Spectra, flow and HBT in Pb-Pb collsions at the LHC

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Viscous hydrodynamics

energy-momentum tensor

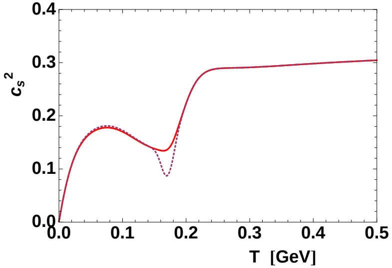
$$T^{\mu\nu} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & p + \Pi & 0 & 0 \\ 0 & 0 & p + \Pi & 0 \\ 0 & 0 & 0 & p + \Pi \end{pmatrix} + \pi^{\mu\nu}$$

- shear viscosity

$$\Delta^{\mu\alpha}\Delta^{\nu\beta}u^\gamma\partial_\gamma\pi_{\alpha\beta} = \frac{2\eta\sigma^{\mu\nu} - \pi^{\mu\nu}}{\tau_\pi} - \frac{1}{2}\pi^{\mu\nu}\frac{\eta T}{\tau_\pi}\partial_\alpha\left(\frac{\tau_\pi u^\alpha}{\eta T}\right)$$

- bulk viscosity

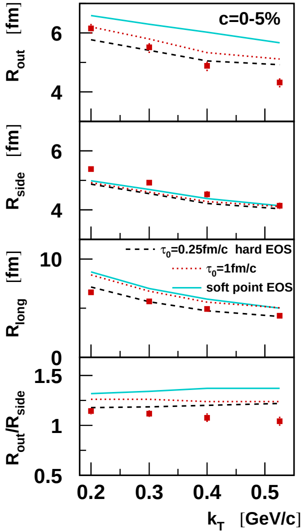
$$u^\gamma\partial_\gamma\Pi = \frac{-\zeta\partial_\gamma u^\gamma - \Pi}{\tau_\Pi} - \frac{1}{2}\Pi\frac{\zeta T}{\tau_\Pi}\partial_\alpha\left(\frac{\tau_\Pi u^\alpha}{\zeta T}\right)$$



lattice based EOS

Chojnacki, Florkowski, Acta Phys Polon. B38, 3249 (2007)

similar results with updated lattice data



Bozek, Wyskiel, Phys. Rev. C79, 044916 (2009)

HBT requires hard EOS

Broniowski et al. Phys. Rev. Lett. 101, 022301 (2008); Pratt Phys. Rev. Lett. 102, 232301 (2009)

Viscosity corrections

- Shear viscosity

$$\delta f = \frac{f_0(1 \pm f_0)}{2T^2(\epsilon + p)} p^\mu p^\nu \pi_{\mu\nu}$$

- Bulk viscosity
  - **quadratic** (Monnai, Hirano (Phys. Rev. C80, 055906 (2009))

$$\delta f = (Ap^2 + Bm^2)\Pi$$

  - **linear** (relaxation time formula) (PB, Phys. Rev. C81 034909 (2010))

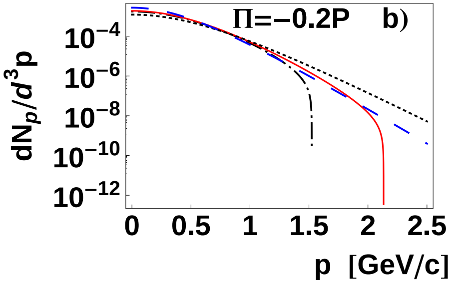
$$\delta f_{bulk} = C \frac{f_0(1 \pm f_0)}{T} \left(\frac{p^2}{3E} - c_s^2 E \right) \Pi$$

  - **exponential** (RF)

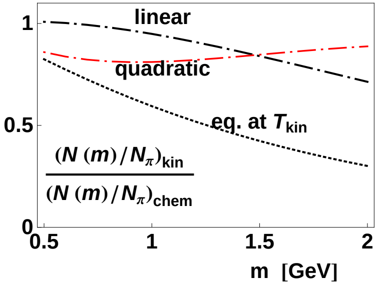
$$f_0 + \delta f = \exp(-\sqrt{m^2 + \lambda^2 p^2} / T_{dec})$$

redshift λ, effective temperature $T_{dec} > T_{freeze}$.

