Electromagnetic signals as probes of the initial state in relativistic nuclear collisions and of viscous hydrodynamics

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McGill

NSERC CRSNG

Outline

Motivation

Our model :Thermal Sources of EM Probes

- QGP Rate (w/ viscous corrections)
- Hadronic Medium Rates (w/viscous corrections)

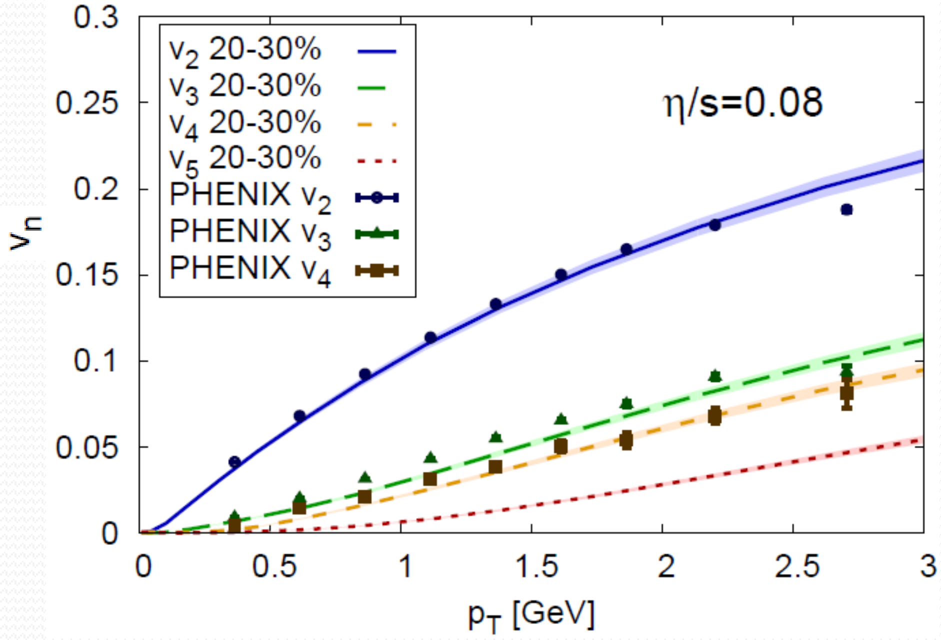
EM Probes & Out-of-Equilibrium Evolution

- Effects of the relaxation time of the shear-stress tensor on v_2
- Effects of intial condition for the shear-stress tensor on v_2

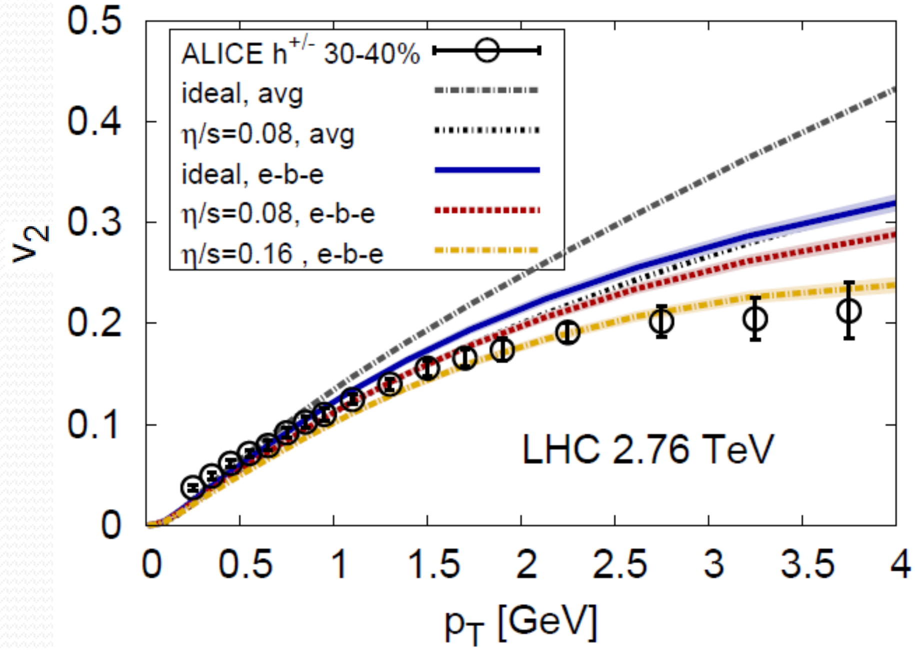
Conclusion and outlook

Hadronic flow & 3+1D Viscous Hydrodynamics

- Hadronic observables played a crucial role in understanding properties of the medium created at RHIC/LHC.
- MUSIC+MC Glauber: RHIC LHC



B. Schenke, et al., Phys. Rev. C 85, 024901 (2012)



B. Schenke, et al., Phys. Lett. B 702, 59 (2011)

3+1D Viscous Hydrodynamics

- Viscous hydrodynamics equations for heavy ions:

$$\partial_\mu T^{\mu\nu} = 0 \longleftarrow \text{Energy-momentum conservation}$$

$$T^{\mu\nu} = T_0^{\mu\nu} + \pi^{\mu\nu} \qquad T_0^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu} \qquad P = P(\epsilon)$$

$$\tau_\pi \Delta^\mu_\alpha \Delta^\nu_\beta u^\sigma \partial_\sigma \pi^{\alpha\beta} = -\left(\pi^{\mu\nu} - \pi^{\mu\nu}_{NS}\right) - \frac{4}{3}\pi^{\mu\nu}(\partial_\alpha u^\alpha) \qquad \tau_\pi = b\frac{\eta}{\varepsilon + P}$$

$$\pi^{\mu\nu}_{NS} = \eta\left(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3}\Delta^{\mu\nu}\nabla_\alpha u^\alpha\right) \qquad \frac{\eta}{s} = \frac{1}{4\pi}$$

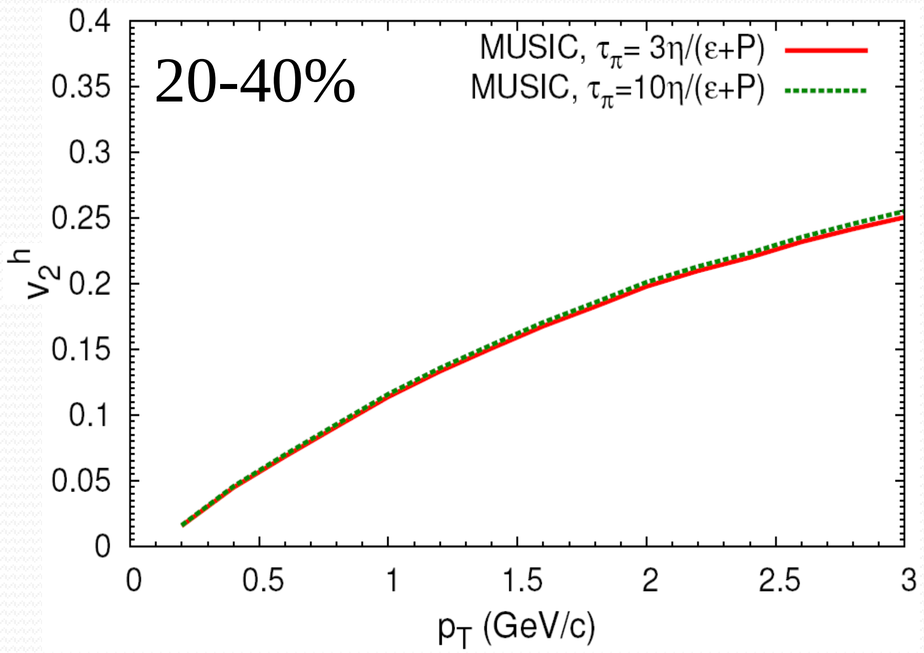
- Lattice QCD EoS [P. Huovinen and P. Petreczky, Nucl. Phys. A 837, 26 (2010).] (s95p-v1)

- Out-of-equilibrium part of $T^{\mu\nu}$, $\pi^{\mu\nu}$, is less constrained by hadronic observables and is thus less known.

- Goal: 1) to explore the effects of changing τ_π on flow of EM probes,
  2) study the effects of init. $\pi^{\mu\nu}$ [rel. to Bjorken flow Navier-Stokes]
- Keep all other initial and freeze-out conditions set by an Optical Glauber model [see B. Schenke, et al., Phys. Rev. C82, 014903, (2010)].

Motivation

- Hadronic observables have limited sensitivity to departures from equilibrium in the evolution the medium, e.g. the relaxation time (τ_π).



