Dissipative dynamics for the expanding anisotropic quark-gluon plasma

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BEST COLLABORATION

Outline

- Introduction
- Kinetic theory approach to highly anisotropic plasmas
  - Anisotropic hydrodynamics (aHydro)
  - Viscous anisotropic hydrodynamics (vaHydro)
- Phenomenological applications
  - First results on pA and AA collisions
  - Electromagnetic probes: photons and dileptons
- Conclusions and outlook

Success of viscous hydrodynamics

- **Viscous hydrodynamics provides a remarkable and successful phenomenological description of the expansion of the quark-gluon plasma**
- **The anisotropic flow coefficients v_n are described with a small value of the shear viscosity over entropy ratio**

$$\frac{\eta}{s} \sim \mathcal{O}\left(\frac{1}{4\pi}\right)$$

- **Hydrodynamics requires as an external input**

- EOS: lattice QCD + hadron resonance gas

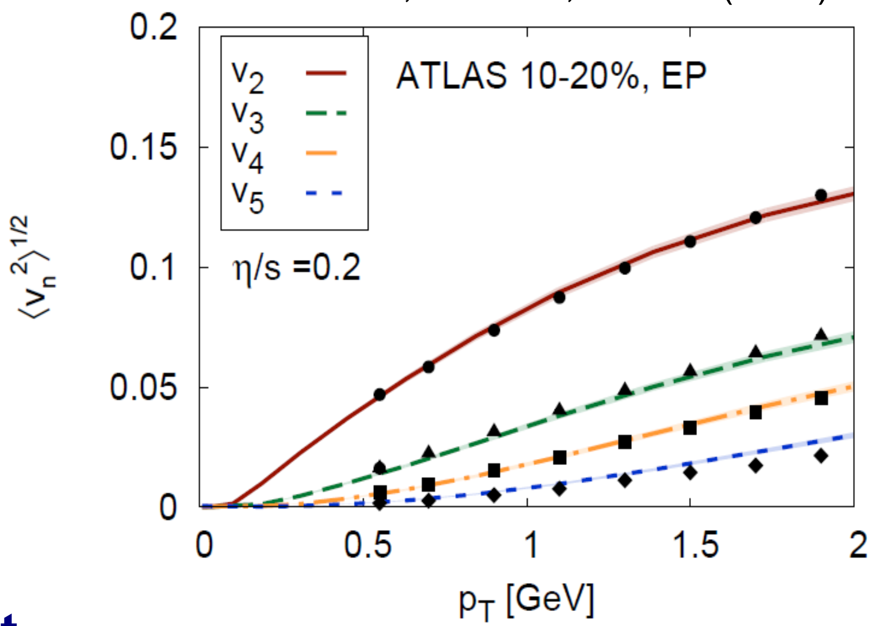
- Hadronization and afterburning

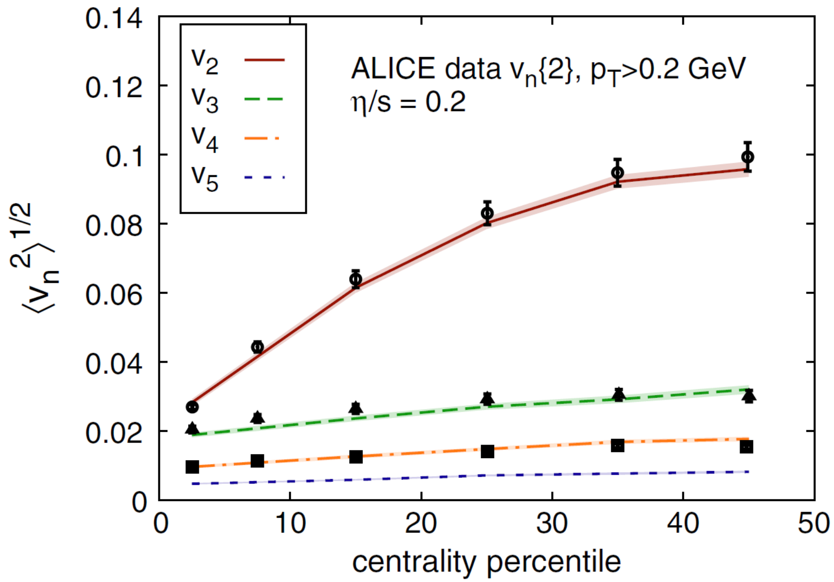
- Evolution for the dissipative hydrodynamical fields: 2nd order viscous hydro + transport coefficients

- Initial Conditions: CGC, Glauber, etc

- Pre-equilibrium dynamics: free streaming, Glasma, etc.

Gale et. al, PRL 110, 012302 (2012)





Why do we need anisotropic hydro?

Anisotropies can be large at early times!!!

The pressure anisotropy in an expanding system (Bjorken) within the Navier Stokes limit

$$\pi_{NS} = -\frac{4\eta}{3\tau}$$

$$\left(\frac{P_L}{P_T}\right)_{NS} = \frac{P_{eq} - \pi_{NS}/2}{P_{eq} + \pi_{NS}}$$

For η/s=1/(4π), T= 400 MeV, τ_o = 0.5 fm/c (RHIC initial conditions)

$$\left(\frac{P_L}{P_T}\right)_{NS} \sim 0.5$$

For η/s=1/(4π), T= 600 MeV, τ_o = 0.25 fm/c (LHC initial conditions)

$$\left(\frac{P_L}{P_T}\right)_{NS} \sim 0.35$$

Sizable pressure anisotropies at early times!!!

