Flow and HBT radii from ideal and viscous hydro

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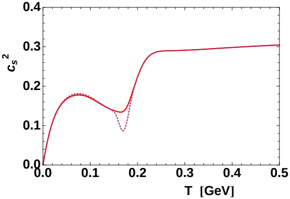
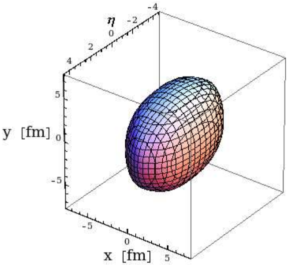
Flow and dissipation, ECT* Trento

3+1D hydrodynamic model

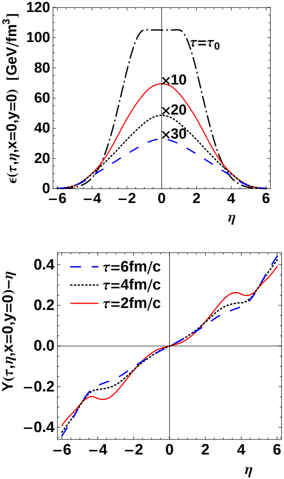
- expansion of dense matter
- ideal hydro: $\epsilon(x_\mu)$, $p(x_\mu)$, $\vec{v}(x_\mu)$.
- hard EOS
- flow + thermal emission + decays
- THERMINATOR Monte-Carlo code

P.B. , Iwona Wyskiel, Phys. Rev. C 79, 044916 (2009)



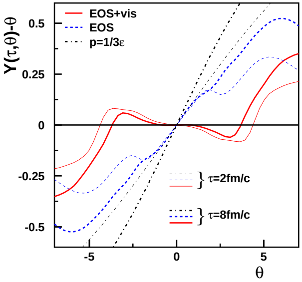


Evolution

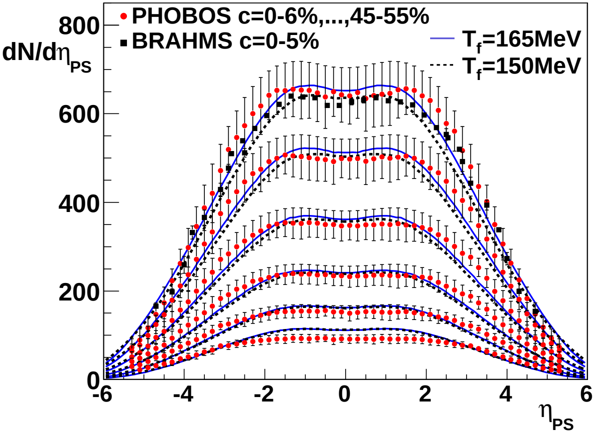


- Bjorken plateau destroyed
- Flow stronger than Bjorken
- Fast cooling

But viscosity!



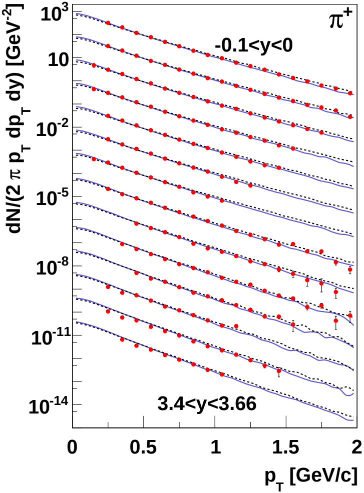
P.B. Phys.Rev. C77 ,034911 (2008)



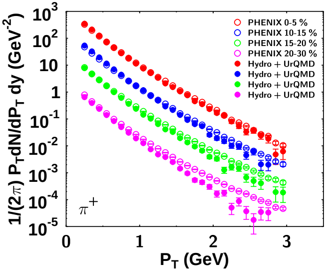
works for centralities $0-40\%$

Spectra $y \neq 0$

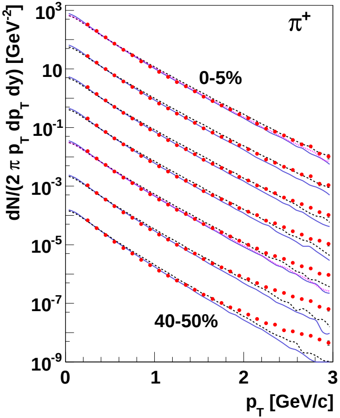
- excellent agreement
- thermal fireball
- no boost-invariance



