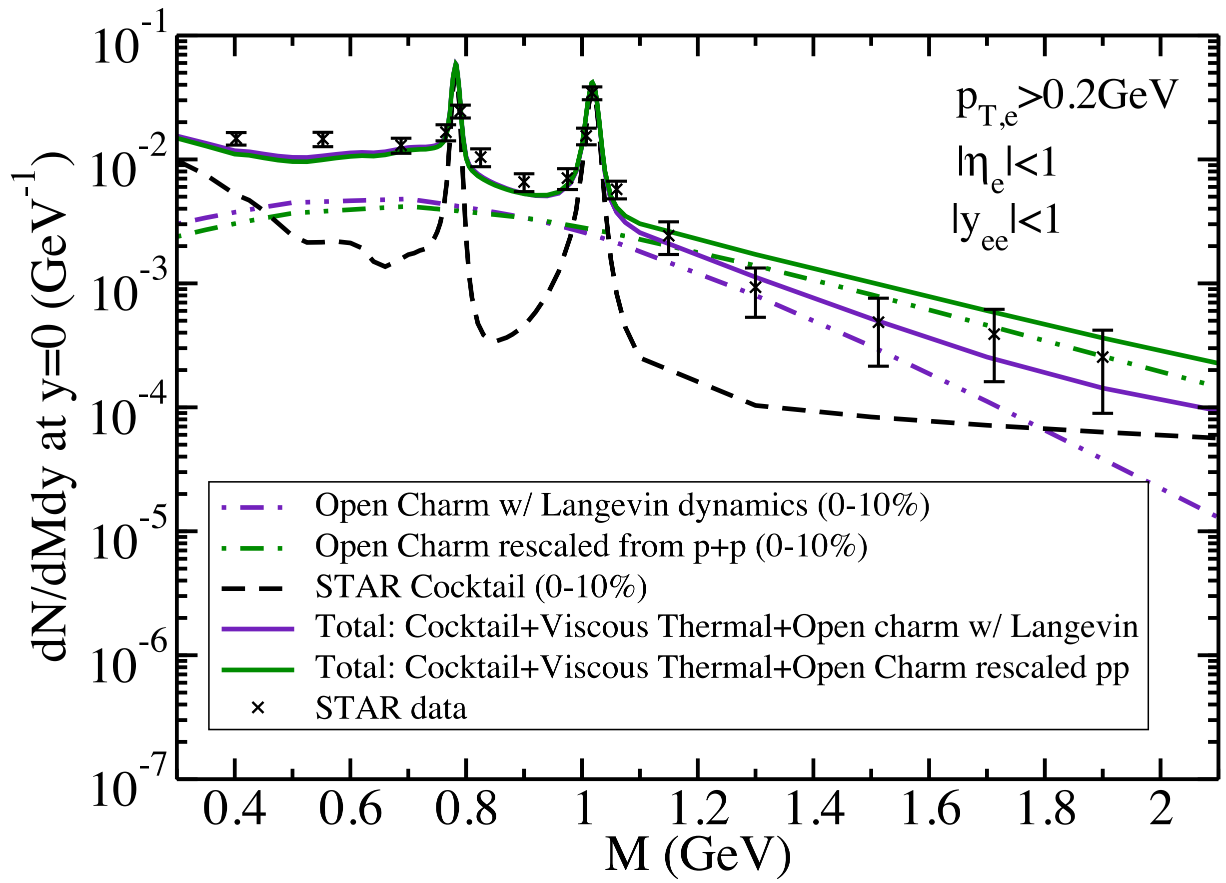
- Low M: HG-dominated
- High-M: QGP dominated

- No open charm here
- $v_2(p_T)$ for different M's contain info on the transition regime
- Viscous effects are moderate

G. Vujanovic et al.,PRC (2014)

Dileptons, some recent results from STAR





- High mass region sensitive to heavy quark energy loss in the plasma

G. Vujanovic et al.,PRC (2014)

Back to photons: 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:

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

- For each source:

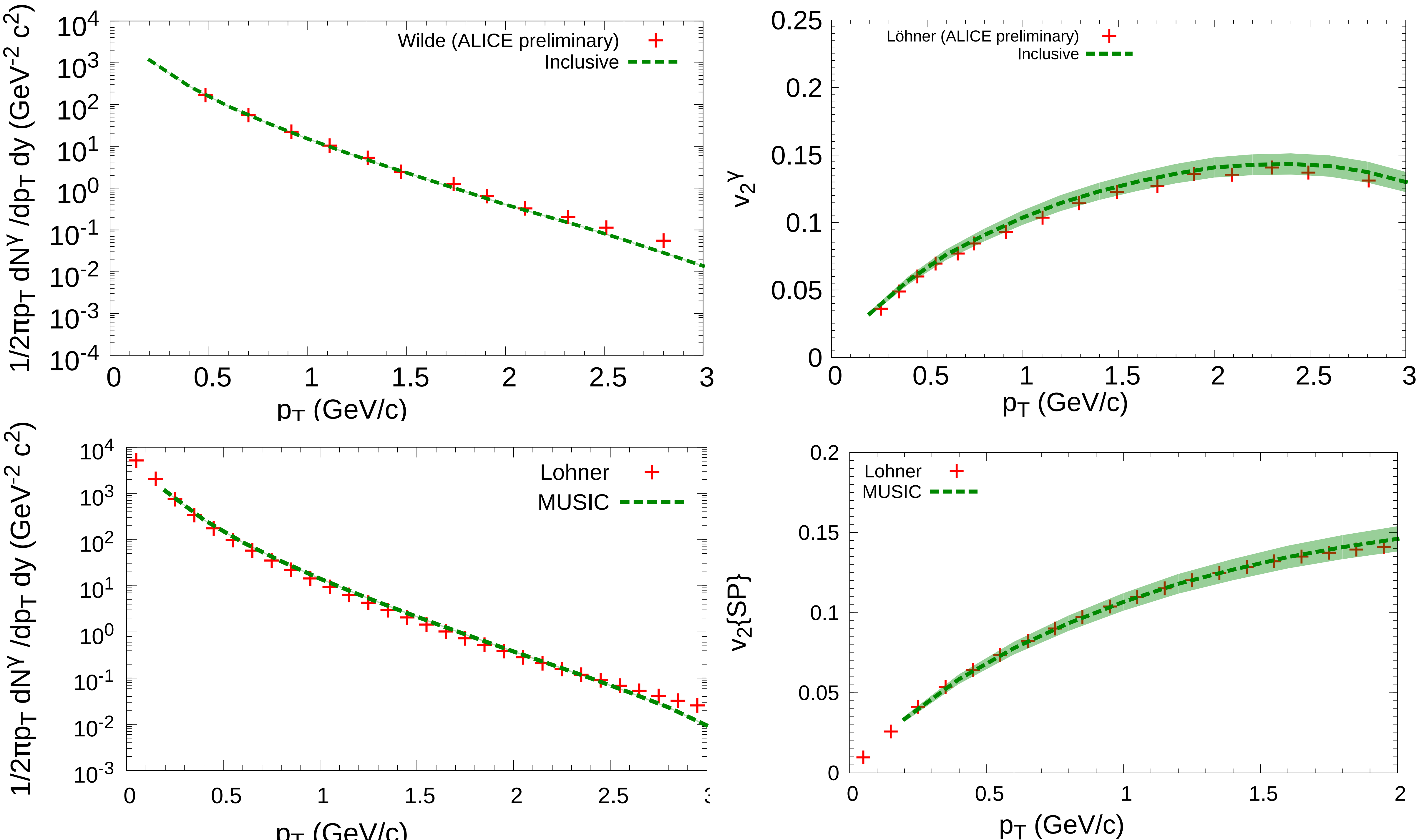
$$\frac{v_2^i = \int d\phi \frac{dN^i}{d\phi}\cos\left(2(\phi-\psi)\right)}{\int d\phi \frac{dN^i}{d\phi}}, \qquad \therefore \boxed{v_2 = \frac{\sum_i N^i v_2^i}{\sum_i N^i}}$$