Pressure anisotropies from kinetic theory

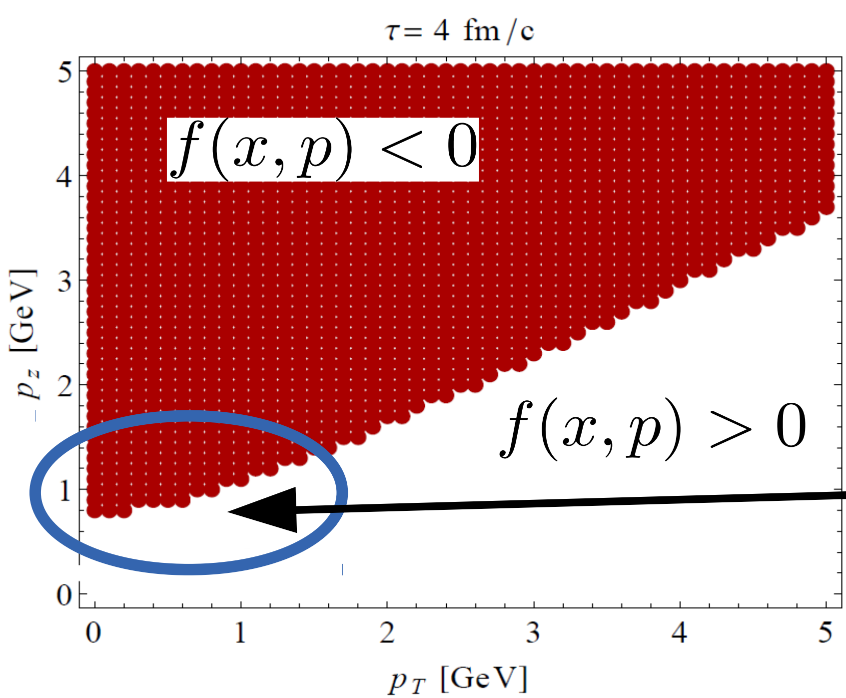
Linearizing around the equilibrium distribution function leads to viscous hydrodynamics

$$f(x,p) = \underbrace{f_{eq}(y_0)}_{} + \underbrace{\delta f(x,p)}_{}$$

Isotropic in momentum space

$$\delta f \ll f_{eq}$$

$$y_0 = \frac{(u\cdot p) - \mu}{T} = \frac{\sqrt{m^2 + |\mathbf{p}|^2} - \mu}{T}$$



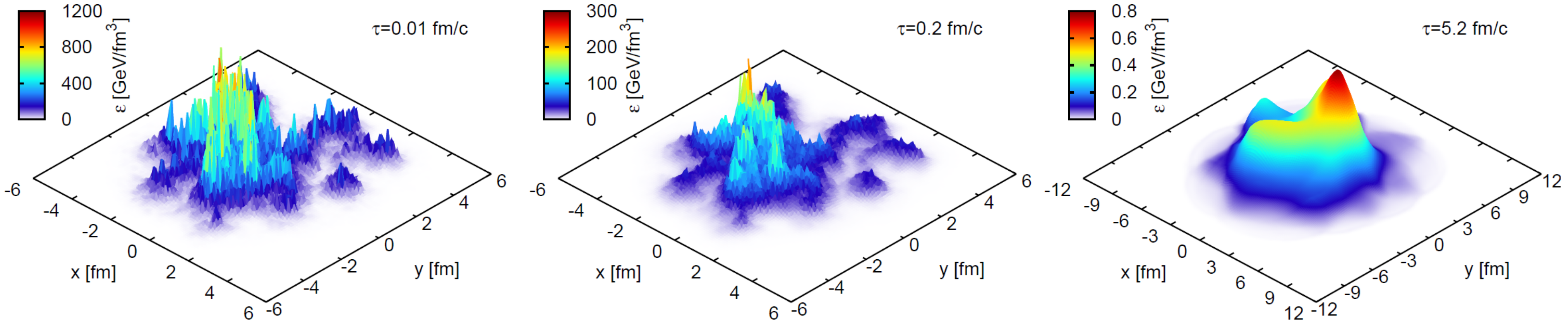
$\eta/s = 1/(4\pi)$ T_0 = 400 MeV τ_0 = 0.5 fm/c

$$\delta f = \frac{p_\mu p_\nu \pi^{\mu\nu}}{2(\mathcal{E}+\mathcal{P})T^2}$$

$$= \frac{\eta}{\mathcal{S}}\left(\frac{p_x^2 + p_y^2 - 2p_z^2}{3T^3\tau}\right)$$

For large anisotropies the expansion around equilibrium is not well defined even in the regions of the phase space where hydro should work

Caveats of hydrodynamical models



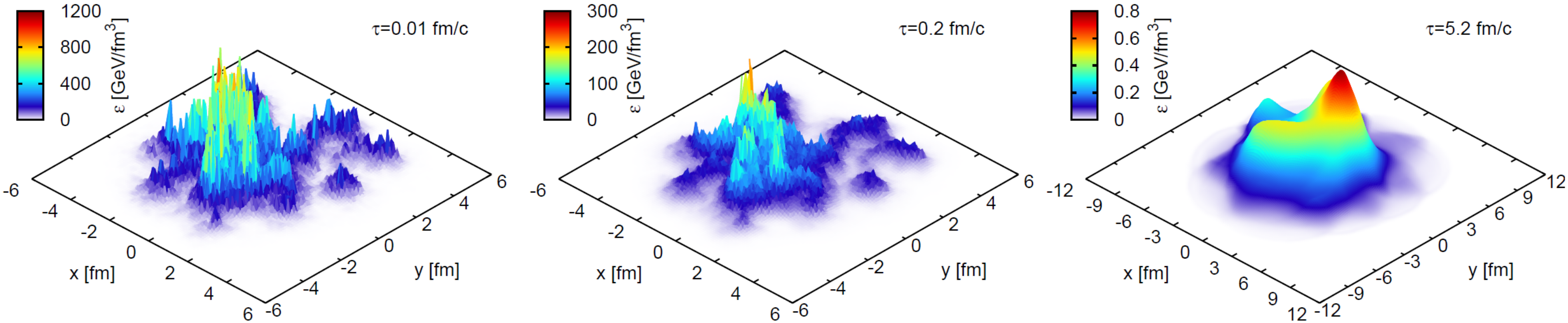
Initial Conditions

From an initial $T^{\mu\nu}$ (given for example, by some pre-equilibrium stage prescription) the initial energy density and fluid velocity are obtained by solving

$$\epsilon_{eq.} = u_\mu u_\nu \underbrace{T^{\mu\nu}}_{\substack{\text{non-equilibrium}\\ \text{energy-momentum tensor}}}$$

- This procedure does not match all the components of the energy momentum tensor
- Gradients of velocity are large at early times $\backsim 1/\tau$

Caveats of hydrodynamical models



What one would like to do

Match each component of the energy momentum tensor

$$T^{\mu\nu}_{hydro}\,|_{\tau_0} = T^{\mu\nu}_{non-eq.}\,|_{\tau_0}$$

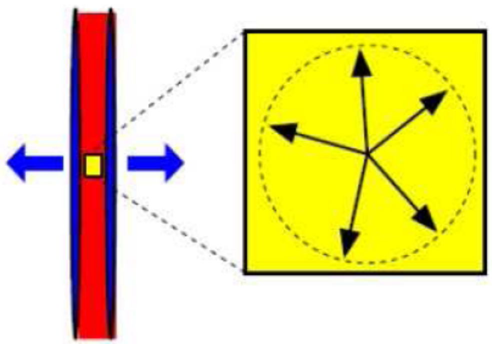
An interesting procedure to get $T^{\mu\nu}(\tau_0)$ from pre-equilibrium dynamics