Motivation

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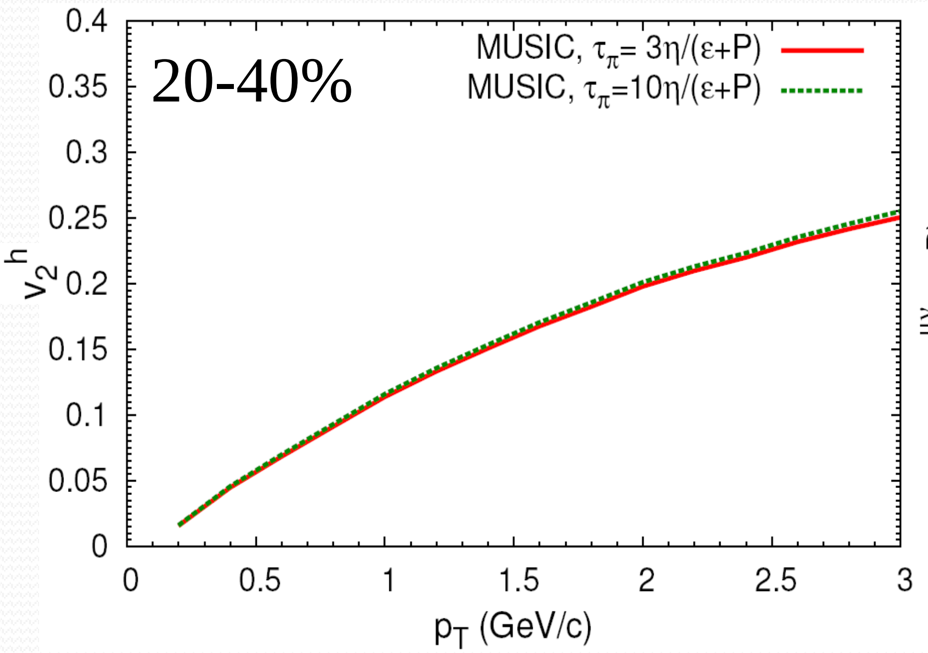
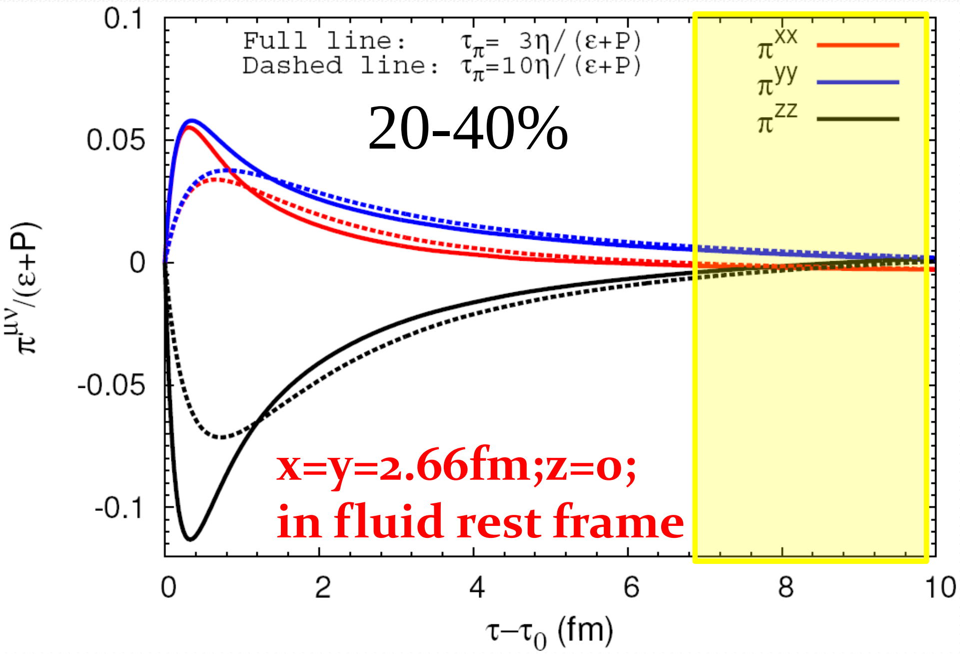
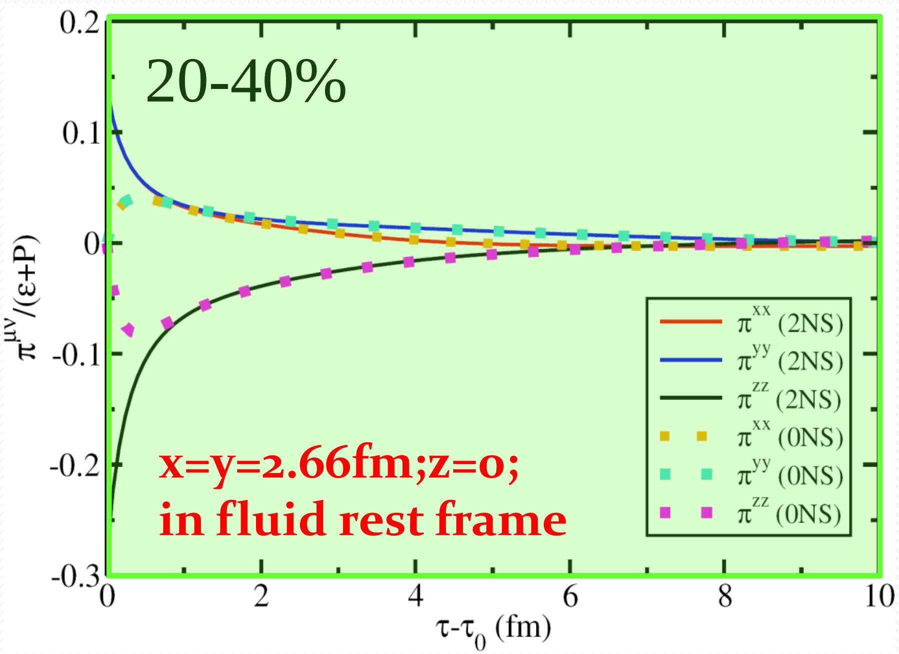


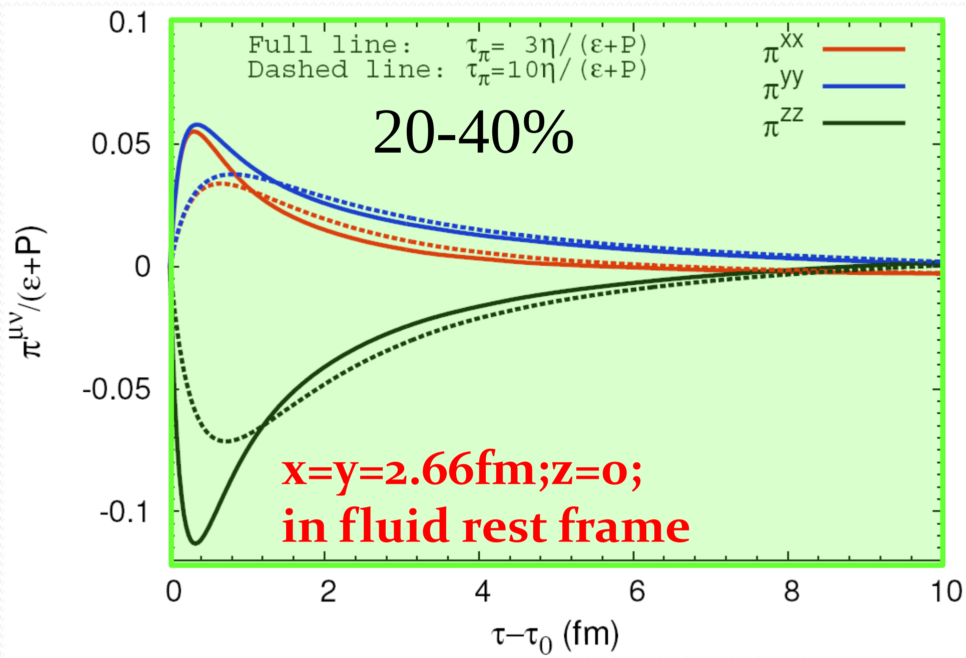


- Why? Hadrons are emitted at late times => only sensitive to freeze-out conditions of the medium, where $\pi^{\mu\nu}$ is small.

Motivation

- Hadronic observables have limited sensitivity to departures from equilibrium in the evolution the medium (τ_π) and to init. cond. ($\pi^{\mu\nu}$) .





- EM probes on the other hand can escape the medium at any time hence are more sensitive to the evolution of the medium (in particular to the size of τ_π) and initial conditions (init. $\pi^{\mu\nu}$). Question: how much?

Viscous Corrections to Dilepton Rates

- Viscous correction to the Born rate in kinetic theory

$$\frac{d^4R}{d^4q} = \int d^3k_1 d^3k_2 n(E_1) n(E_2) v_{12} \sigma \delta^4(q - k_1 - k_2)$$

Israel-Stewart ansatz: $n(E) \to n(E) + \frac{C}{2} n(E)\left(1 \pm n(E)\right) \frac{k^\mu}{T}\frac{k^\nu}{T}\frac{\pi^{\mu\nu}}{\epsilon + P}$

- Dusling & Lin, Nucl. Phys. A 809, 246 (2008). Stay tuned for Mikko Laine talk: recent developments thermal dilepton rates.

- Hadronic Medium (HM) Rate:

$$\frac{d^4R}{d^4q} = \frac{\alpha^2}{\pi^3}\frac{L(M)}{M^2}\frac{m_V^4}{g_V^2}\left\{-\frac{1}{3}[Im\ D_V^R]_\mu^\mu\right\} n_{BE}(q^0)$$

- Self-Energy [Eletsky, et. al., Phys. Rev. C, 64, 035202 (2001)]

$$\Pi_{Va}(p,T) = -\frac{m_a m_V T}{\pi p}\int \frac{d^3k}{(2\pi)^3}\frac{\sqrt{s}}{k^0} f_{Va}(s) n_a(k^0)$$

Israel-Stewart viscous correction

- For details see G. Vujanovic et. al., Nucl. Phys. A 904-905 (2013) 557c

Viscous Corrections to Photon Rates

- QGP phase (compton scattering and annihilation)

$$E\frac{d^3R_{\text{hard}}}{d^3p} = N\int \frac{d^3p_1}{2E_1(2\pi)^3}\frac{d^3p_2}{2E_2(2\pi)^3}\frac{d^3p_3}{2E_3(2\pi)^3}\pi|\mathcal{M}|^2\delta^4(p_1+p_2-p_3-p)f(p_1)f(p_2)(1\pm f(p_3))$$

$$E\frac{dR_{\text{soft}}}{d^3p} = \frac{i}{2(2\pi)^3}(\Pi_{12})^{\mu}_{\mu}(Q)$$ ← viscous correction to HTL

Israel-Stewart viscous correction (for $f(p_1)$, $f(p_2)$, $f(p_3)$)

- Ref.: C. Shen J.-F. Paquet, C. Gale and U. Heinz, in preparation; Talk by Chun Shen on Monday

- HM Kinetic Theory: SU(3) MYM + U(1) Vector Meson Dominance

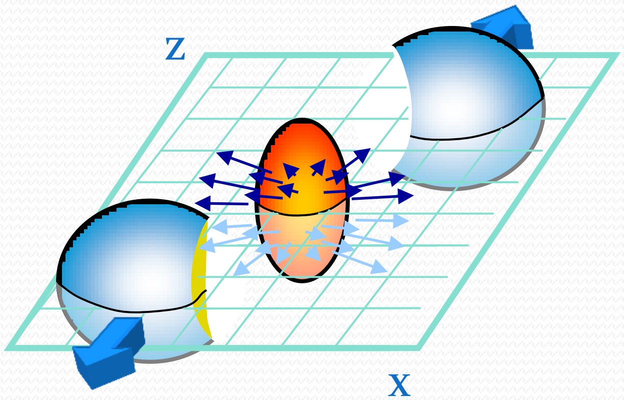
$$E\frac{d^3R}{d^3p} = N\int \frac{d^3p_1}{2E_1(2\pi)^3}\frac{d^3p_2}{2E_2(2\pi)^3}\frac{d^3p_3}{2E_3(2\pi)^3}\pi|\mathcal{M}|^2\delta^4(p_1+p_2-p_3-p)f(p_1)f(p_2)(1\pm f(p_3))$$