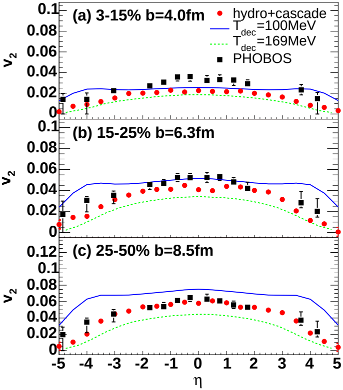
Spectra $b \neq 0$

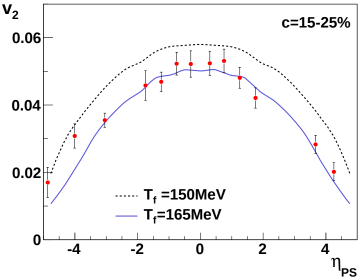


Nonaka, Bass (2007)



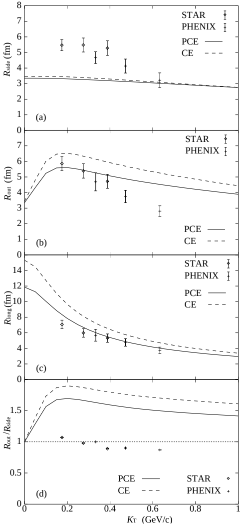
Elliptic flow



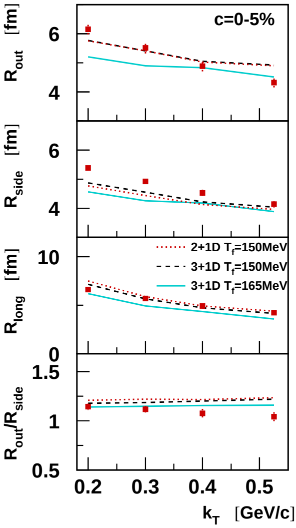


Hirano, Heinz, Karzeev, Lacey, Nara (2006)

HBT radii



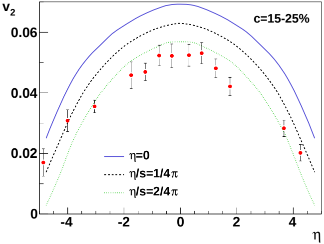
Hirano, Tsuda

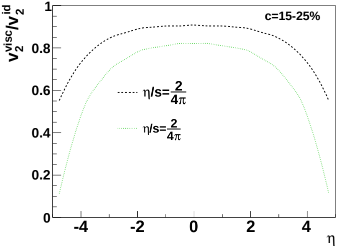


Agreement within 10%

Estimate of viscous effects

dissipative effects at freeze-out $f = f_0 + \delta f$



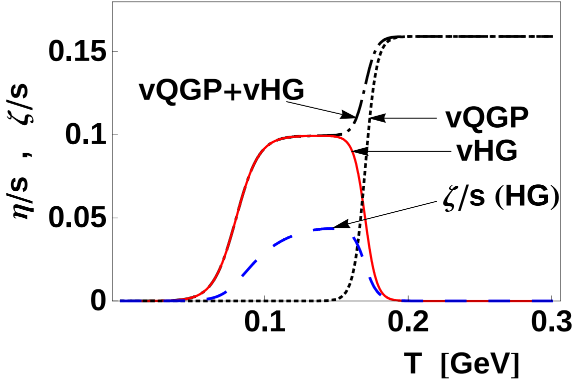


- Reduction of v_2
- Important at large η

Limits of ideal hydro - summary

- works too well for spectra
- works well for HBT
- π-proton splitting?
- cannot be trusted for v_2