Keegan et. al, arXiv:1605.04287 ➡ ***Talk by Mazeliauskas***

Our proposal: develop a theoretical framework that allows us to evolve all the components of $T^{\mu\nu}$ from a far-from-equilibrium initial state which is highly anisotropic in momentum-space

➡ Viscous Anisotropic hydrodynamics

Viscous hydro vs. vaHydro

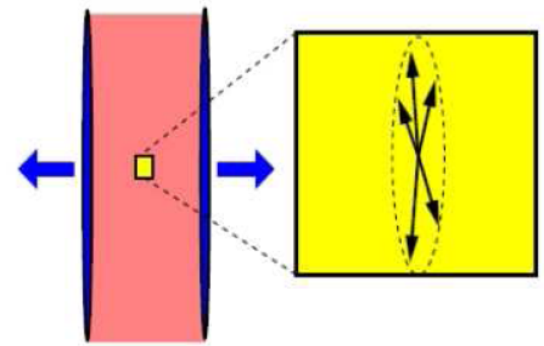


Viscous hydrodynamics

$$f(x,p) = f_{eq} + \delta f(x,p)$$

The equilibrium distribution f_{eq} function is isotropic in momentum space

All the momentum space anisotropies are perturbations around the equilibrium distribution function



Viscous anisotropic hydrodynamics

$$f(x,p) = f_a + \delta \tilde{f}(x,p)$$

The leading order distribution function f_a encodes the largest anisotropies developed at early times

Deviations from the spheroidal form of the leading order term are treated as small perturbations

Foundations of vaHydro

$$f(x,p) = \underbrace{f_a(\sqrt{p_\mu p_\nu \Xi^{\mu\nu}}, \Lambda(x))}_{\text{Local anisotropic background}} + \underbrace{\delta\tilde{f}(x,p)}_{\text{Residual dissipative corrections}}$$

Foundations of vaHydro

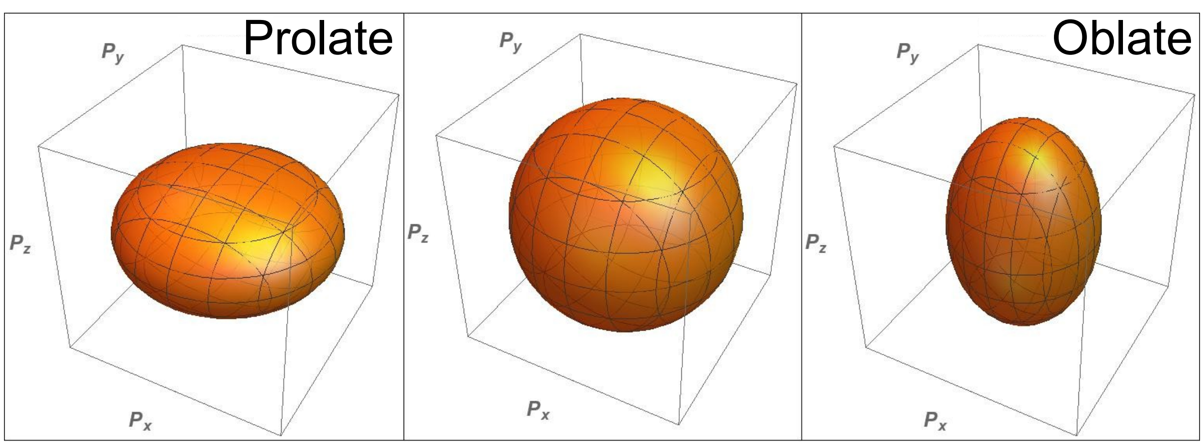
$$f(x,p) = \underbrace{f_a(\sqrt{p_\mu p_\nu \Xi^{\mu\nu}}, \Lambda(x))}_{\text{Local anisotropic background}} + \underbrace{\delta \tilde{f}(x,p)}_{\text{Residual dissipative corrections}}$$

aHydro: large viscous effects are encoded in the leading order term.

$$f_a\left(\sqrt{p_\mu p_\nu \Xi^{\mu\nu}}, \Lambda(x)\right) = f_{eq.}\left(\sqrt{p_T^2 + (1+\xi)p_z^2}, \Lambda(x)\right)$$