Israel-Stewart viscous correction (for $f(p_1)$, $f(p_2)$, $f(p_3)$)

- M. Dion et al. Phys. Rev. C 84 064901 (2011)

A measure of flow (v_n)

- Elliptic Flow & higher harmonics



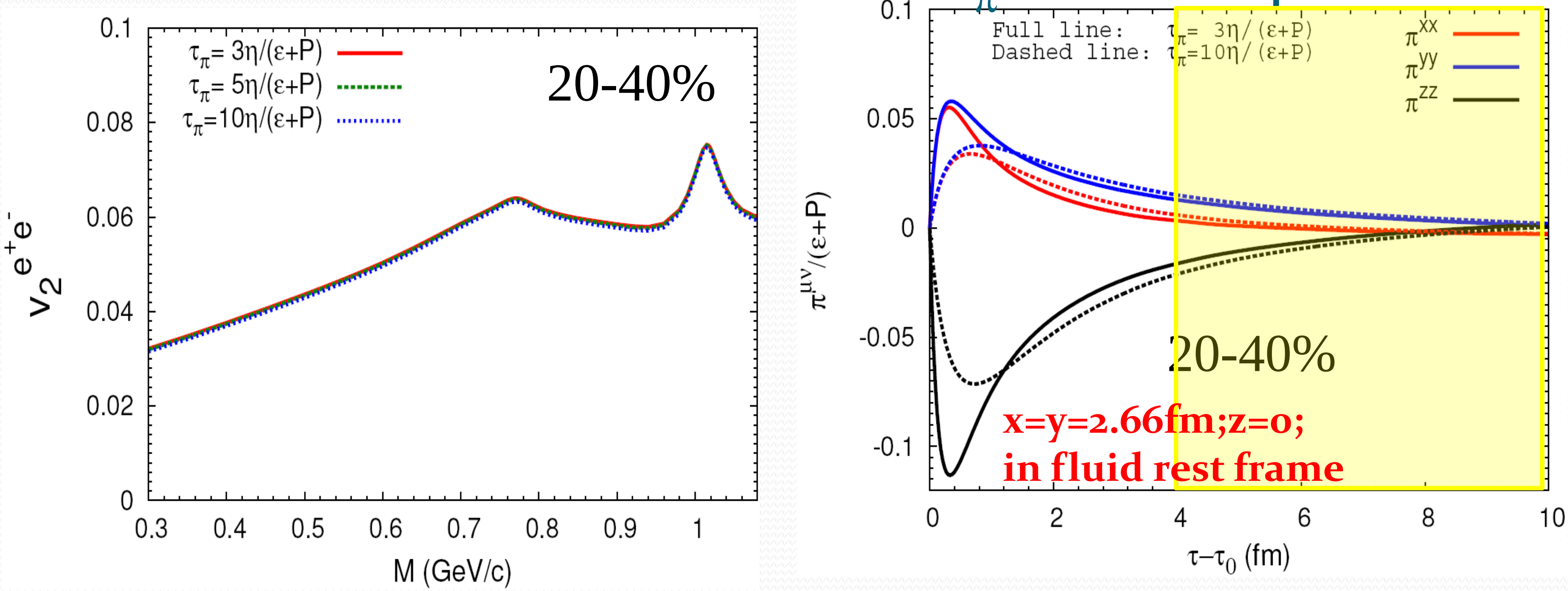
- A nucleus-nucleus collision is typically not head on; an almond-shape region of matter is created.
- This shape and its pressure profile gives rise to elliptic flow.

- To describe the evolution of the shape use a Fourier decomposition, i.e. flow coefficients v_n

$$\frac{dN}{dMp_T dp_T d\phi dy} = \frac{1}{2\pi}\frac{dN}{dMp_T dp_T dy}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos(n\phi - n\psi_n)\right]$$

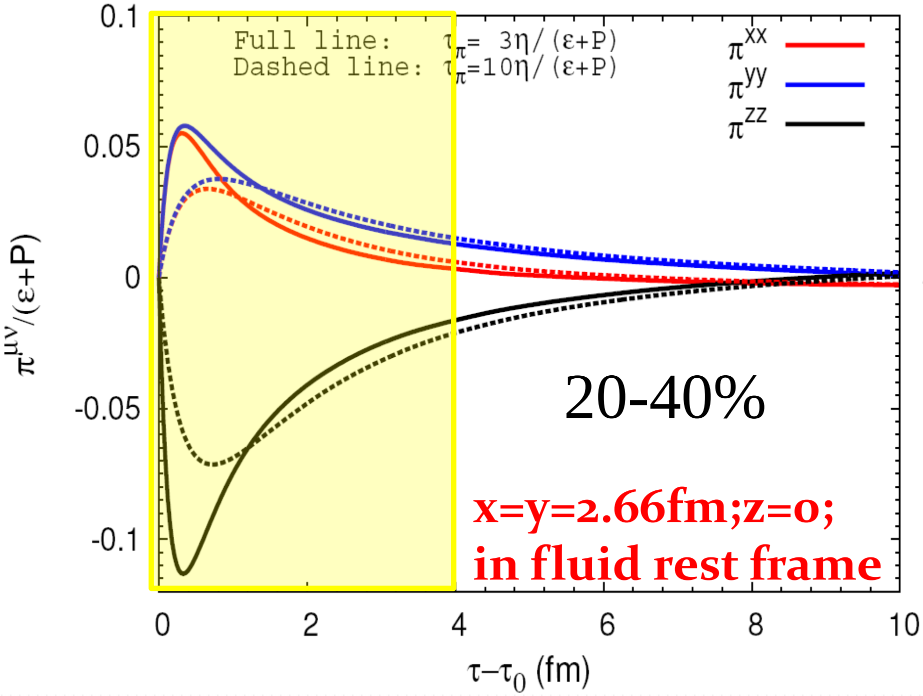
- Important note: when computing v_n's from several sources, one performs a yield weighted average.

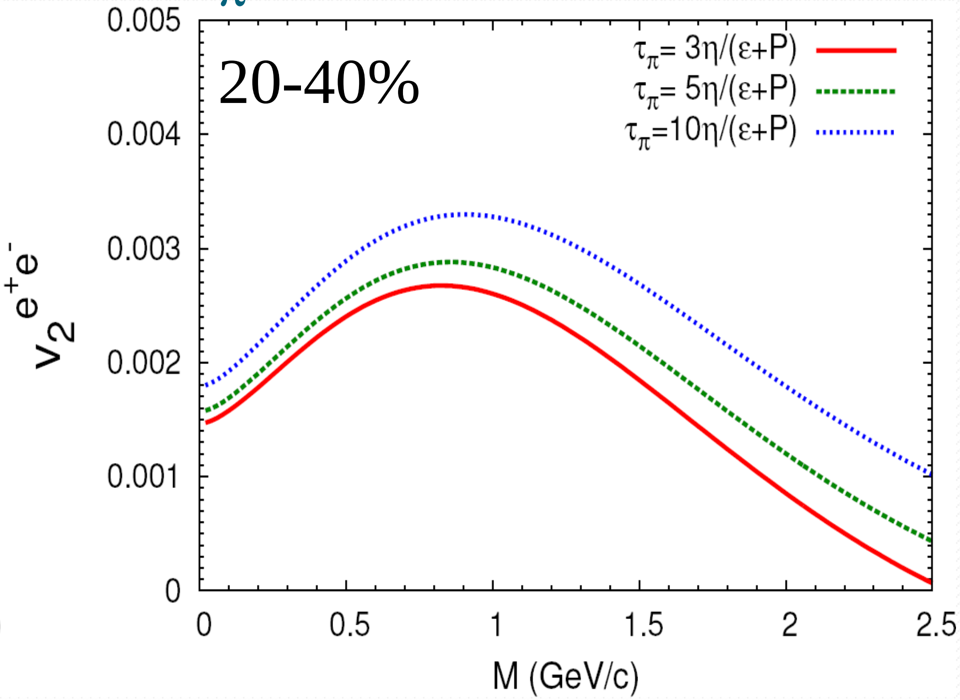
Effects of relaxation time τ_π: HM Dilepton



- Hadronic Medium (HM); the difference in the evolution of $\pi^{\mu\nu}(\tau)$ as one increases τ_π (dashed lines vs solid lines)is very small at late times (where HM dominates).
-

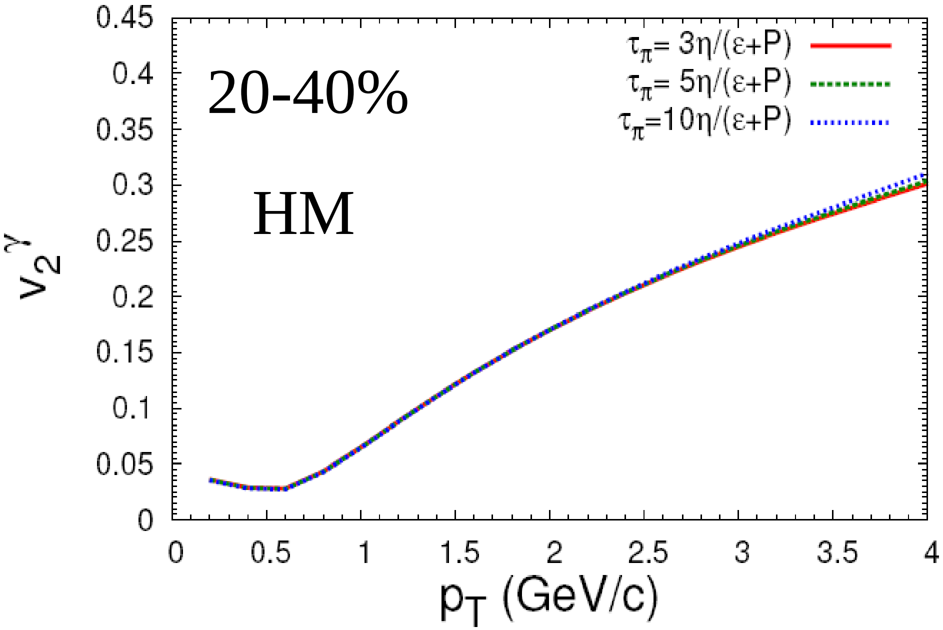
Effects of relaxation time τ_π: QGP dileptons