- 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? How important is bremsstrahlung?
- Early-times magnetic field effects? (Basar, Kharzeev, Skokov, PRL (2012); Basar, Kharzeev, Shuryak, arXiv: 1402.2286). v_3?
- Glasma effects (McLerran, Schenke, arXiv:1403.7462)
- 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? (Gabriel's talk)

What is really measured

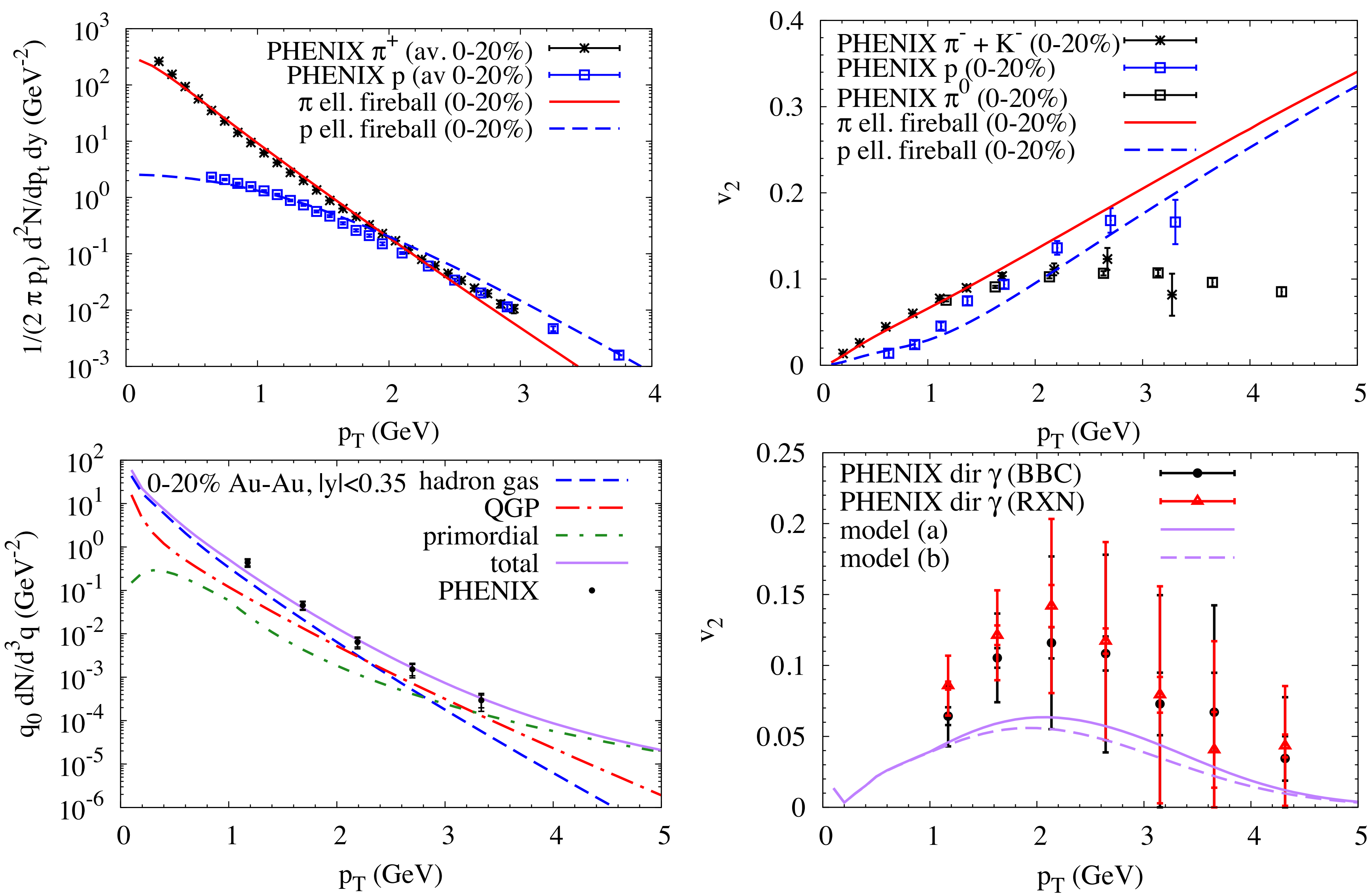


Cocktail photons

See J.-F. Paquet's poster

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?