$$\Xi^{\mu\nu} = u^\mu u^\nu + \xi z^\mu z^\nu$$

M. Martinez, M. Strickland, NPA848 183 (2010)
Florkowski, Ryblewski, PRC83 034907 (2011)



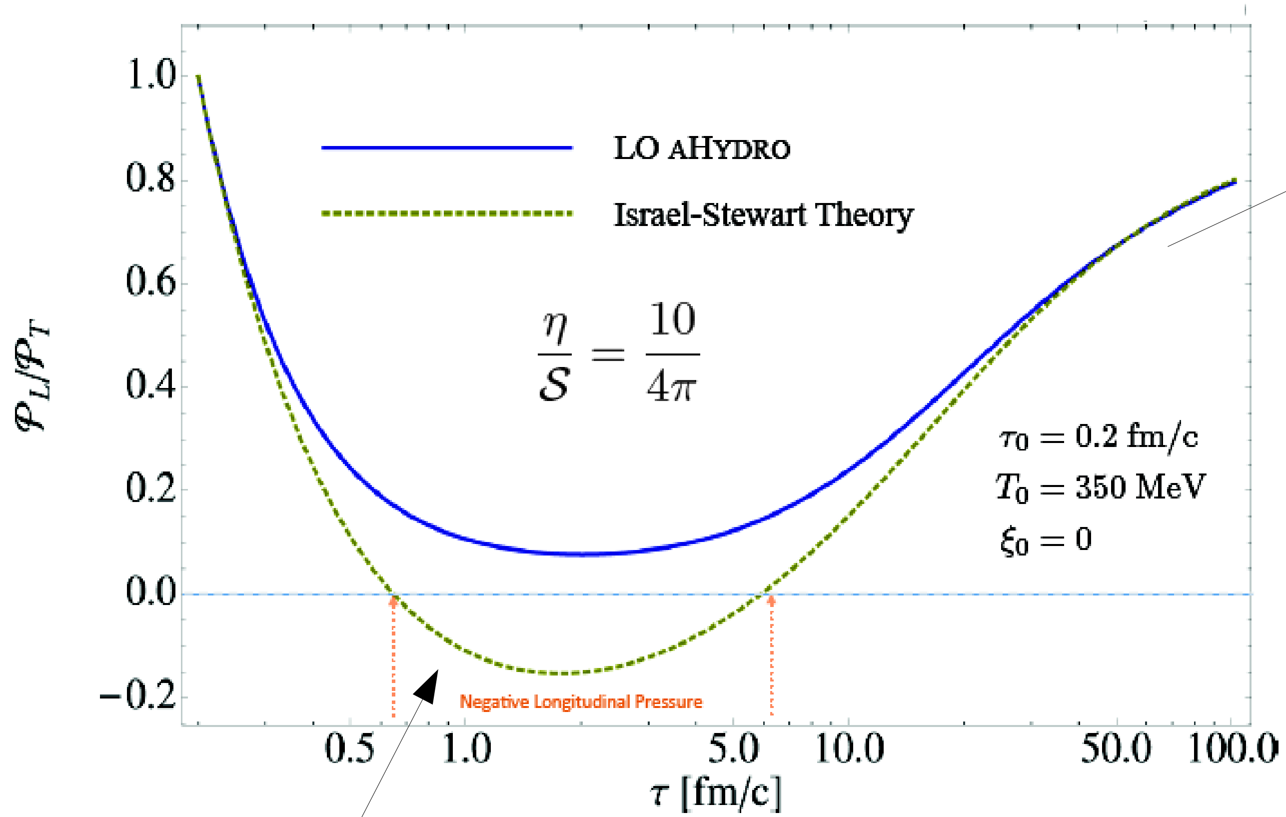
$\xi > 0$ $\qquad$ $\xi = 0$ $\qquad$ $-1 < \xi < 0$

- Λ is the temperature-like scale
- ξ regulates the longitudinal component of the shear viscous tensor
- For simplicity no chemical potential

Viscous hydro vs. aHydro

Consider Bjorken expansion and massless particles

M. Martinez, M. Strickland, NPA848 183 (2010)



aHydro recovers the late time hydrodynamical behavior

Longitudinal pressure can be negative for IS theory.

Similar findings: Florkowski, Ryblewski, PRC83 034907 (2011)

Foundations of vaHydro

$$f(x,p) = \boxed{f_a(\sqrt{p_\mu p_\nu \Xi^{\mu\nu}}, \Lambda(x))} + \boxed{\delta\tilde{f}(x,p)}$$

The energy-momentum tensor for an anisotropic plasma reads as

$$\begin{aligned} T^{\mu\nu} &= \langle p^\mu \, p^\nu \rangle \\ &= \mathcal{E} u^\mu u^\nu - (\mathcal{P}_\perp + \tilde{\Pi})\Delta^{\mu\nu} + \mathcal{P}^{\mu\nu} + \tilde{\pi}^{\mu\nu} \end{aligned}$$

with

$$\mathcal{E} \equiv \langle (u\cdot p)^2 \rangle_a, \qquad \tilde{\Pi} \equiv -\tfrac{1}{3}\langle \Delta^{\alpha\beta} p_\alpha p_\beta \rangle_{\tilde{\delta}},$$

$$\tilde{\pi}^{\mu\nu} \equiv \langle p^{\langle\mu} p^{\nu\rangle} \rangle_{\tilde{\delta}}, \qquad \mathcal{P}_L \equiv \langle p_z^2 \rangle_a,$$

$$\mathcal{P}_\perp \equiv \frac{1}{2}\langle (p_x^2 + p_y^2) \rangle_a, \quad \mathcal{P}^{\mu\nu} \equiv (\mathcal{P}_L - \mathcal{P}_\perp) z^\mu z^\nu,$$

where $\langle \cdots \rangle = \int_{\mathbf{p}} (\cdots) f\,, \quad \langle \cdots \rangle_a = \int_{\mathbf{p}} (\cdots) f_a\,, \quad \langle \cdots \rangle_{\tilde{\delta}} = \int_{\mathbf{p}} (\cdots) \delta\tilde{f}$

Bazow, Heinz, Strickland, PRC90,054910 (2014), Bazow, Martinez, Heinz, PRD93, 034002 (2016)

Foundations of vaHydro

- Eqs. of motion of the energy density and fluid velocity are obtained from the conservation laws

$$D_\mu T^{\mu\nu} = 0$$

- Eqs. of motion of the residual dissipative currents are obtained from moments method (Denicol et. al, PRD85, 114047 (2012))

$$\dot{\tilde{\pi}}^{\mu\nu} = \int_{\mathbf{p}} p^{\langle\mu} p^{\nu\rangle} \underbrace{\delta \dot{\tilde{f}}}_{}$$

Use Boltzmann equation:

$$\delta\dot{\tilde{f}} = -\dot{f}_a - (u \cdot p)^{-1}\left(p \cdot \nabla(f_a + \delta\tilde{f}) - \mathcal{C}[f]\right)$$

- One needs a relation between the EOS. For conformal systems

$$\mathcal{E} = 2\mathcal{P}_T + \mathcal{P}_L$$

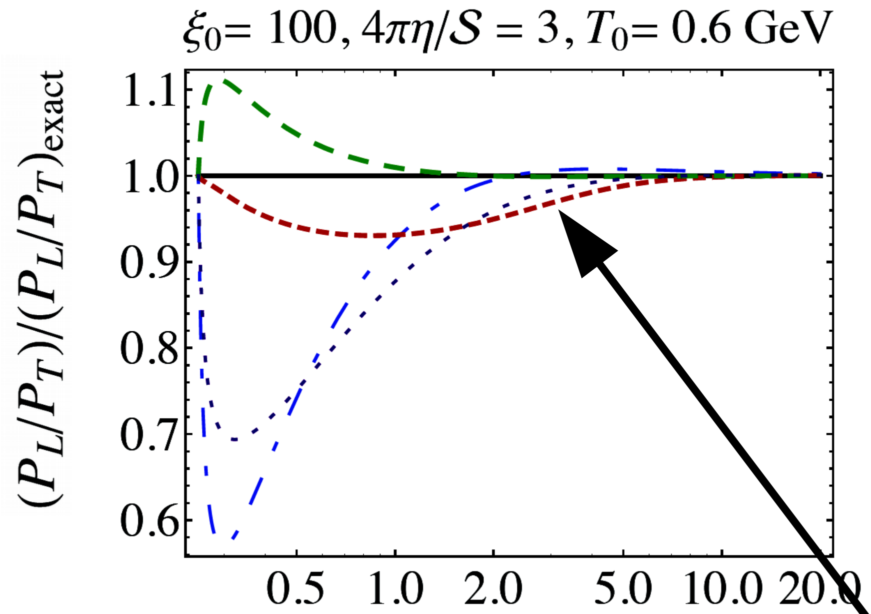
- We require the dynamical Landau matching conditions. For instance