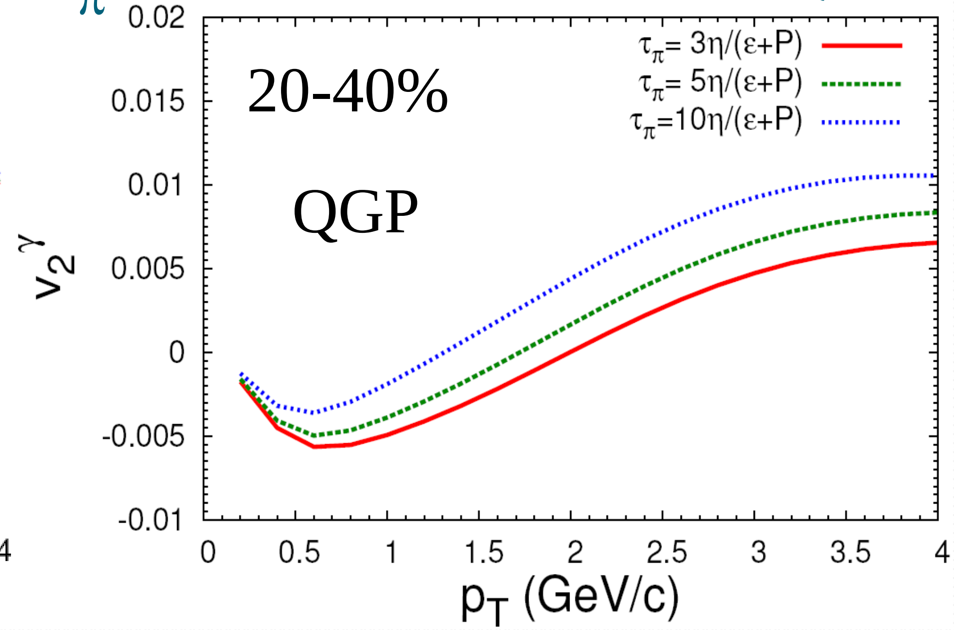


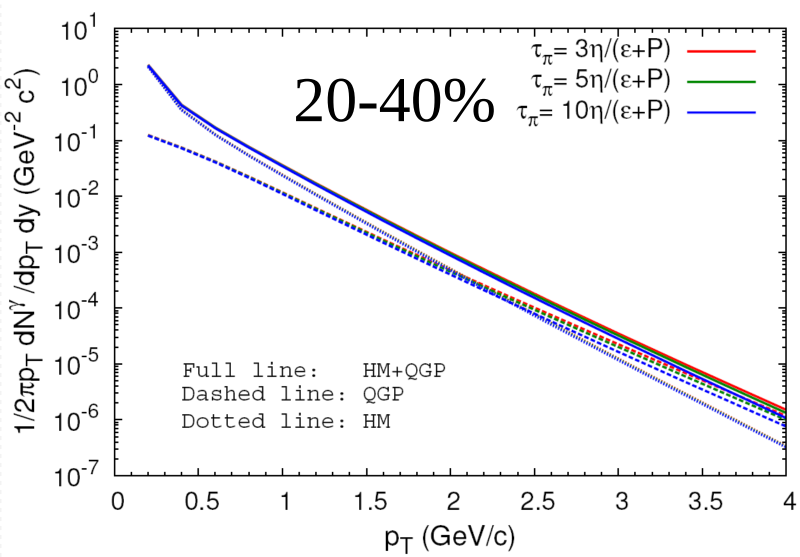


- QGP is probing the medium at early times. Increasing τ_π augments the medium memory of its early out-of equilibrium state (=> larger $\pi^{\mu\nu}(\tau)$).

Effects of relaxation time τ_π: Photon's HM and QGP

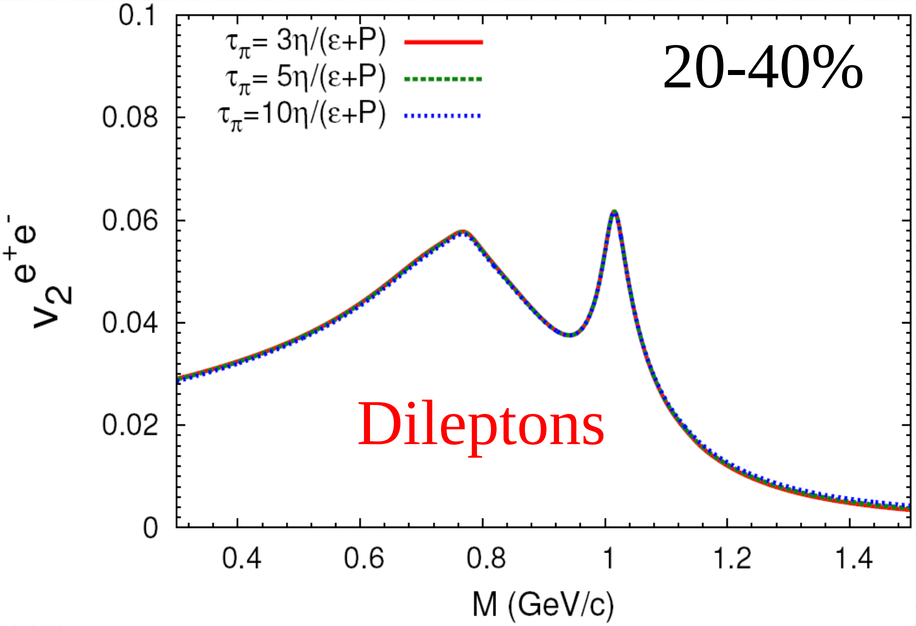


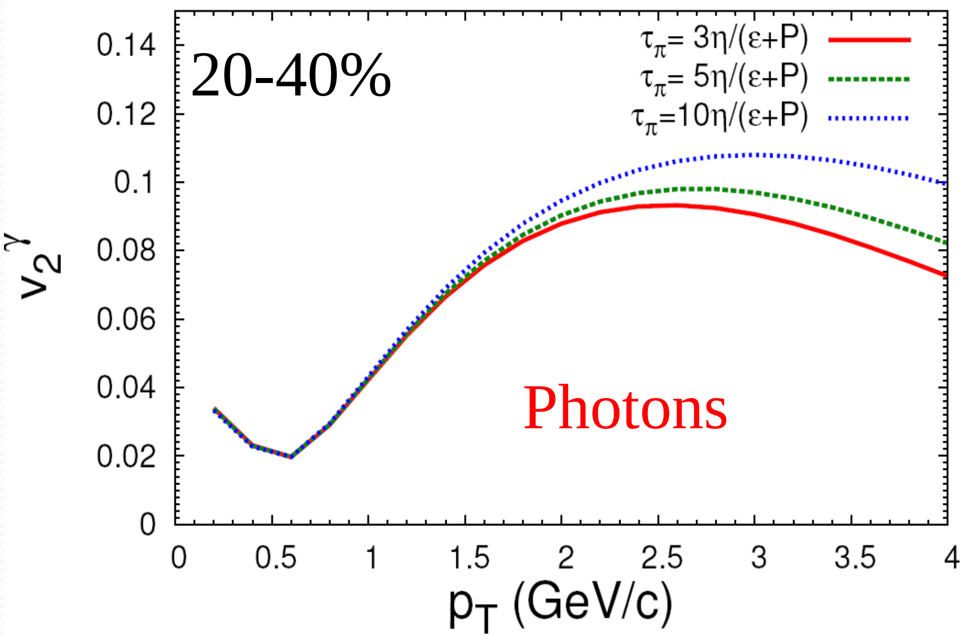


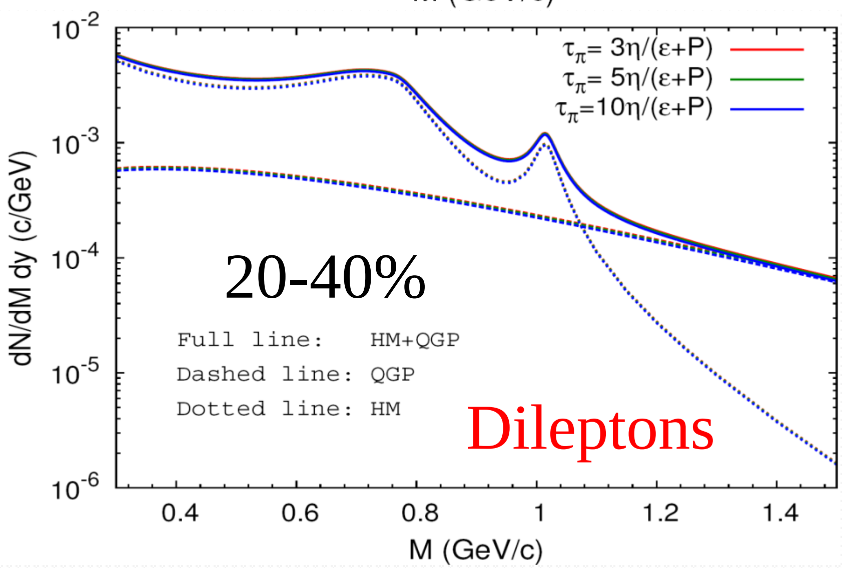


- τ_π affects photons in a similar way.
- Photon yield is largely unaffected.
- The photon yield from HM and QGP are of the same order of magnitude => QGP's contribution is visible in total v_2