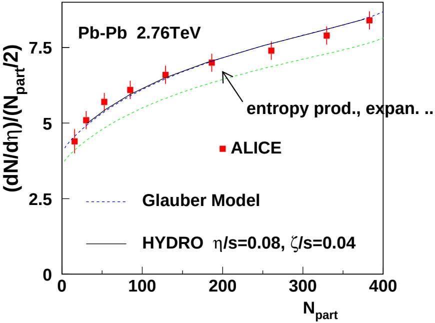
momentum distribution - protons



particle ratios



Mixed model - $\alpha = 0.15$



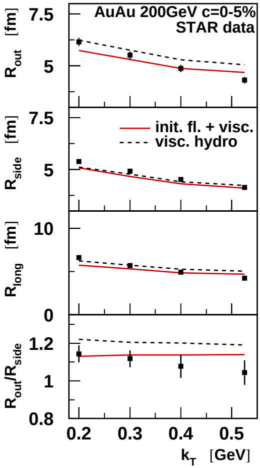
PB , arXiv:1101.1791

- $\frac{dN}{d\eta} = \frac{dN^{pp}_{inel}}{d\eta}\left(\frac{1-\alpha}{2}N_{part} + \alpha N_{bin}\right)$
- Glauber model initial entropy density

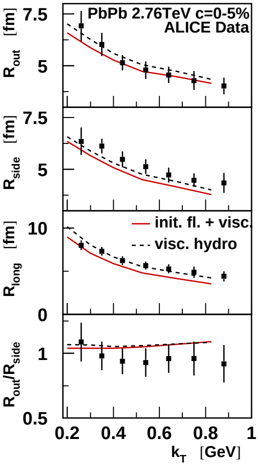
$$s(x,y) \propto \left(\frac{1-\alpha}{2}\rho_{part}(x,y) + \alpha\rho_{bin}(x,y)\right)$$

HBT - strong flow

Au-Au 200GeV

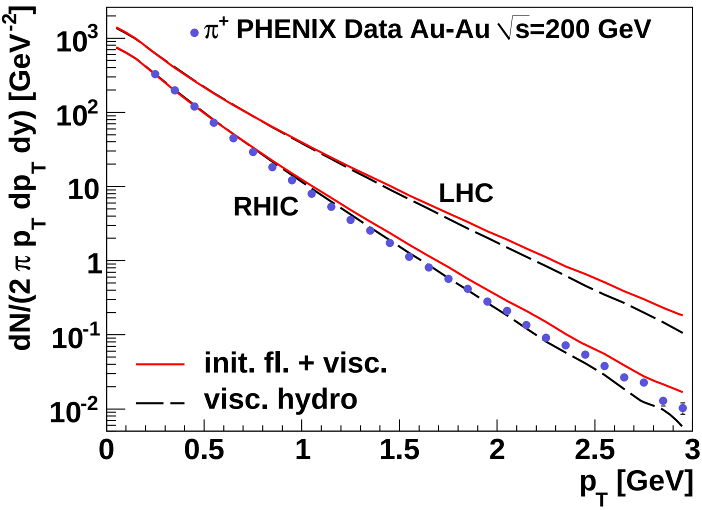


Pb-Pb 2.76TeV



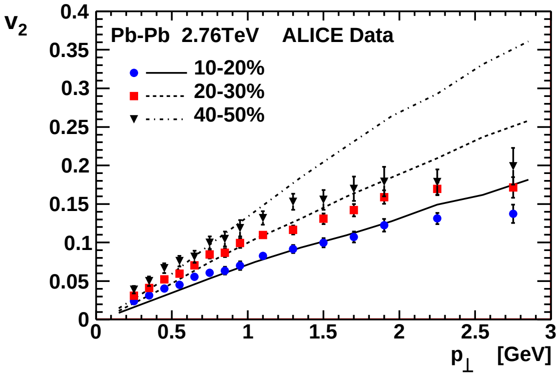
Stronger flow at LHC
Initial flow less important at LHC