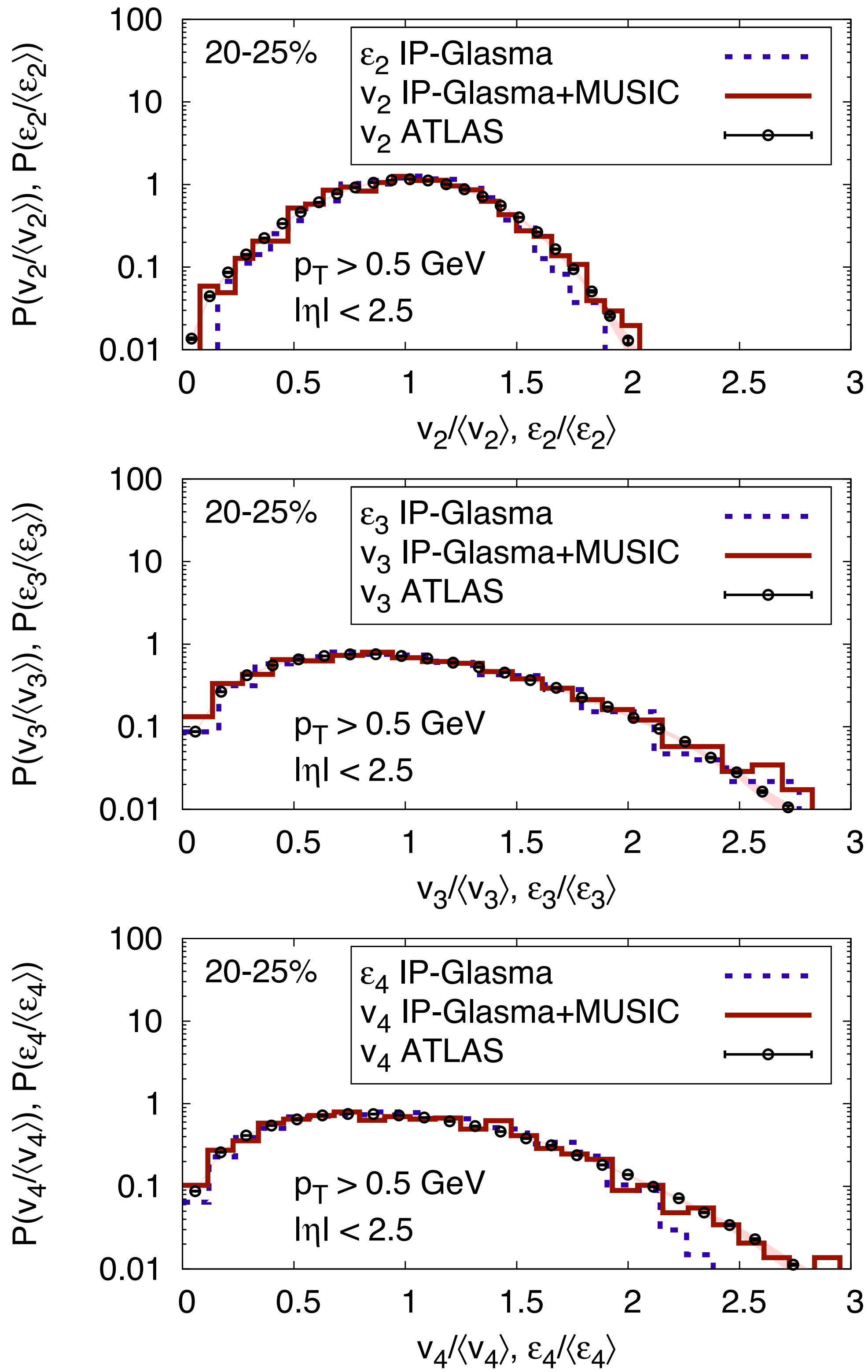


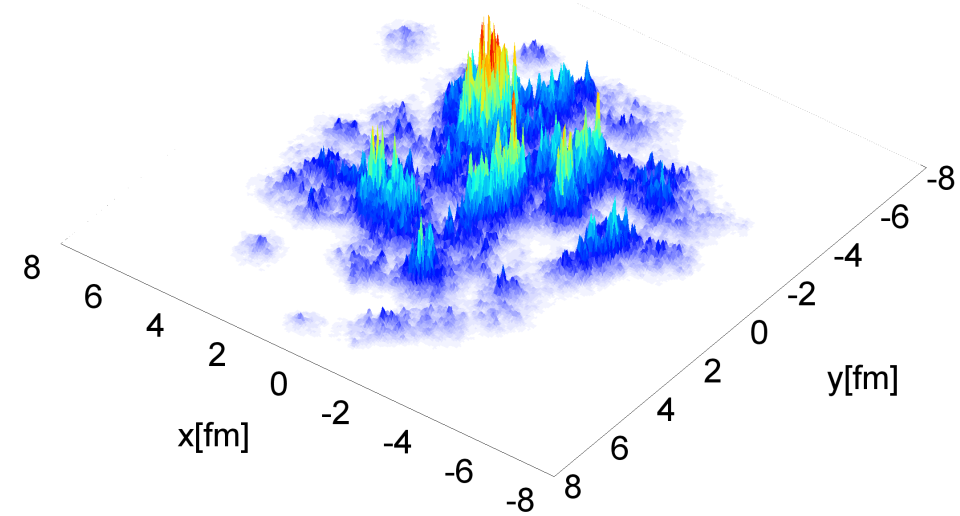
- Smooth fireball, Primordial flow, a slightly different set of resonances, baryons

van Hees, Gale, Rapp, PRC (2011)

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:

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

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)

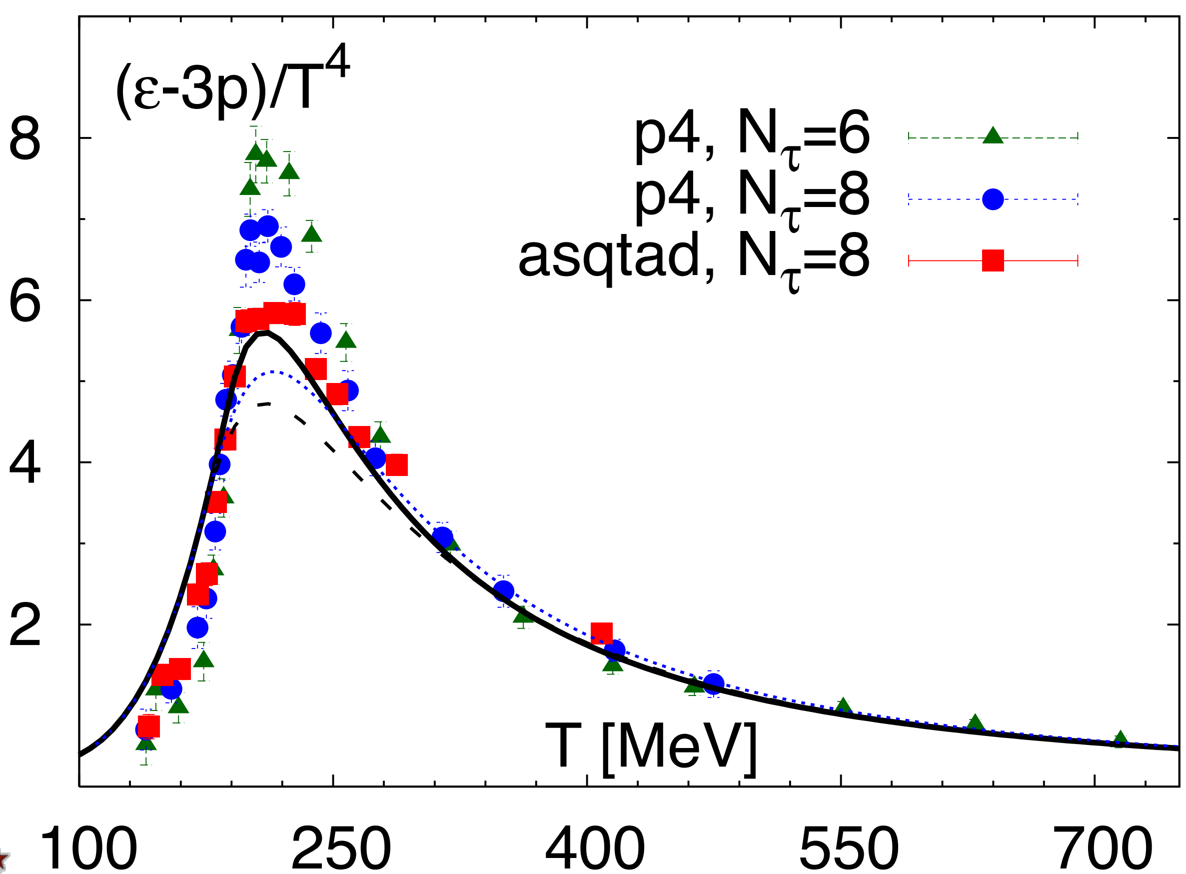
$$\zeta \gtrsim 2\eta\left(\frac{1}{3}-c_s^2\right)$$

A. Buchel, Phys. Lett. (2008)

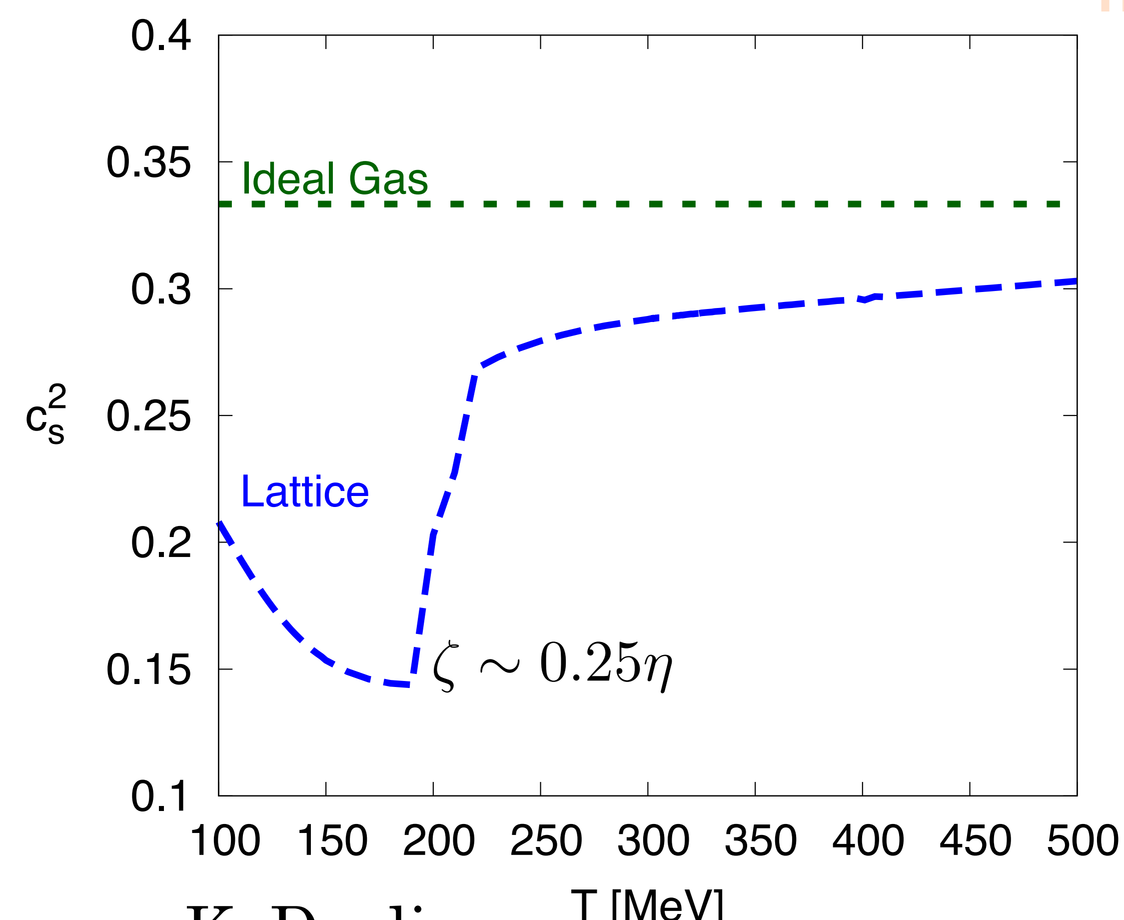
$$\zeta \approx 73\eta\left(\frac{1}{3}-c_s^2\right)^2$$