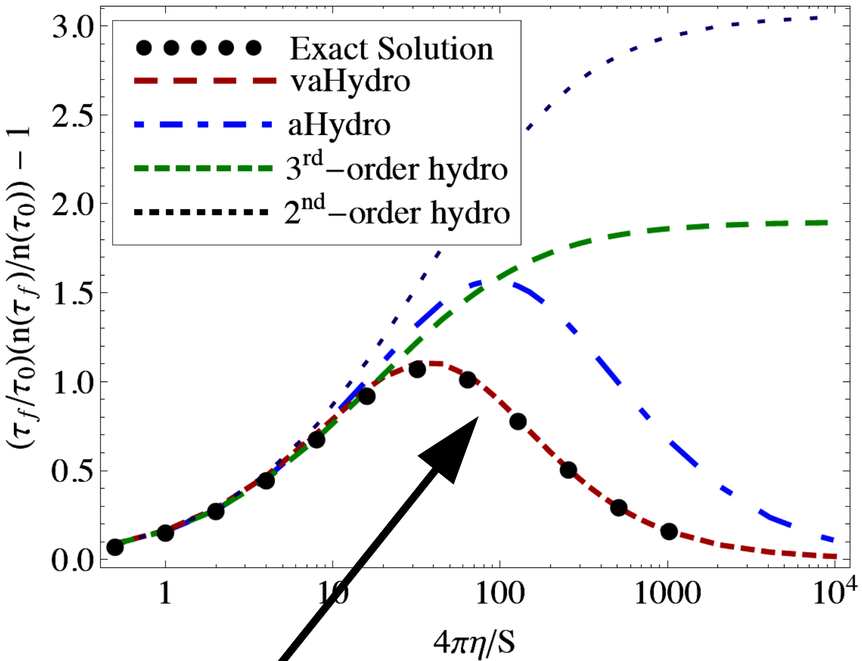
$$\mathcal{E}(\xi, \Lambda) = \mathcal{E}(T)$$

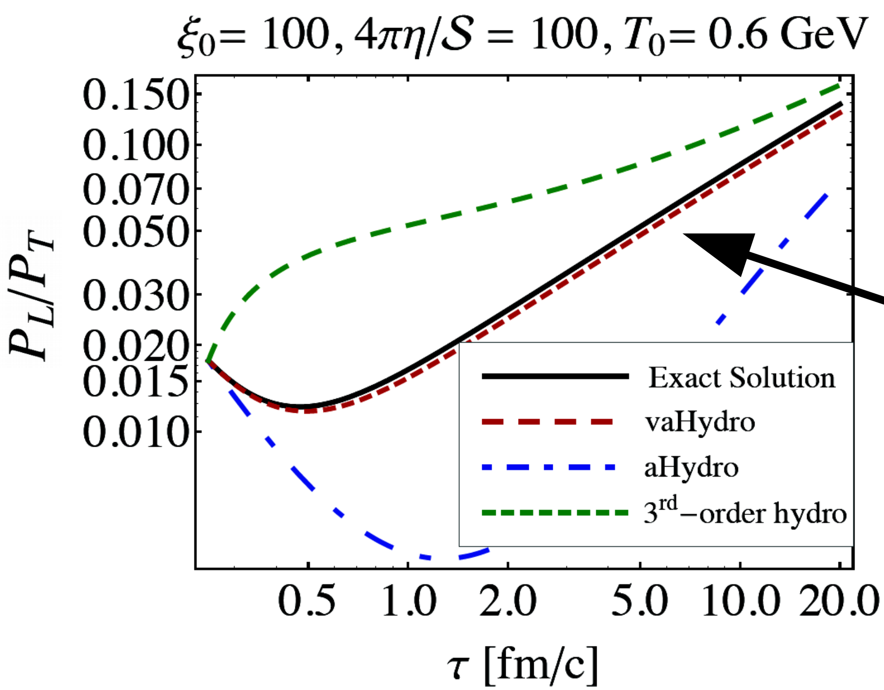
Other approaches: Molnar, Niemi, Rischke, arXiv:1602.00573
Florkowski, Tinti, Strickland, Ryblewski, NPA946, 29 (2016)

Bazow, Heinz, Strickland, PRC90,054910 (2014), Bazow, Martinez, Heinz, PRD93, 034002 (2016)