Viscosity in HG vs. viscosity in QGP



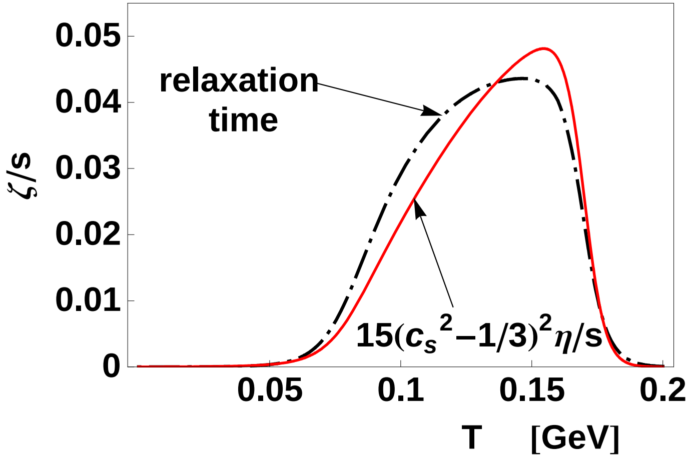
$$\frac{\eta_{QGP}}{s} = \frac{1}{2\pi} = 0.16 \qquad \frac{\eta_{HG}}{s} = 0.1$$

Shear+ bulk viscosity in HG

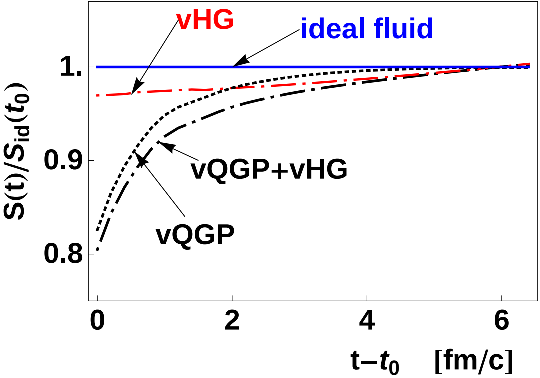
$$p^\mu \partial_\mu f_0 = -\frac{p_\mu u^\mu}{\tau_{HG}} \delta f \;\; \rightarrow \;\; \delta f$$

- $\Pi = \sum \int \frac{d^3p}{(2\pi)^3} \frac{\tau_{HG} m^2}{3ET} f_0(1 \pm f_0) \left(\frac{p^2}{3E} - c_s^2 E \right) \partial_\mu u^\mu = -\zeta \partial_\mu u^\mu$
- $\delta f_{bulk} = C \frac{f_0(1 \pm f_0)}{T} \left(\frac{p^2}{3E} - c_s^2 E \right) \Pi$