G. Denicol et al., arXiv:1403.0962

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



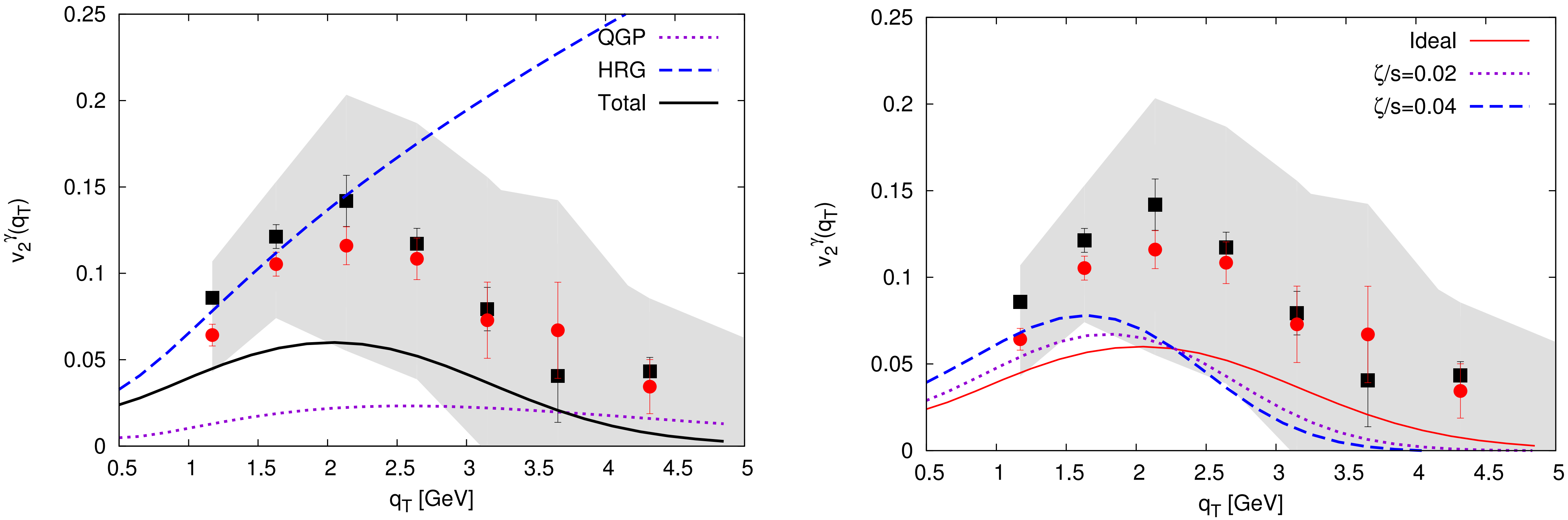
Huovinen & Petreczky



K. Dusling

Bulk viscosity effects on photons?

Ideal photon $v_2(q_T)$ | Viscous photon $v_2(q_T)$

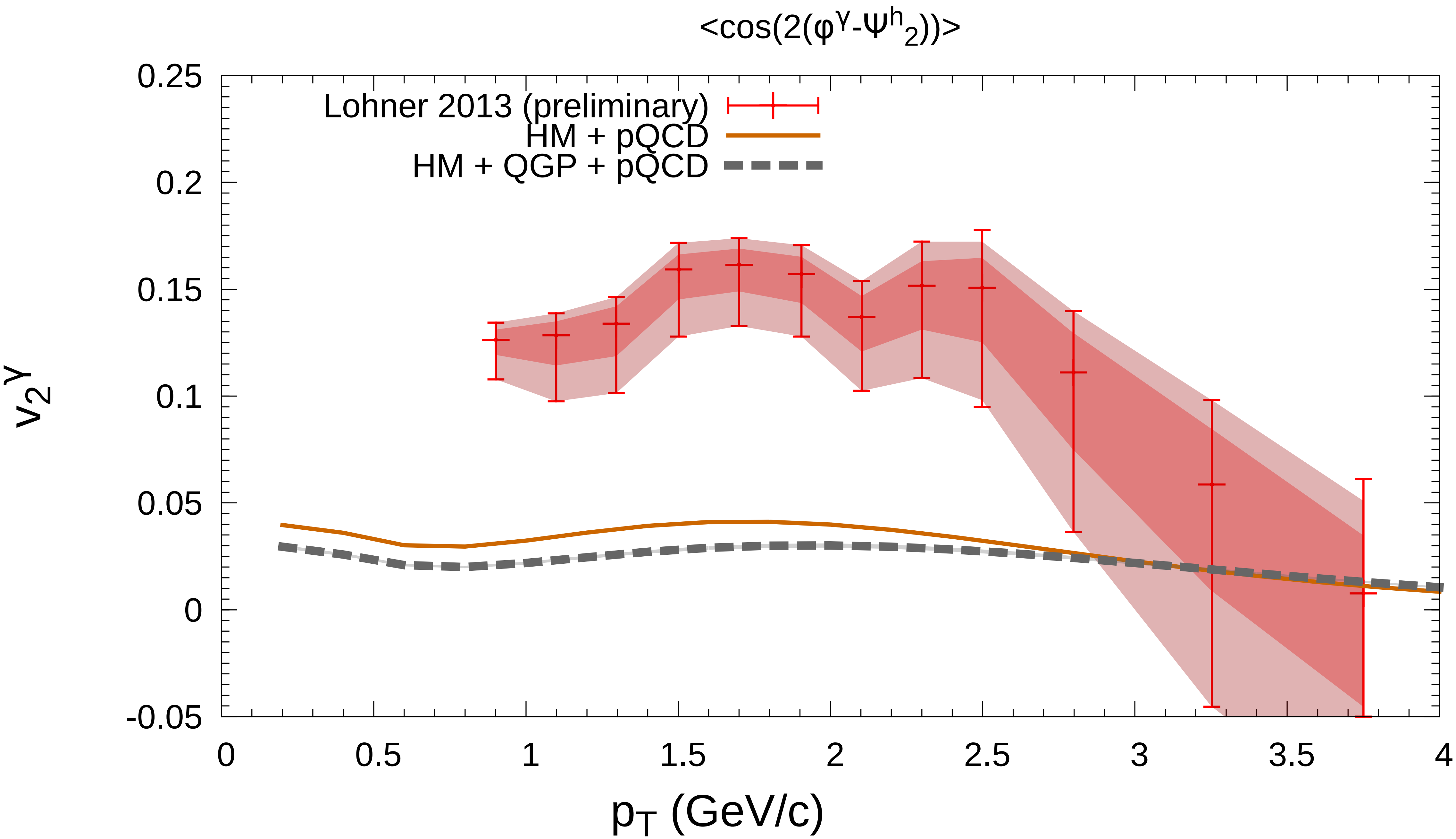


K. Dusling (2012)

- Bulk viscosity enhances the elliptic flow
- Effects are however large enough: a consistent inclusion of bulk is warranted.
- $\frac{\zeta}{s}(T)$ etc..