Effects of relaxation time τ_π on thermal EM v_2

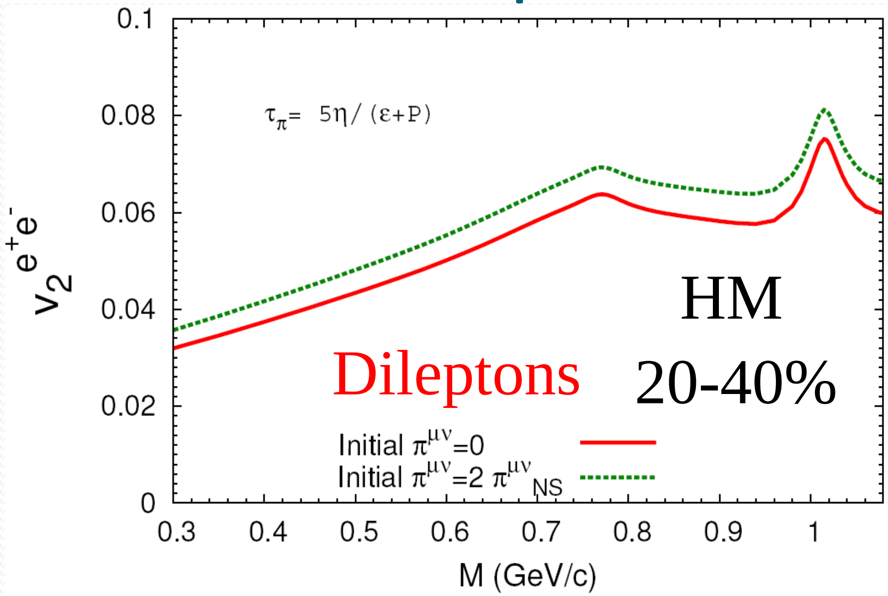


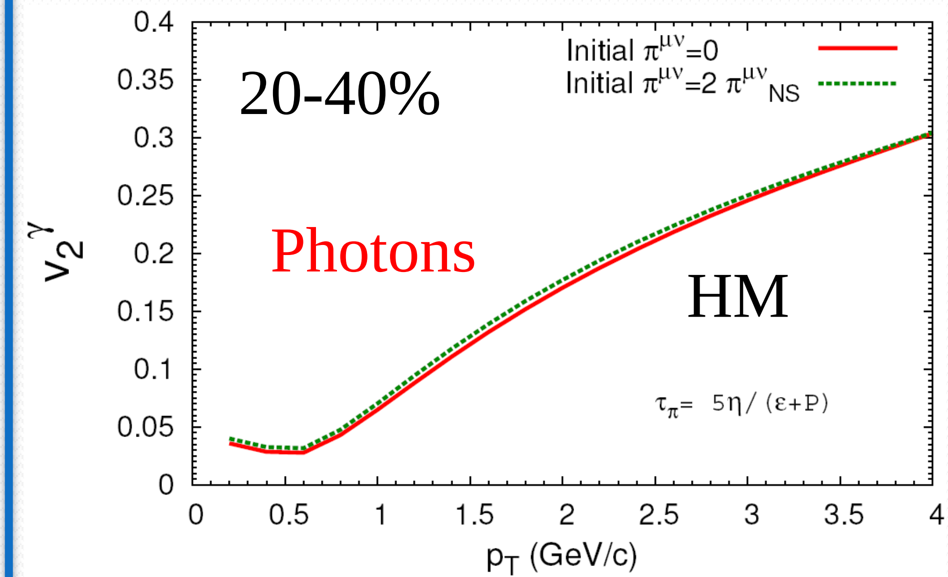


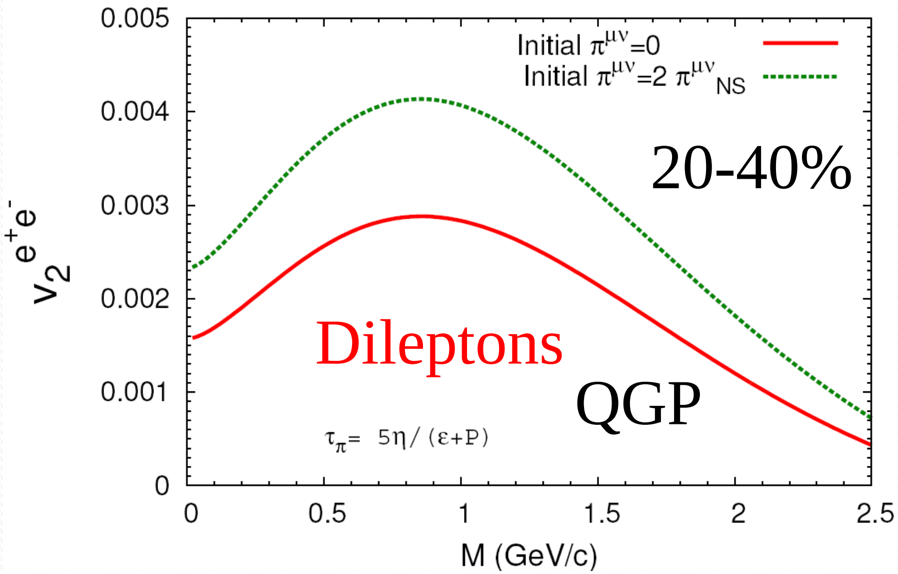


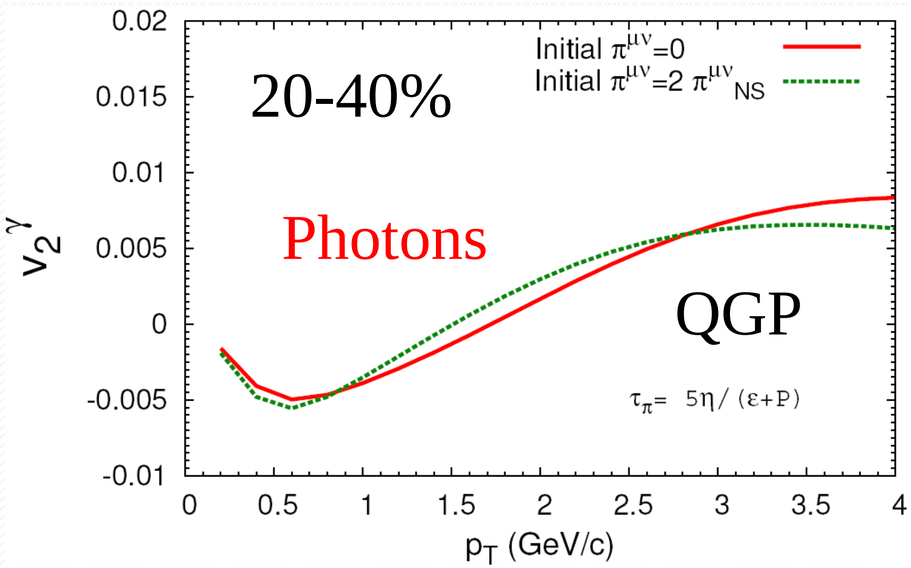
- HM+QGP (yield weighted average).
- Photons: the increase of QGP's v_2 (by increasing τ_π) is seen in the total v_2
- Dileptons: QGP's v_2 increase is diluted at low M where HM dominates. Yield is unaffected.