Testing vaHydro: conformal systems

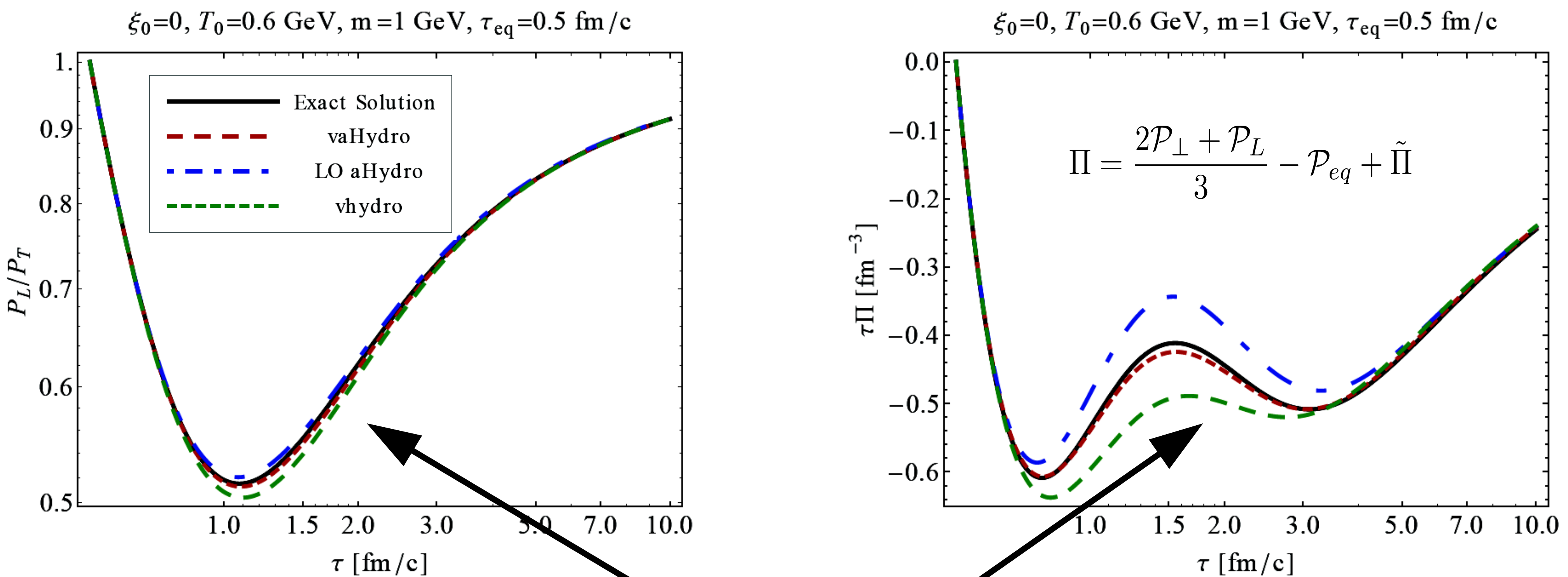






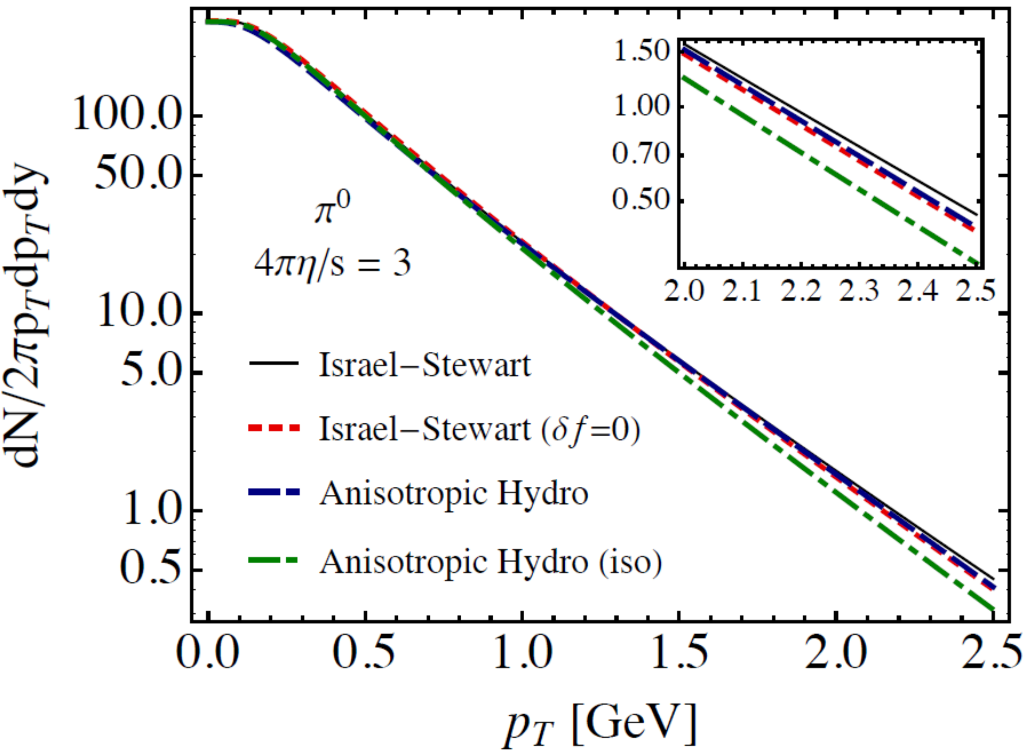
vaHydro provides an excellent approximationto the exact 0+1 boost invariant RTA Boltzmann solution for both small and large values of the shear viscosity

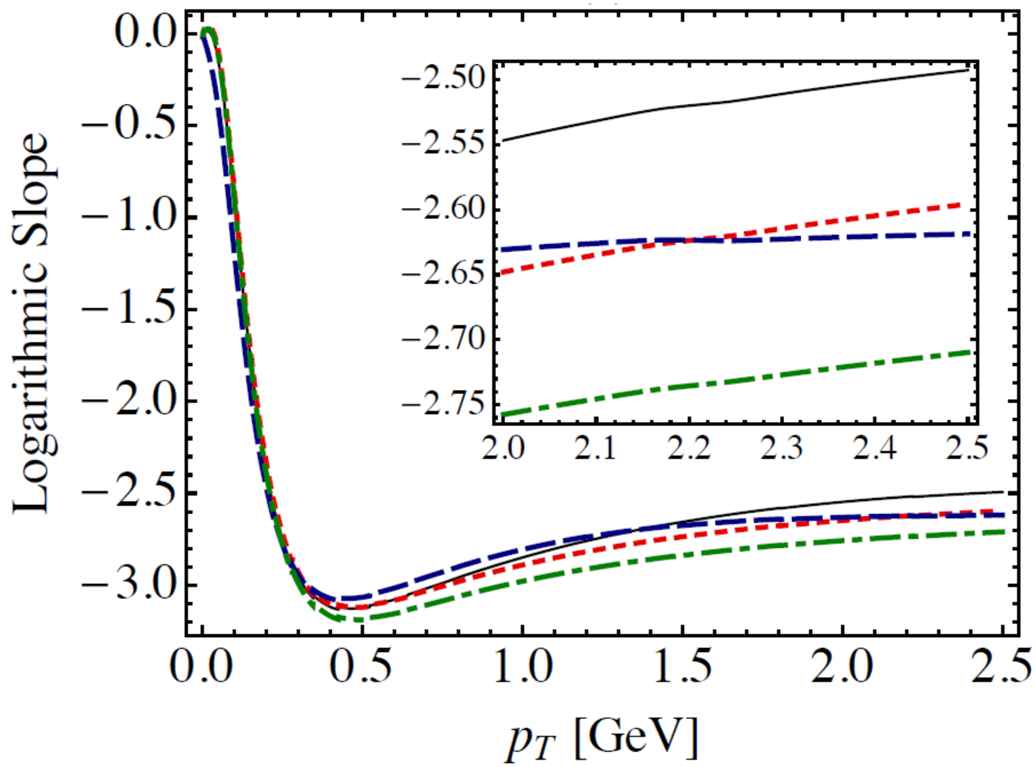
Testing vaHydro: nonconformal systems



vaHydro provides an excellent approximation to the exact 0+1 boost invariant RTA Boltzmann solution for massive particles.