Switching off the QGP?

LHC - 2.76 TeV
Pb + Pb 20-40%

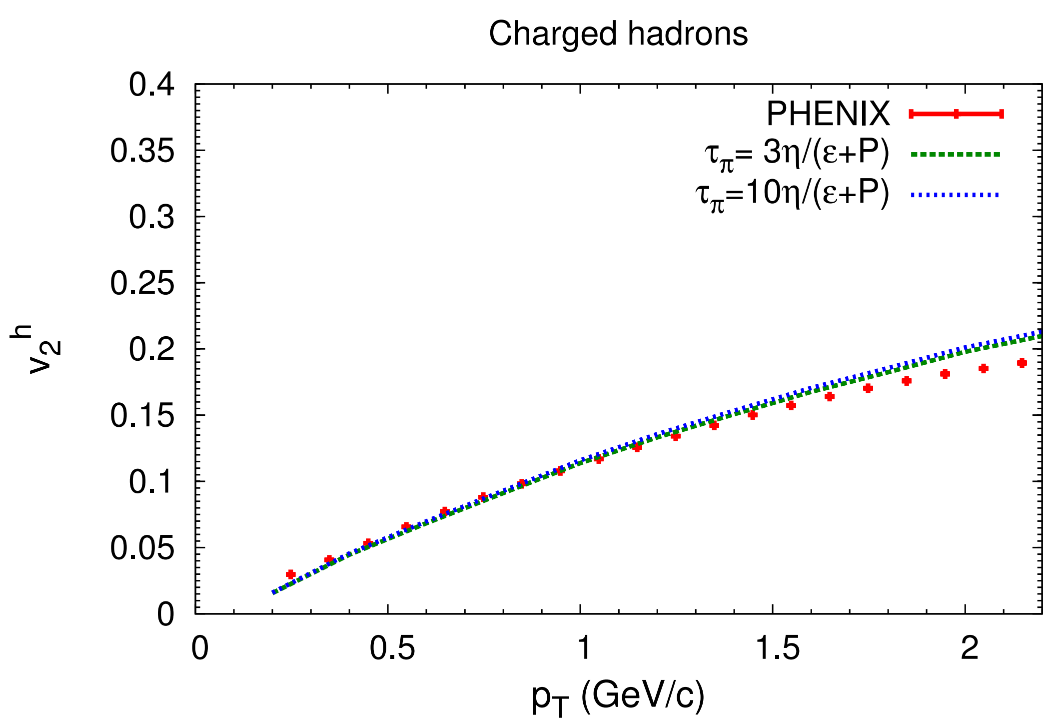


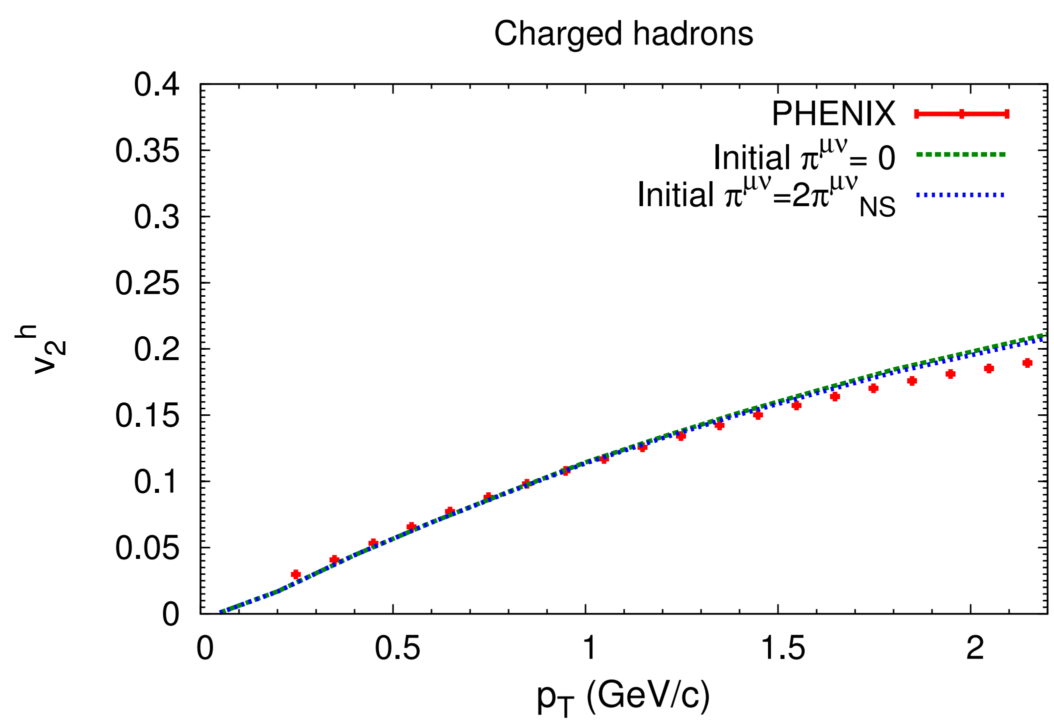
Charles Gale

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?
- What about $\pi_0^{\mu\nu}$?