EM probes and non-zero initial $\pi^{\mu\nu}$







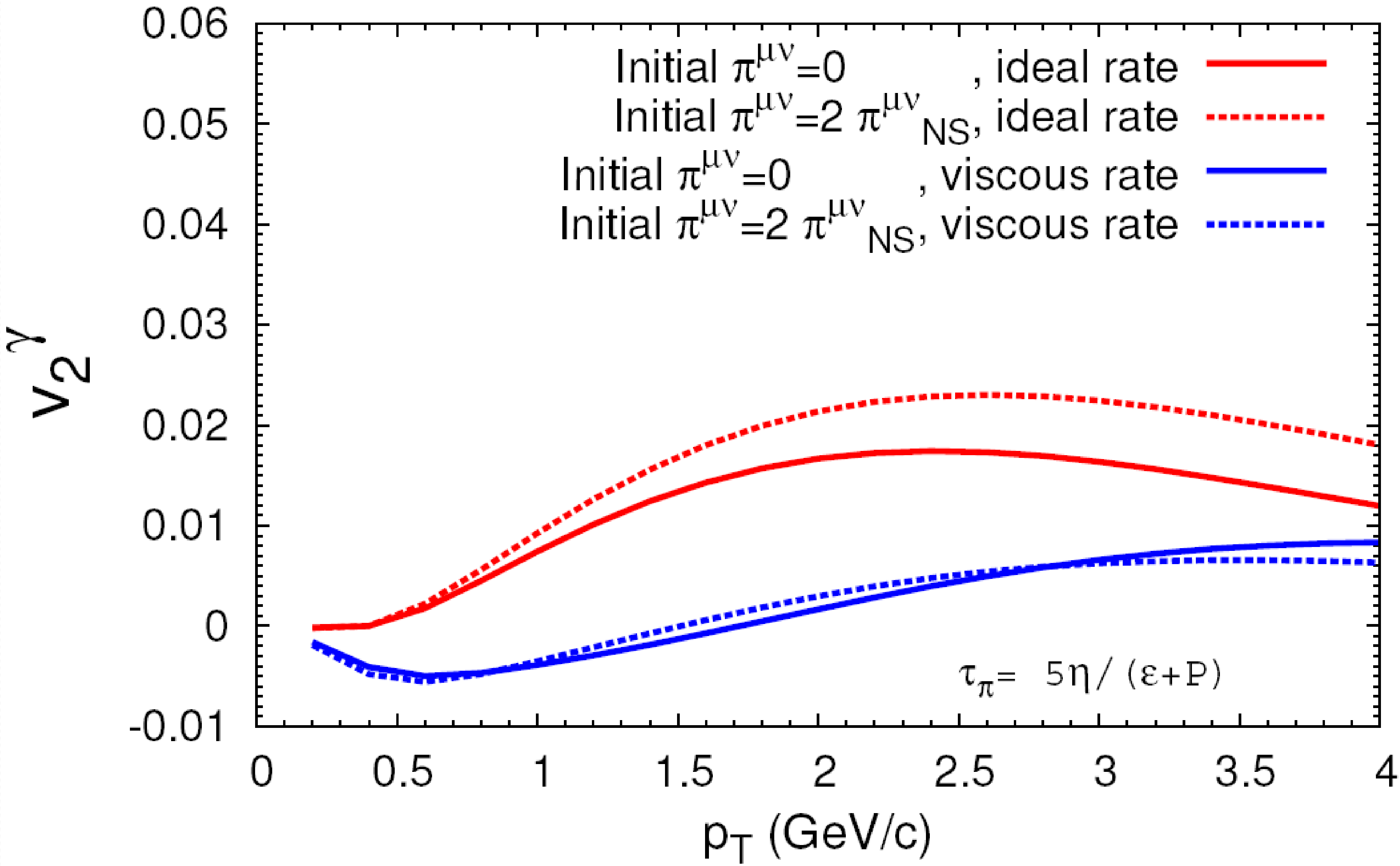


Conclusions & Outlook

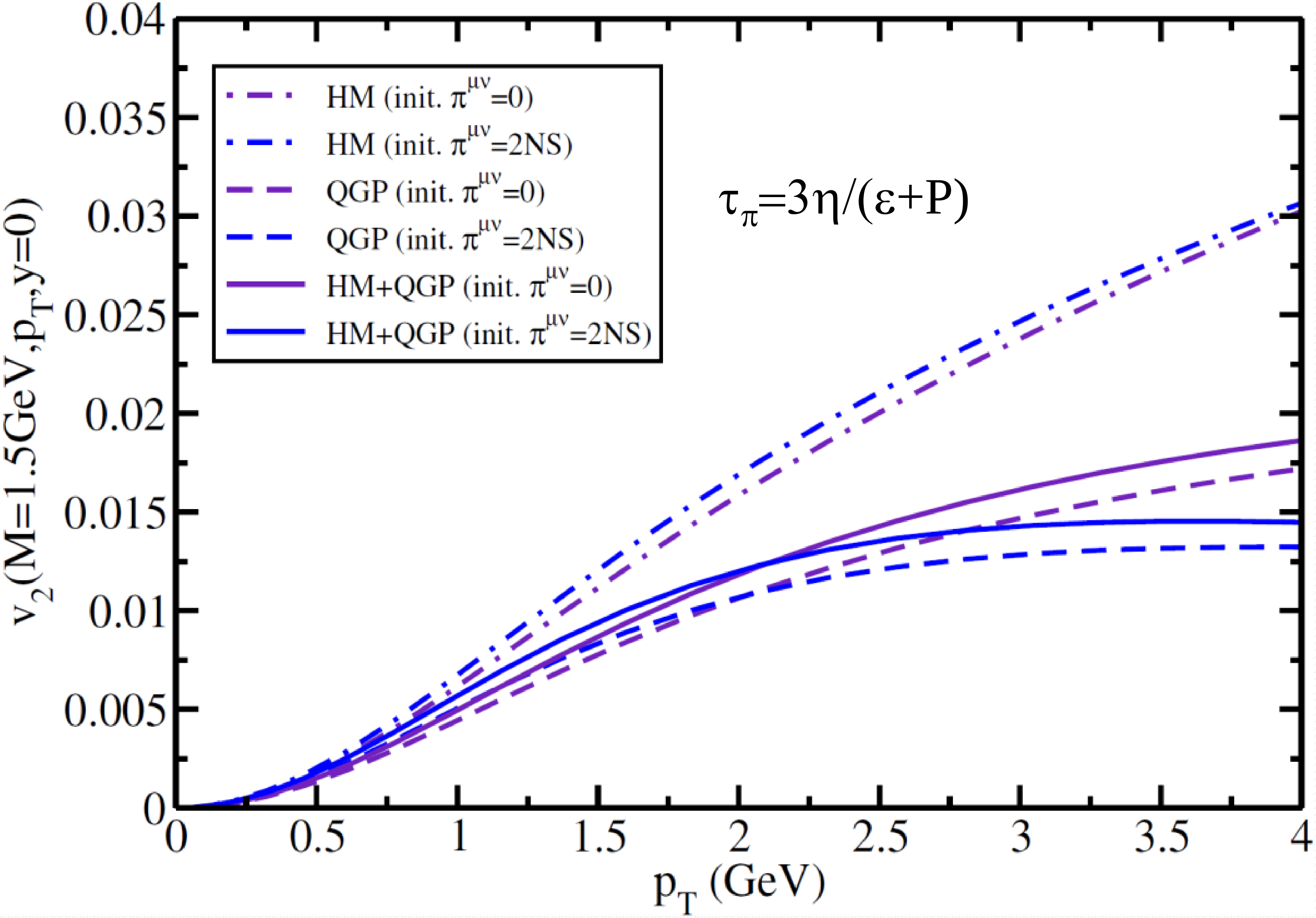
- EM probes are sensitive the medium initial departure from equilibrium (initial $\pi^{\mu\nu}$) as well as the medium capacity to relax towards equilibrium (τ_π). Hadronic observables are essentially insensitivity to these parameters.
- v_2 is increased as one increases τ_π and initial $\pi^{\mu\nu}$.
- QGP is more sensitive than HM, owing to the time evolution of $\pi^{\mu\nu}$.
- Prospective 1: Constraints of initial $\pi^{\mu\nu}$ and τ_π from experimental data on EM flow.
- Prospective 2: Sensitivity to initial conditions and relaxation time for v_2 of EM probes can be used to test the limits of validity of our current description of EM emission.

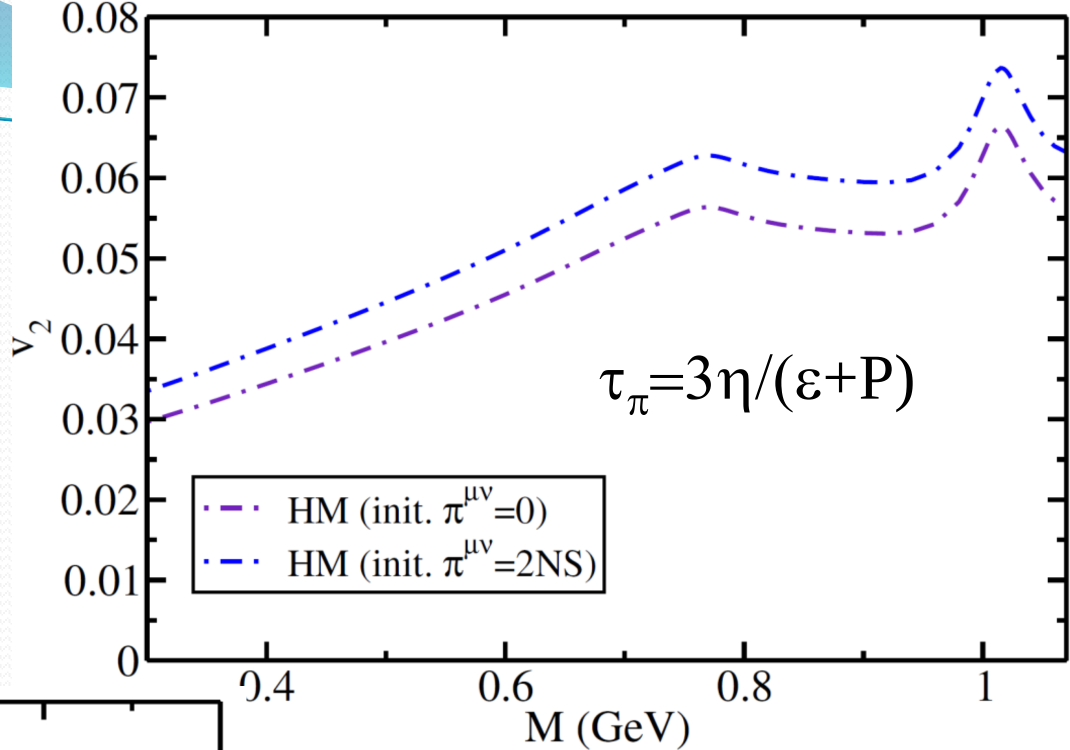
A specials thanks to:

Chun Shen
Igor Kozlov
Ralf Rapp

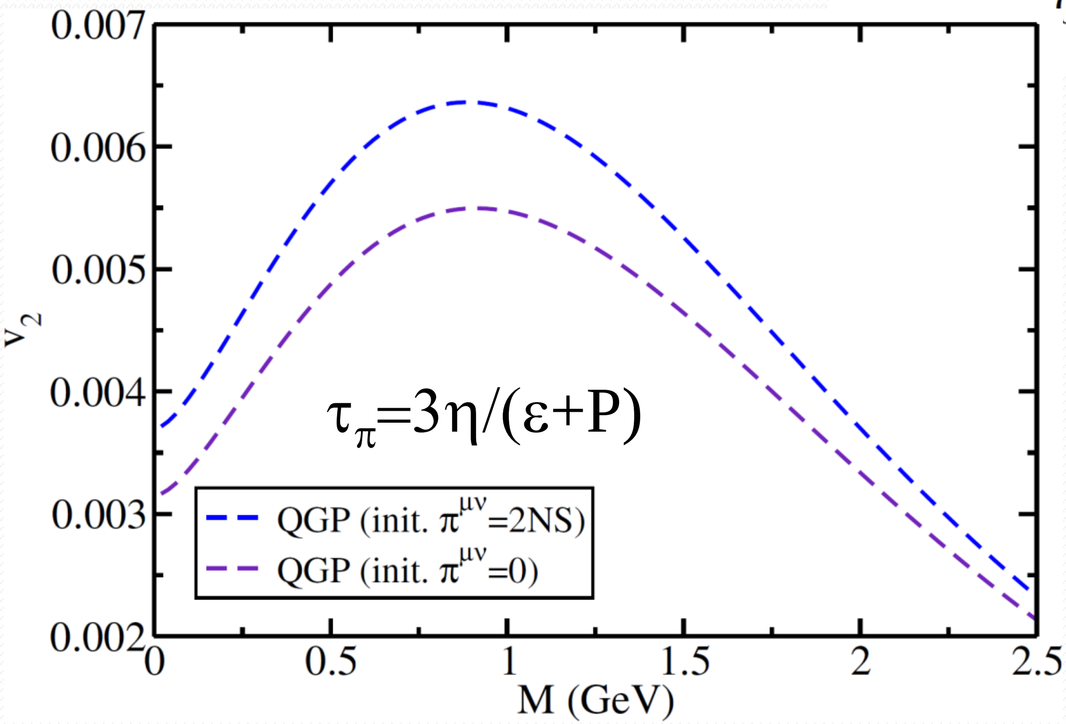

Initial π^μν=0 , ideal rate
Initial π^μν=2 π^μν_NS, ideal rate
Initial π^μν=0 , viscous rate
Initial π^μν=2 π^μν_NS, viscous rate
τ_π= 5η/(ε+P)
v_2^γ
p_T (GeV/c)
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
0.5
1
1.5
2
2.5
3
3.5
4