AA collisions: 1+1 dim. expansion

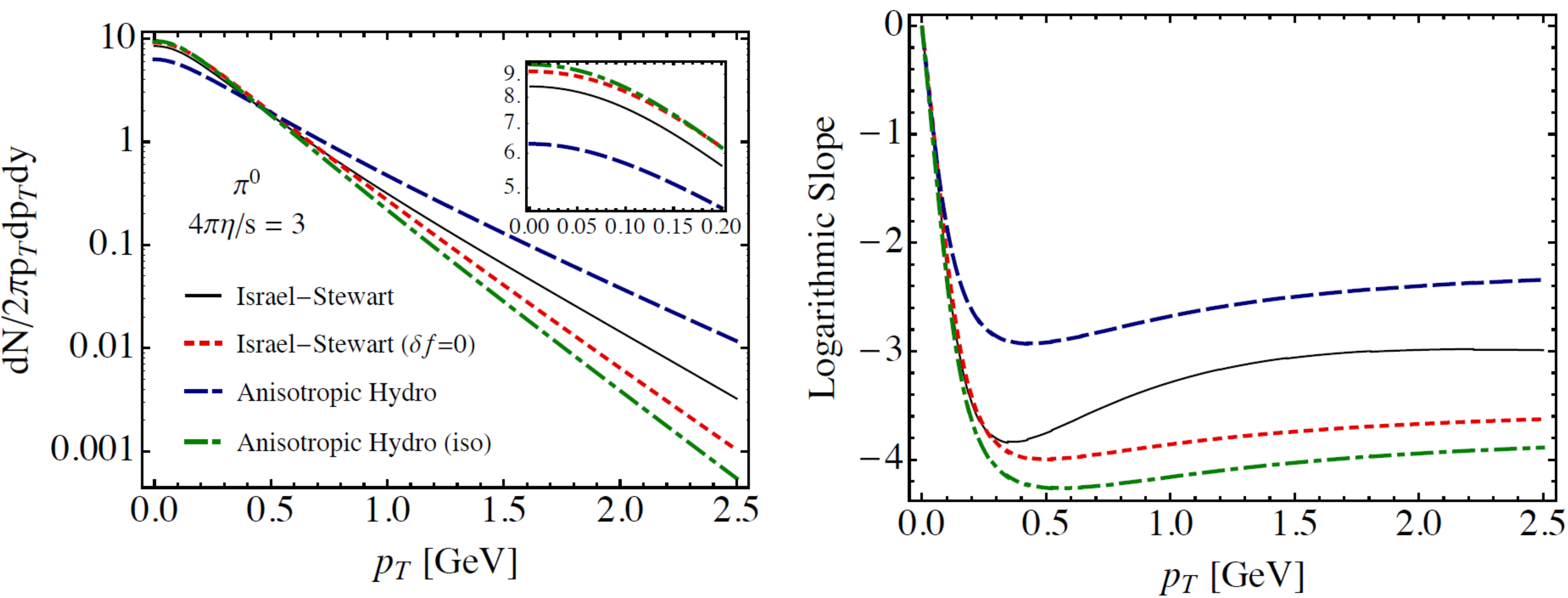




- Anisotropic hydro softens the transverse momentum spectrum since it reduces the pressure anisotropy and thus the transverse shear pressure.
- Larger differences between IS viscous hydro and anisotropic hydro are observed for large values of shear viscosity

M. Noupush et. al. PRC 92 044912 (2015)

pA collisions: 1+1 dim. expansion

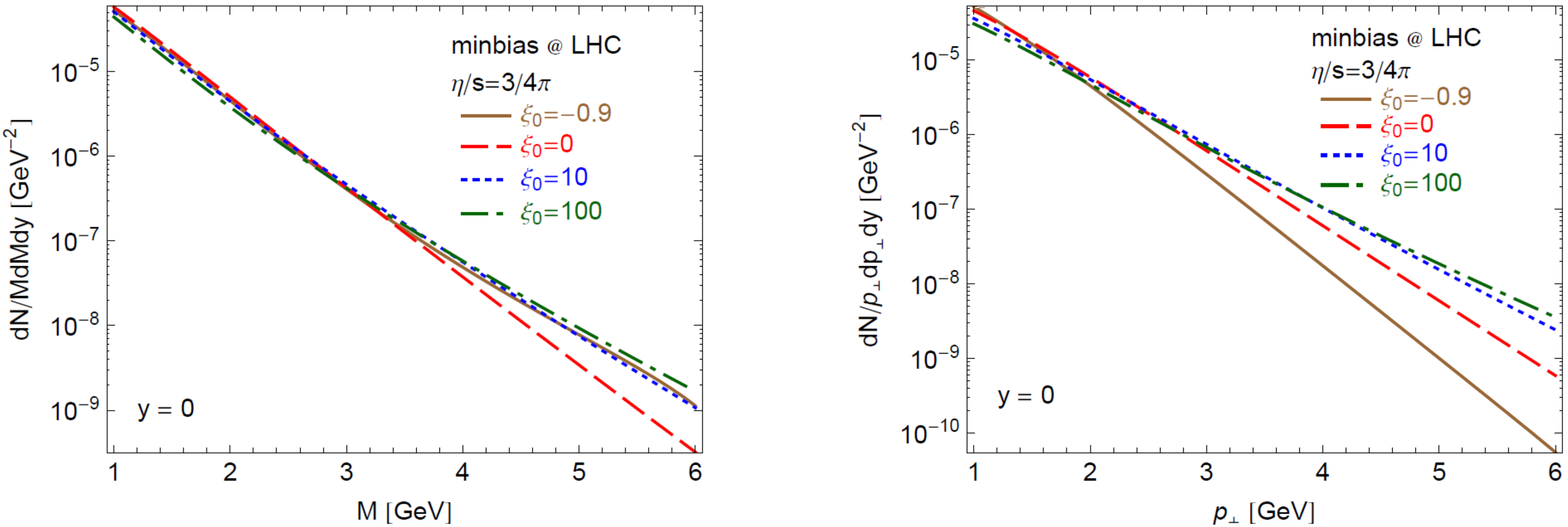


- aHydro improves the description of smaller systems compared to viscous IS hydro since the pressure anisotropies get larger.
- aHydro hardens the transverse momentum spectrum for smaller systems