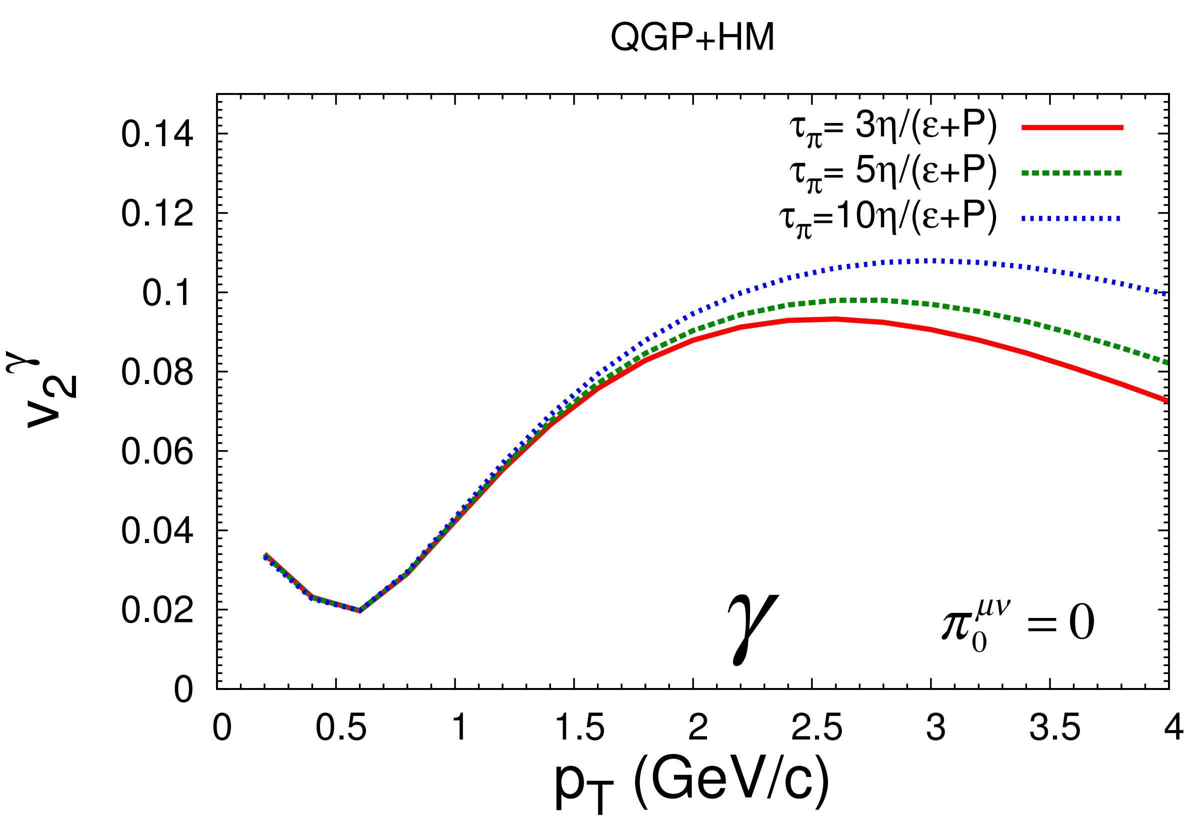


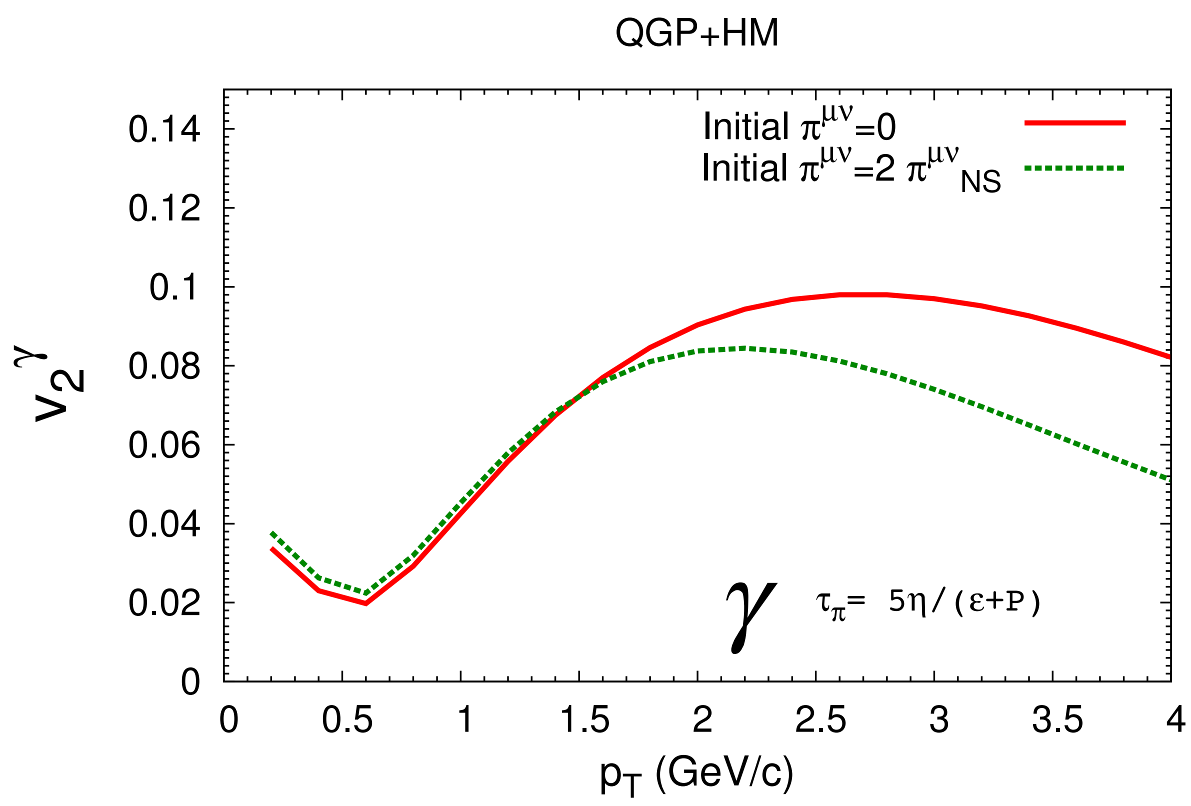


Au+Au, 200 AGeV
20-40%

Vujanovic et al., arXiv:1404.3714

More on the hydro modelling and photon production, part II

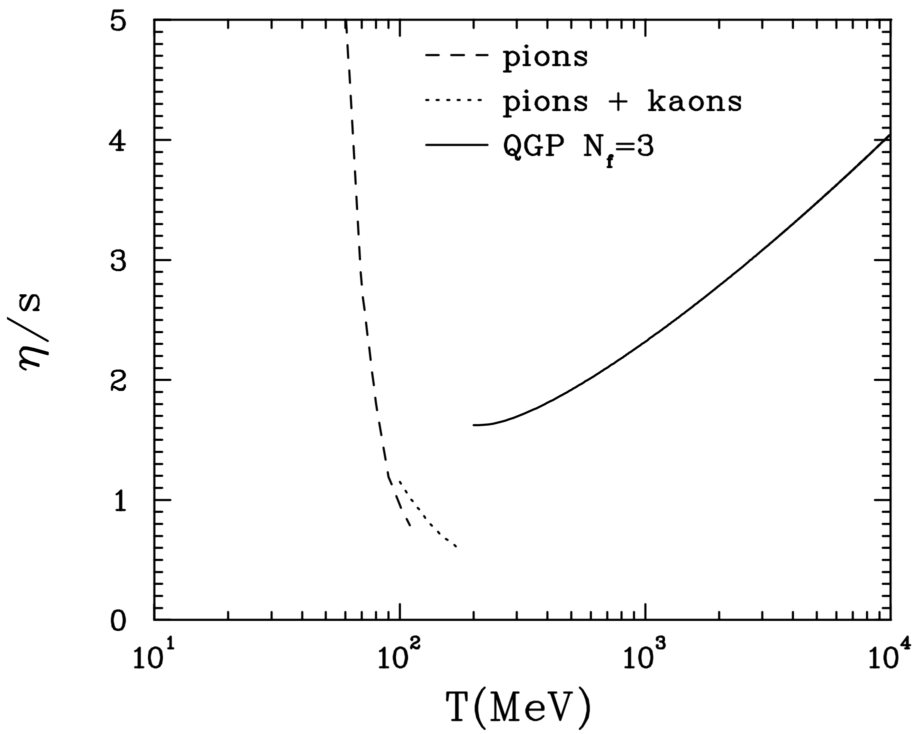




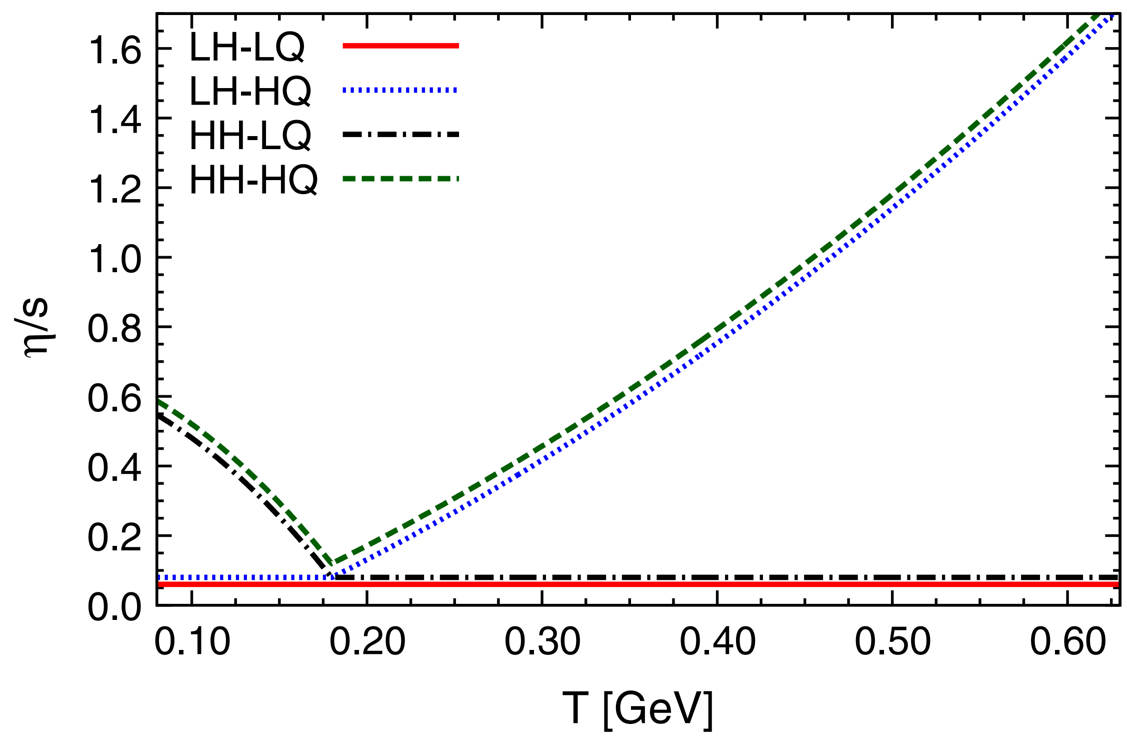