Spectra

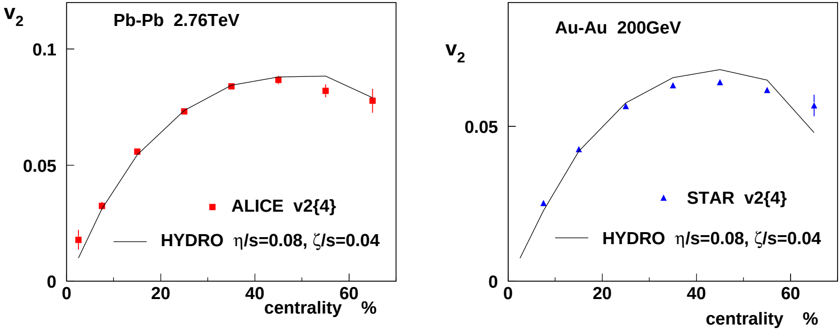


P.B. Phys.Rev.C83 (2011) 044910

Hydro at $\sqrt{s} = 2.76$TeV



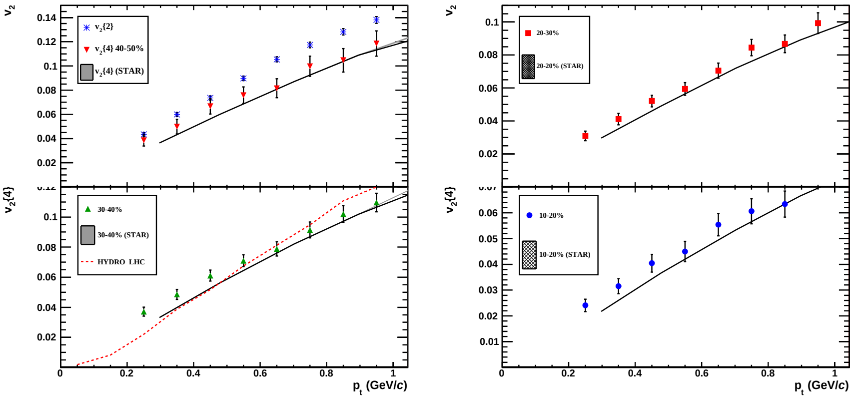
Nearly-perfect fluid



P.B. Phys.Lett.B699 (2011) 283

Glauber i.c. $\rightarrow \eta/s = 1/4\pi$

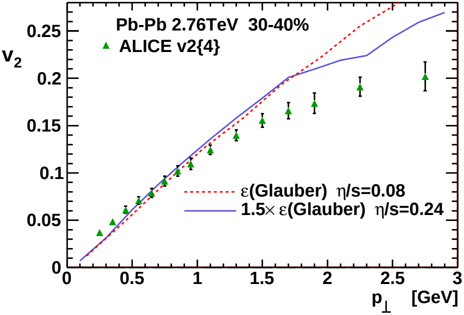
similar to other calulations: Luzum, Schenke et al., Song et al.



Does hydro break down?

- fluctuations
  - $p_\perp$ dependent
  - not seen at RHIC
- larger eccentricity - larger viscosity
  - hadronic viscosity? - not seen at RHIC
- jet remnants

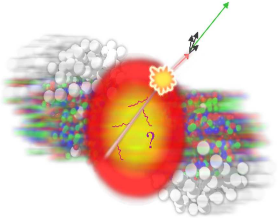
Large eccentricity

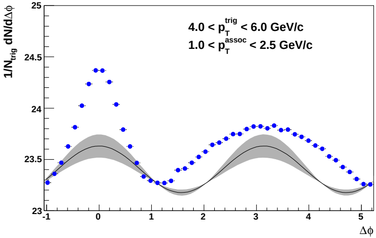


hydro: $v_2(p_\perp) \propto p_\perp$

$\epsilon_{KLN} \simeq 1.25\epsilon_{Glauber}$

why larger hadronic viscosity?

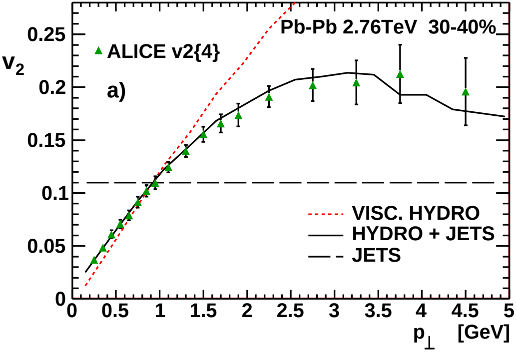




Jets (ATLAS, CMS, ALICE)

particles in jet cone

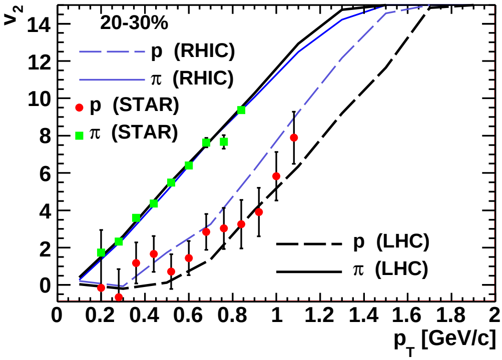
- Jet emission from surface
  geometry $\rightarrow v_2(p_\perp) \simeq p_\perp$ independent
- Asymmetric flow
  hydro + statistical emission $\rightarrow v_2(p_\perp) \propto p_\perp$



10% of jet particles $p_\perp < 1$GeV
nonthermal $\rightarrow$ fragmentation outside of the fireball

cannot be eliminated as non-flow

Liao, Koch, Phys. Rev. Lett. 103 (2009) 042302



stronger pion-proton splitting ↔ stronger flow
thermal-jet coalescence, jet proton-pion ratio

Conclusions

- Hydro describes soft particles (most of)
- Hard EOS
- Strong transverse flow
- Small viscosity **sQGP**
  $\eta/s = 0.08$, $\zeta/s = 0.04$
- Jet remnants? (fluctuations or non-hydro component)