Bulk viscosity

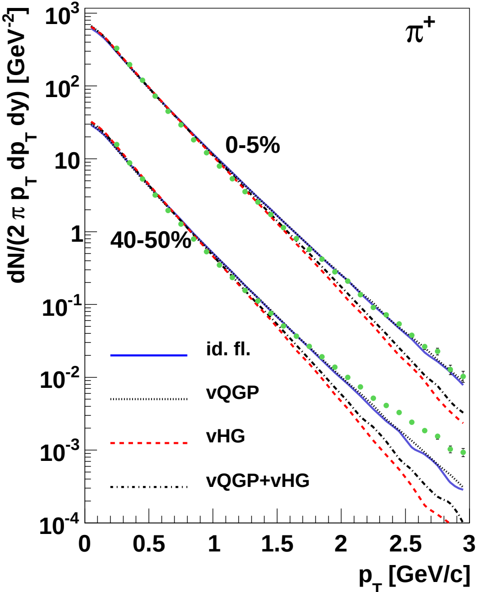


Entropy production and initial conditions



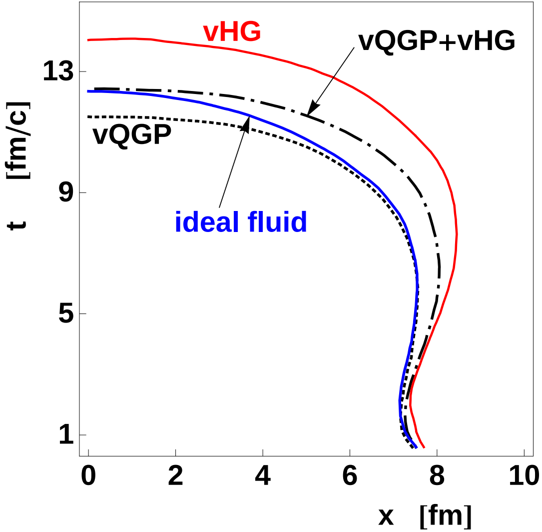
- 20% in QGP
- 2-3% in HG

Spectra

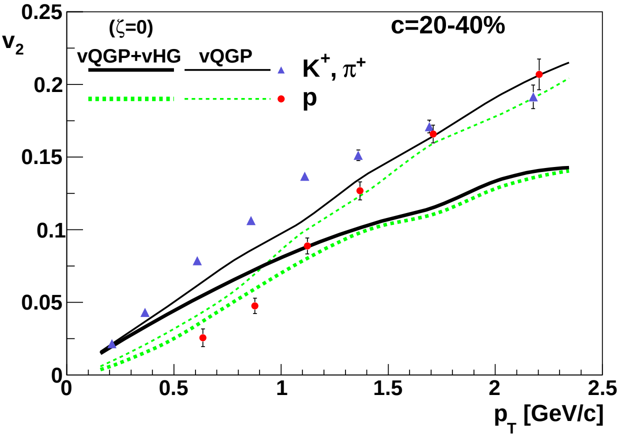


- different freeze-out temperatures
- different initial energy density
- bulk viscosity important !!

Freeze-out

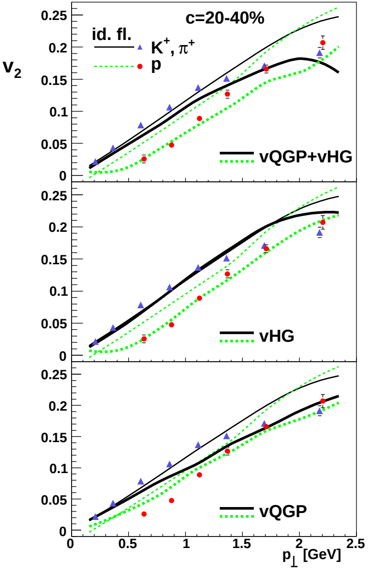


v_2 without bulk viscosity



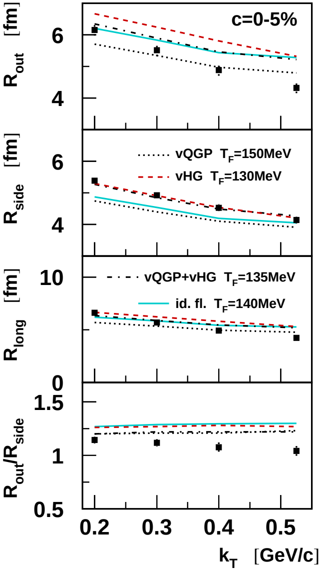
reduction of v_2 from viscous flow and δf

v_2 HG, QGP or both?



- viscosity in HG important
  vHG or vHG+vQGP
- bulk viscosity important

few % differences in HBT



sizes depend on freeze-out time (and flow)

vQGP+vHG favored!!

Technical summary

	id. fl.	vQGP	vHG	vQGP+vHG	vQGP+vHG ($\zeta = 0$)
T_F	140MeV	150MeV	130MeV	135MeV	150MeV
spectra	$< 2GeV$	$< 2GeV$	$< 1.2GeV$	$< 1.2GeV+$	$< 2GeV$
v_2	$\simeq$	reduced	$\simeq$	$\simeq$	strong red.
p/π v_2	no	no	yes	yes	no
HBT	±15%	±10%	±15%	±10%	±10%

viscosity in HG seems favored by v_2 (vHG or vQGP+vHG)
viscosity in QGP (early transverse push ?) improves spectra, HBT

Conclusions

- HG masks v_2 measure of viscosity
- add HBT into the game
- extracting η_{QGP} difficult (τ_0, initial push, ...)