- Photons are sensitive to early time dynamics; hadrons less so
- Those extra dimensions are not typically explored in hydro

Vujanovic et al., arXiv:1404.3714

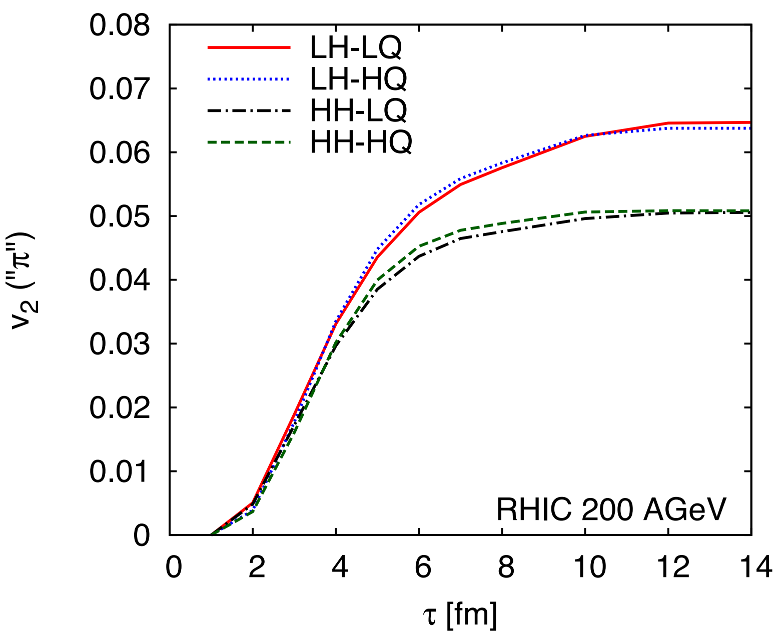
On the temperature-dependence of the shear viscosity



Csernai, Kapusta, McLerran PRL (2006)