M. Noupush et. al. PRC 92 044912 (2015)

Dileptons from an anisotropic plasma

3+1 dim. aHydro (no event by event fluctuations)
R. Ryblewski, M. Strickland, PRD92 025026 (2015)

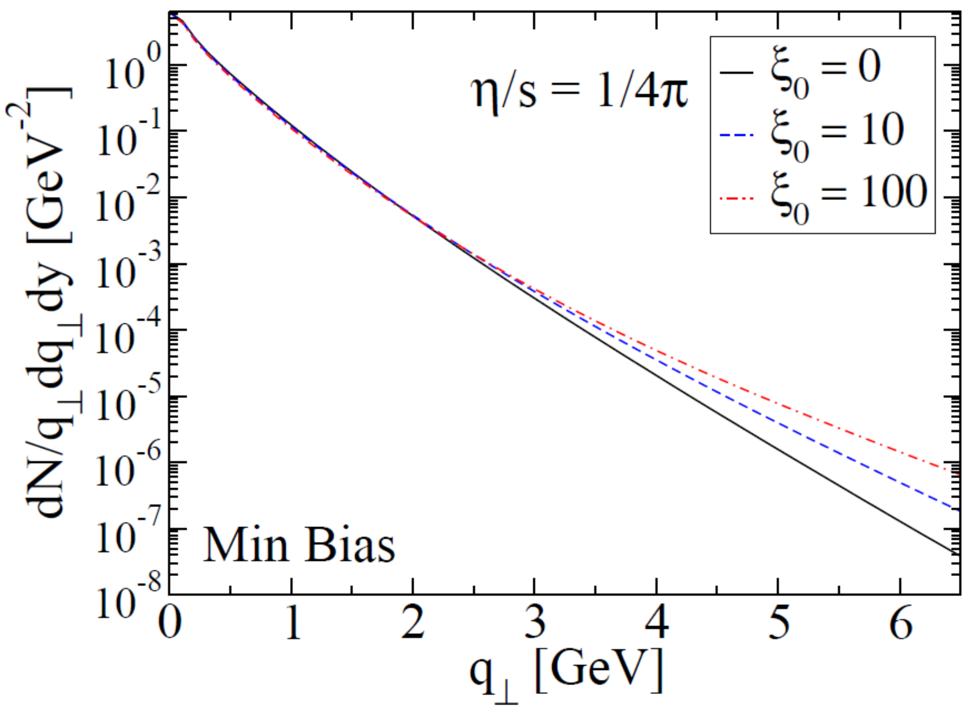


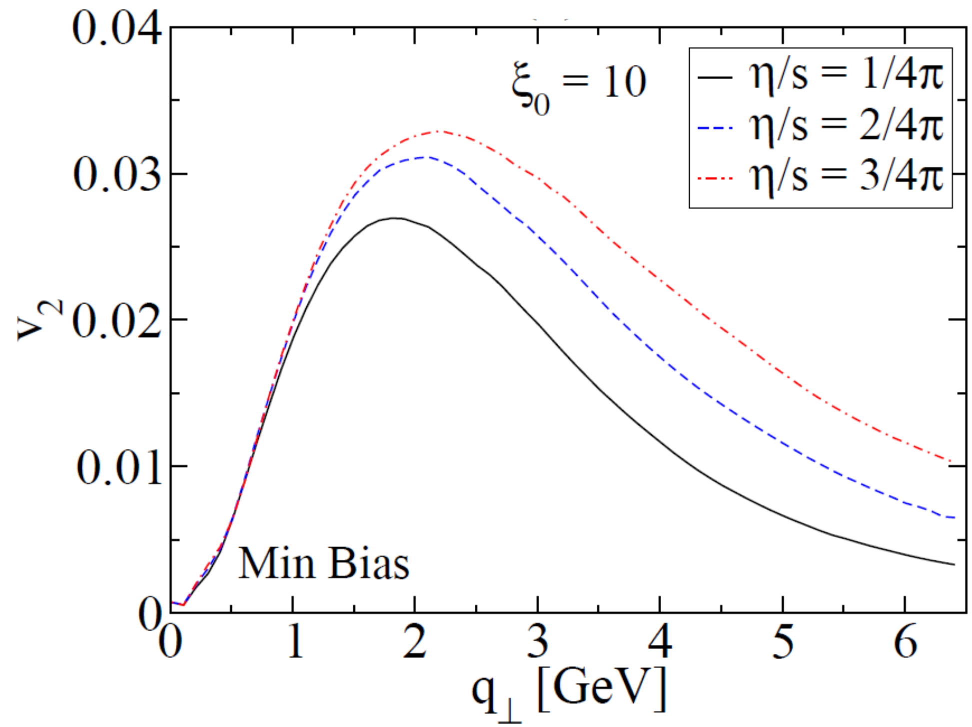
Dilepton yield is sensitive to the initial anisotropy

Bjorken expansion: Martinez, Strickland, PRL100 102301 (2007), PRC 78 034917 (2008), Eur. Phys. J C61 905 (2009)

Photons from an anisotropic plasma

3+1 dim. aHydro (no event by event fluctuations)
L. Bhattacharya, R. Ryblewski, M. Strickland, PRD93 065005 (2016)





Photon spectrum and photon elliptic flow coefficient v_2 are sensitive to the initial anisotropy!!!

Conclusions

Viscous Anisotropic Hydrodynamics:

- Improves the validity of fluid dynamic approach

  - at early time dynamics.

  - near the transverse edge of the fireball

- Exact solutions of the Boltzmann equation have helped to quantify the accuracy and validity of vaHydro.
- vaHydro handles large momentum-space anisotropies better than IS which are important during the evolution of the fireball.

Conclusions

Viscous Anisotropic Hydrodynamics:

- Sizable difference between the predictions of IS viscous hydro and anisotropic hydrodynamics are observed in smaller systems
- Dileptons and photons are sensitive to the initial anisotropy of the system

Outlook

Viscous Anisotropic hydrodynamics

- Chemical equilibrium of quarks and gluons
- Bottomonia suppression
- 3+1 numerical code of vaHydro (forthcoming OSU-Kent)

  - Event by event fluctuations with vaHydro

Anisotropic hydro meets cold atoms

- Bluhm and Schaefer:

  PRA92 043602 (2015), PRL116 115301 (2016)