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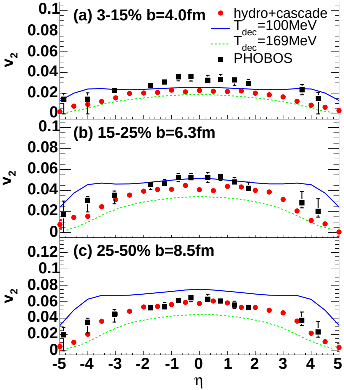
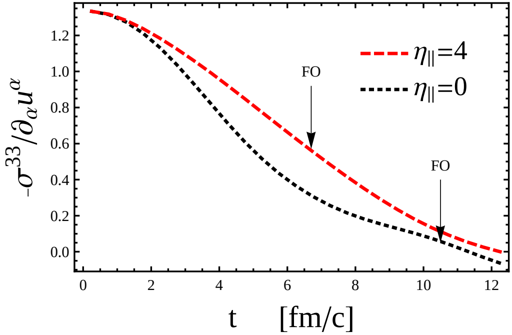


Hirano, Heinz, Karzeev, Lacey, Nara (2006)

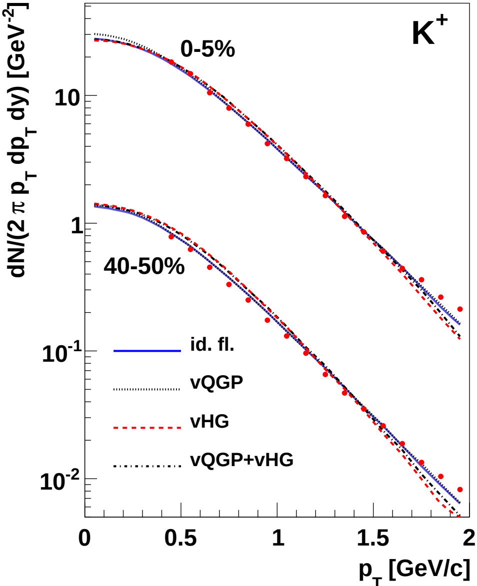
Rapidity dependence of shear viscosity effects

$$\frac{\nabla_\mu u_\nu + \nabla_\nu u_\mu - \frac{2}{3}\Delta_{\mu\nu}\nabla_\alpha u^\alpha}{\partial_\alpha u^\alpha} = \frac{shear}{bulk}$$

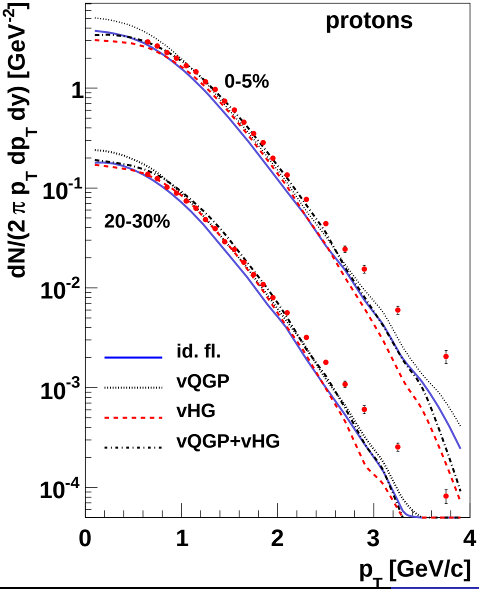


Shear viscosity dominates at large η

Kaon spectra

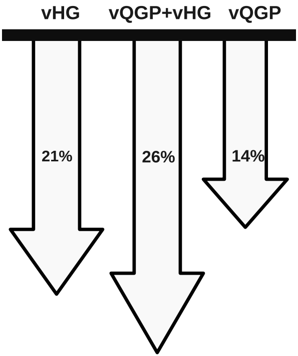


Proton spectra



v_2 reduction

centrality=30-40%



HG dissipation important !!

No effect of viscosity on HBT