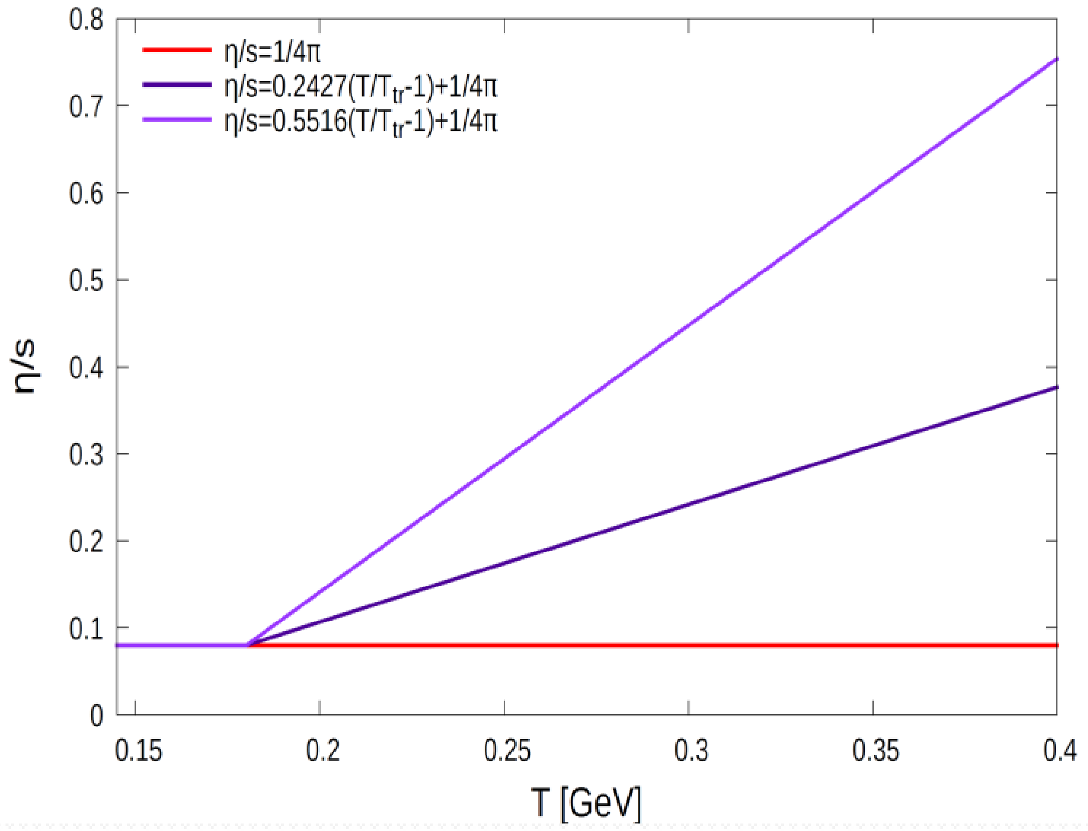


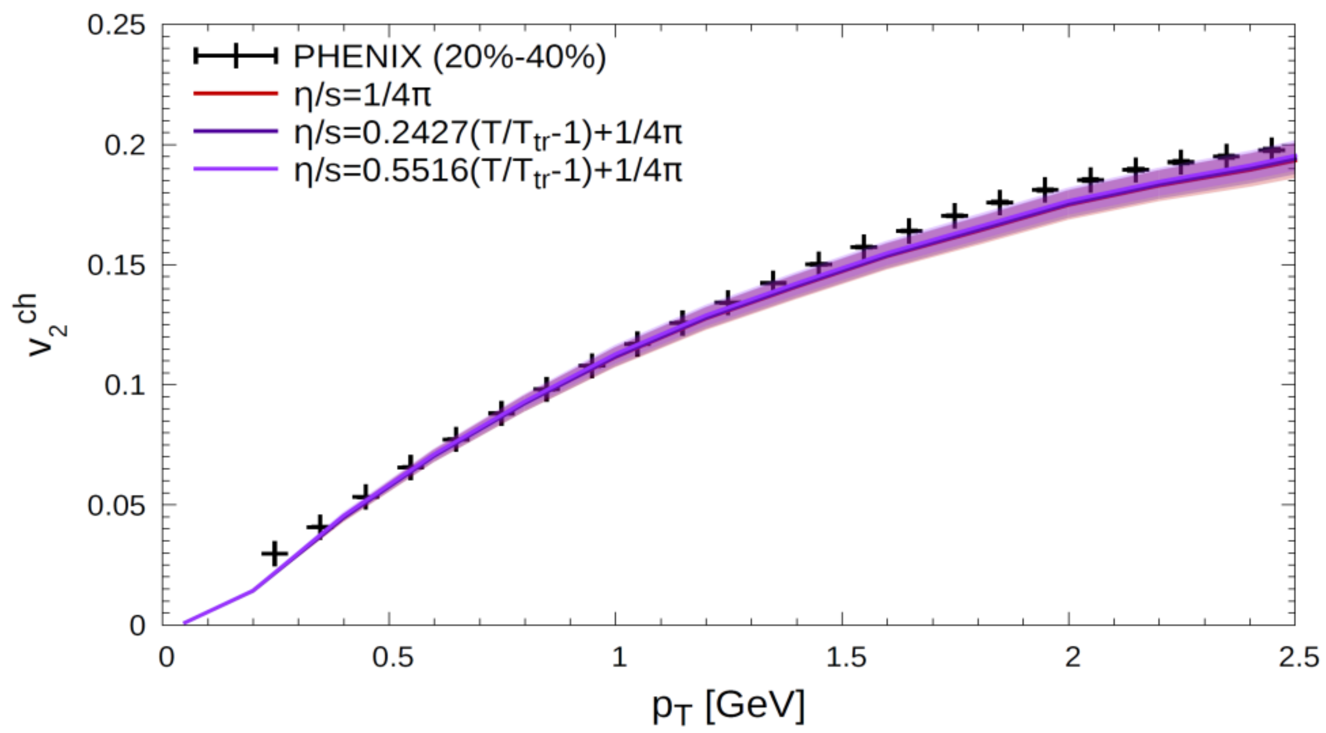
Niemi, Denicol et al., PRL (2011)

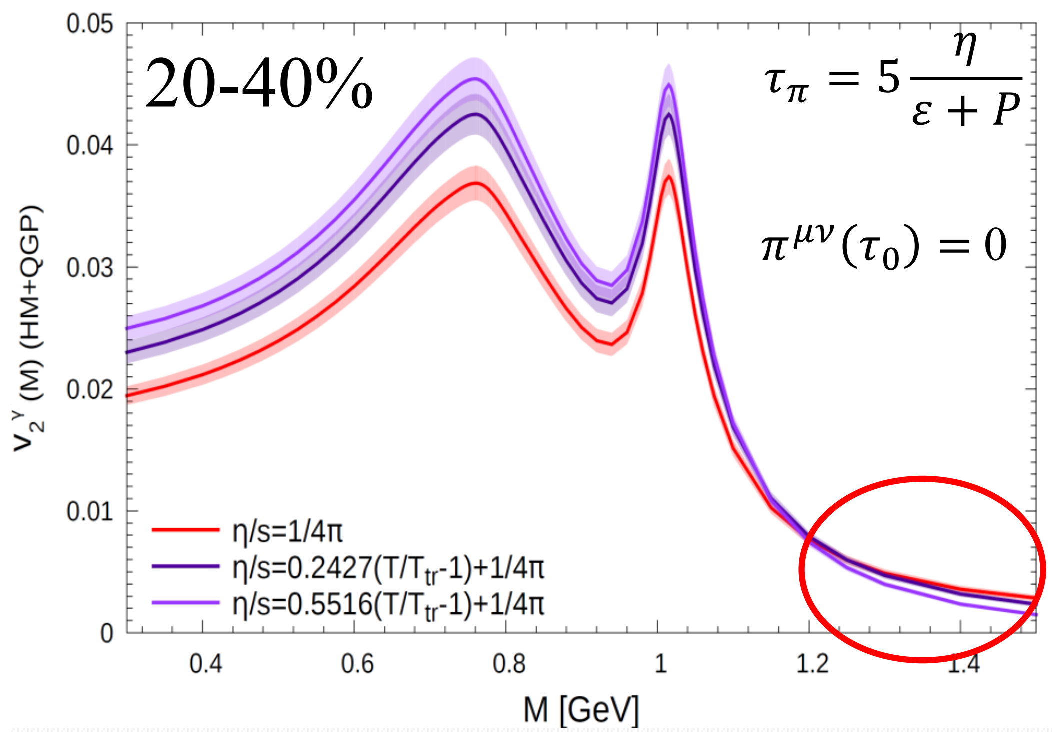


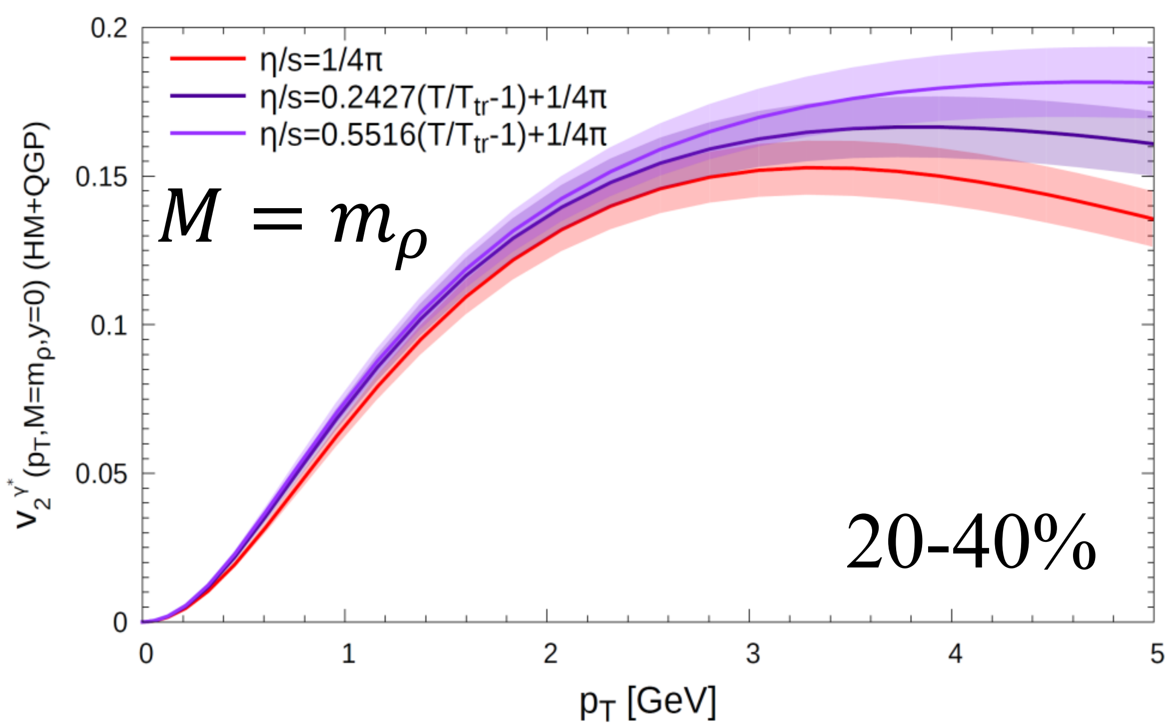
RHIC energies: suitable to study the low T, but not so sensitive to high T

Help from EM observables?









G. Vujanovic, parallel talk QM 2014

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Conclusions

- The status of EM rates and their integration in dynamical models is still in flux
- The fluid dynamical paradigm is not yet established
- 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
- . . .

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