$v_2(p_T)$ from non-zero initial $\pi^{\mu\nu}$ HM/QGP



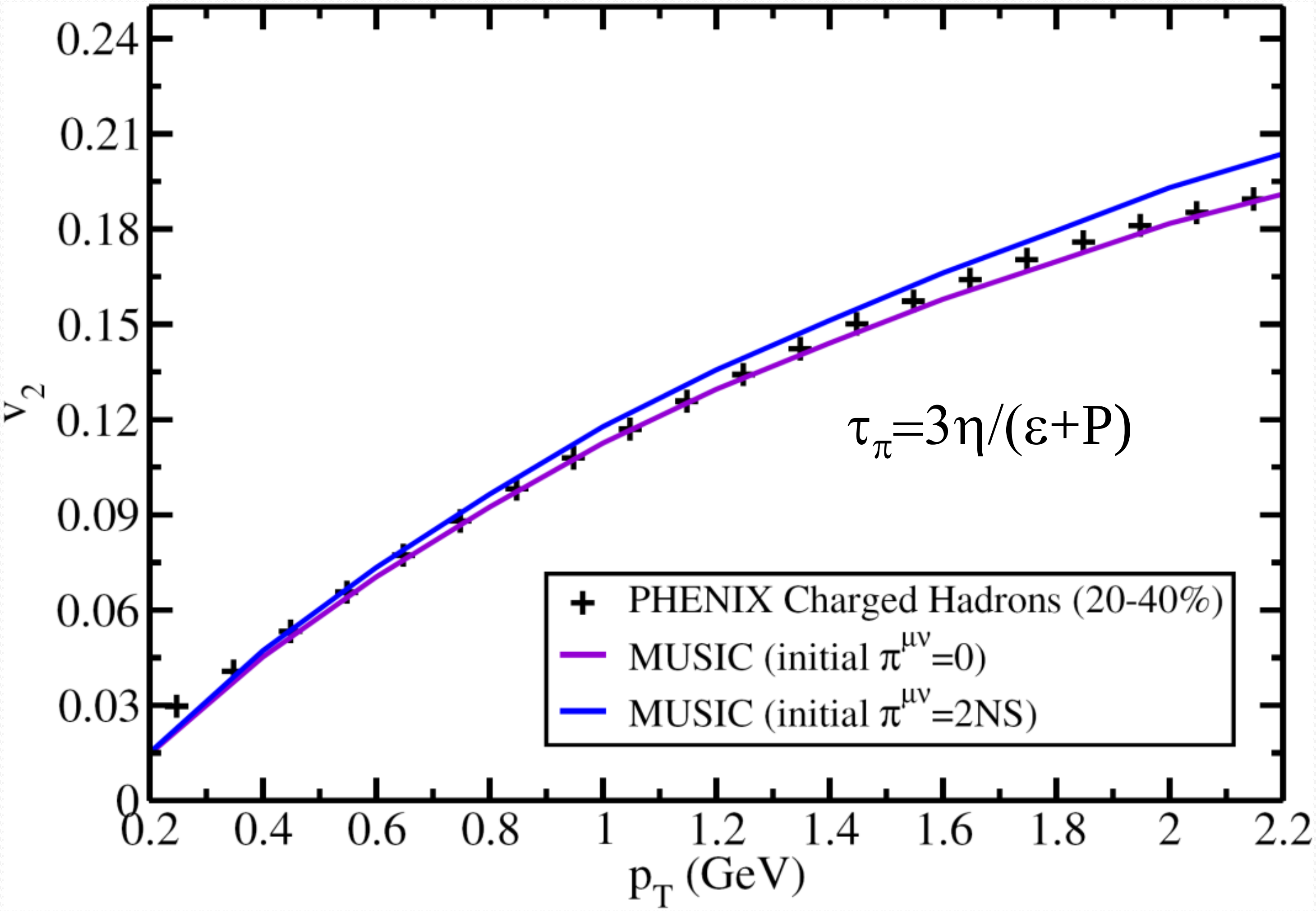


0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
v_2
0.4
0.6
0.8
1
M (GeV)
$\tau_\pi=3\eta/(\varepsilon+P)$
HM (init. $\pi^{\mu\nu}$=0)
HM (init. $\pi^{\mu\nu}$=2NS)

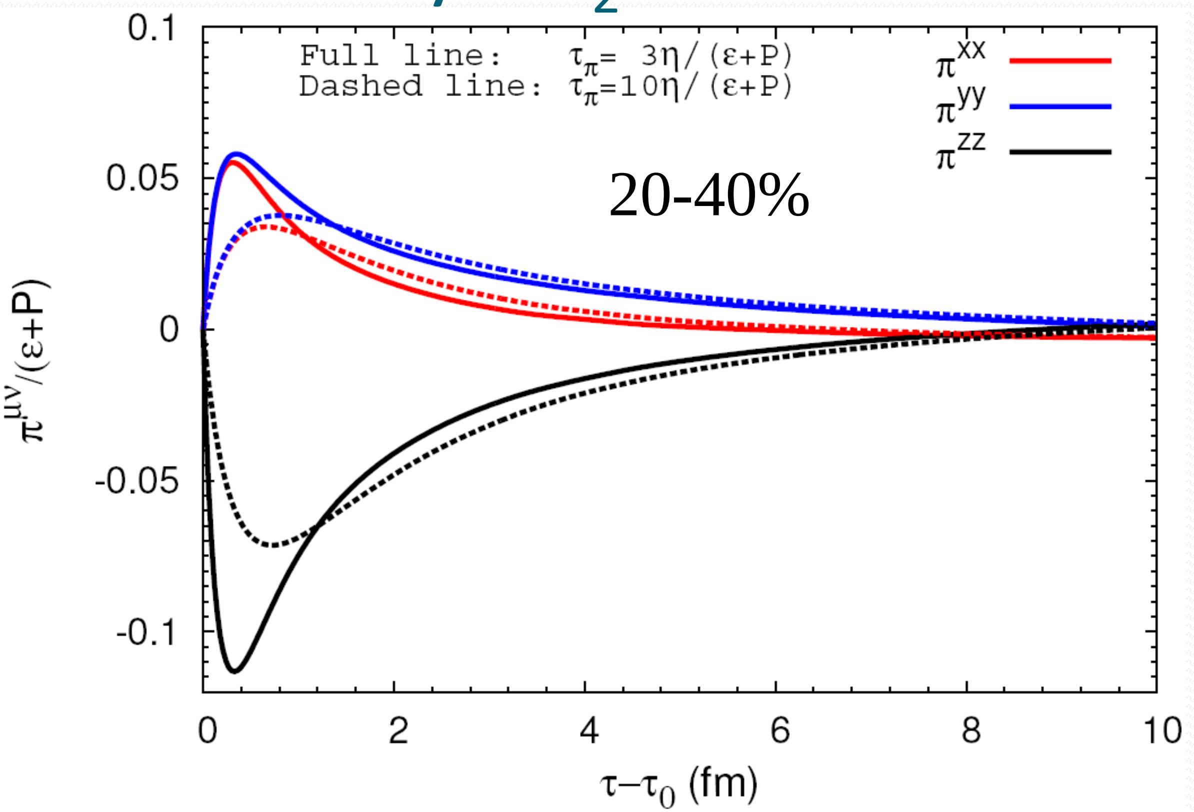


0.007
0.006
0.005
0.004
0.003
0.002
v_2
0
0.5
1
1.5
2
2.5
M (GeV)
$\tau_\pi=3\eta/(\varepsilon+P)$
QGP (init. $\pi^{\mu\nu}$=2NS)
QGP (init. $\pi^{\mu\nu}$=0)

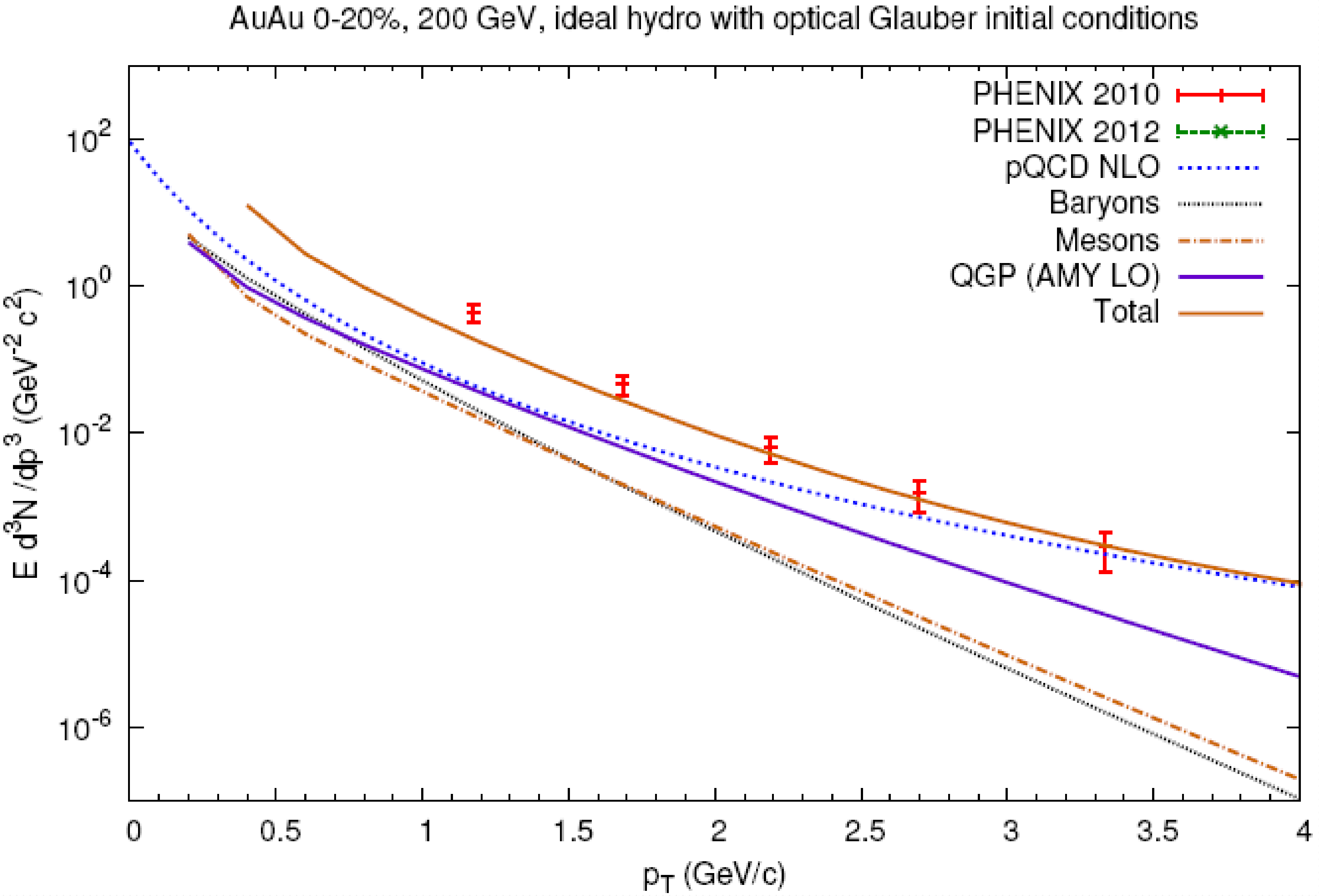
Hadron v_2 Spectra from MUSIC



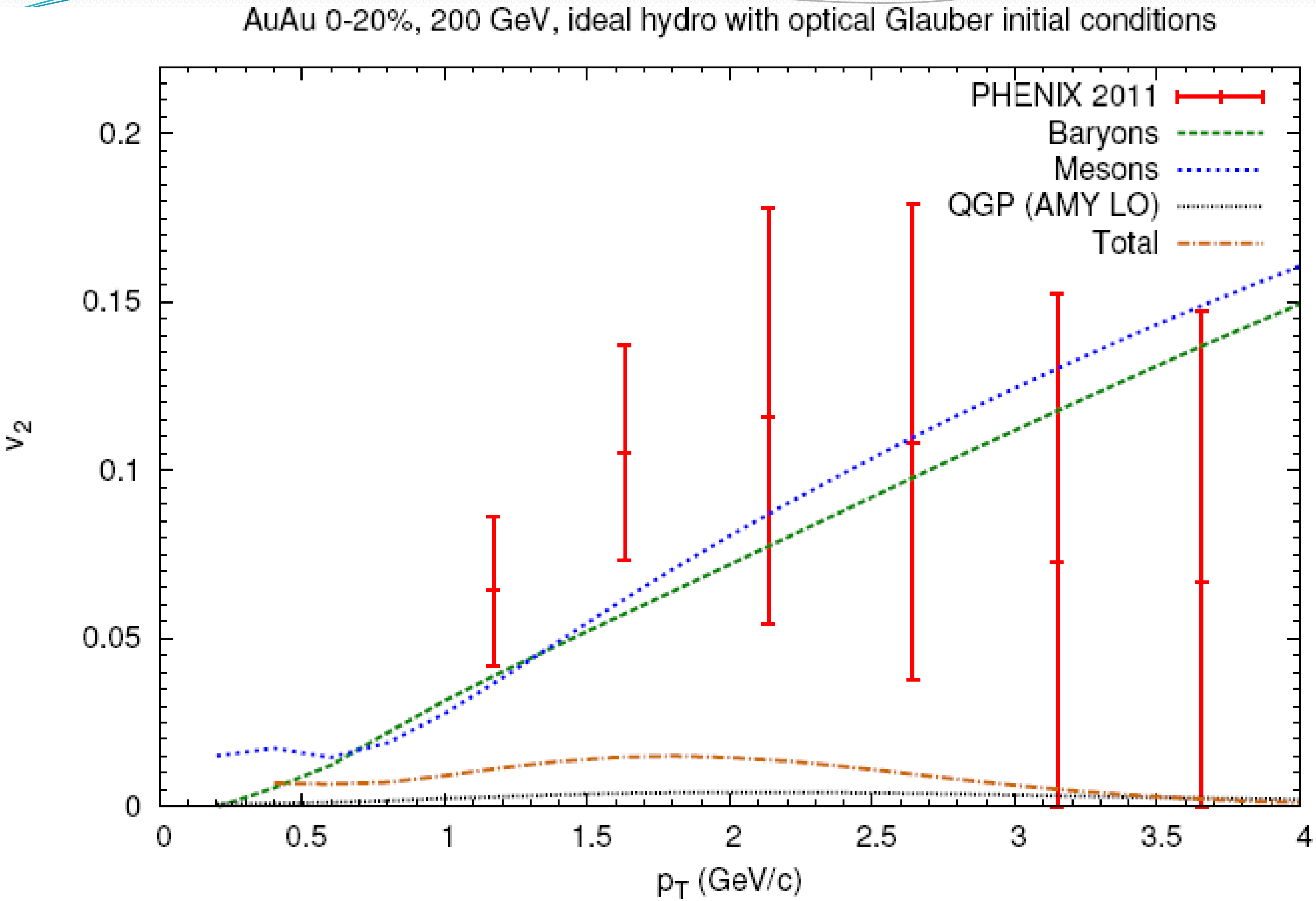
Why is v_2 increased?



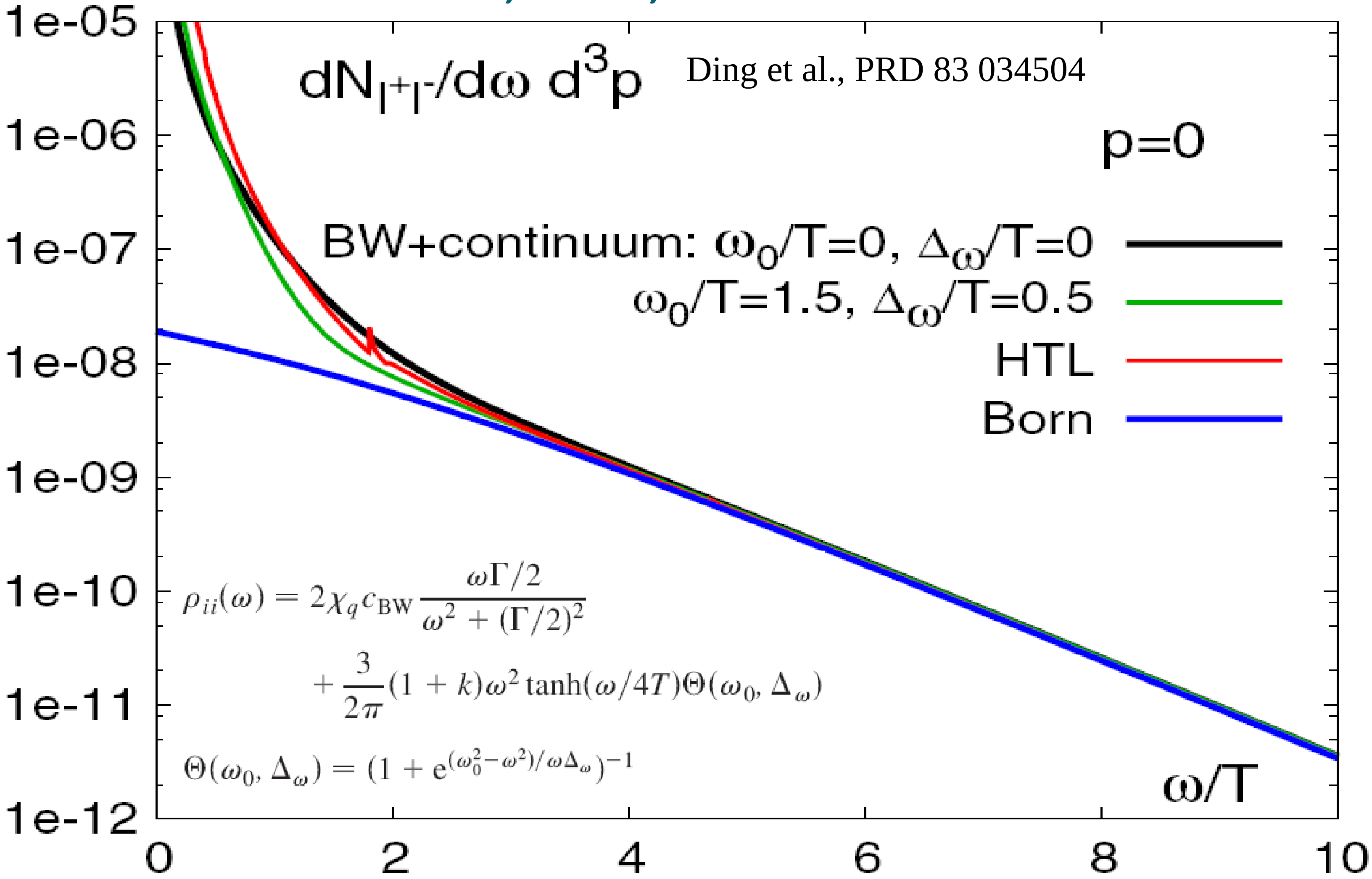
- Why is v_2 increased? Non-linear evolution of $\pi^{\mu\nu}$ couples the large π^{zz} to the flow in the transverse plane.



AuAu 0-20%, 200 GeV, ideal hydro with optical Glauber initial conditions
PHENIX 2010
PHENIX 2012
pQCD NLO
Baryons
Mesons
QGP (AMY LO)
Total
$E\, d^3N/dp^3\ (GeV^{-2} c^2)$
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
0
0.5
1
1.5
2
2.5
3
3.5
4
p_T (GeV/c)


AuAu 0-20%, 200 GeV, ideal hydro with optical Glauber initial conditions
PHENIX 2011
Baryons
Mesons
QGP (AMY LO)
Total
v_2
0
0.05
0.1
0.15
0.2
0
0.5
1
1.5
2
2.5
3
3.5
4
p_T (GeV/c)

Born, HTL, and Lattice QCD



$$\rho_{ii}(\omega) = 2\chi_q c_{\mathrm{BW}} \frac{\omega\Gamma/2}{\omega^2 + (\Gamma/2)^2} + \frac{3}{2\pi}(1+k)\omega^2 \tanh(\omega/4T)\Theta(\omega_0, \Delta_\omega)$$

$$\Theta(\omega_0, \Delta_\omega) = (1 + e^{(\omega_0^2-\omega^2)/\omega\Delta_\omega})^{-1}$$