Sensitivity of collective flow to off-equlibrium effects

Piotr Bożek

Rzeszów University/Institute of Nuclear Physics Kraków

with Iwona Wyskiel

energy-momentum tensor

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

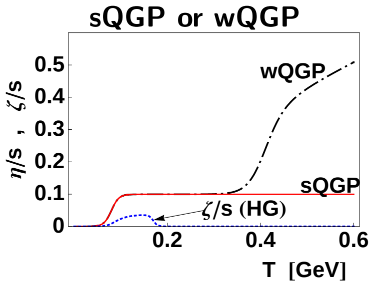
- shear viscosity

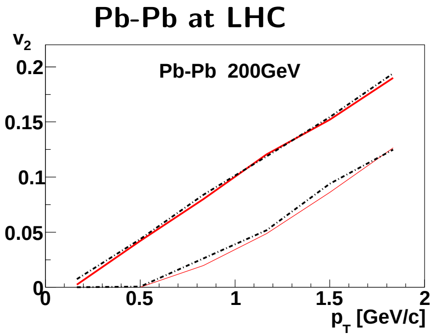
$$\Delta^{\mu\alpha}\Delta^{\nu\beta}u^{\gamma}\partial_{\gamma}\pi_{\alpha\beta} = \frac{2\eta\sigma^{\mu\nu} - \pi^{\mu\nu}}{\tau_{\pi}} - \frac{1}{2}\pi^{\mu\nu}\frac{\eta T}{\tau_{\pi}}\partial_{\alpha}\left(\frac{\tau_{\pi}u^{\alpha}}{\eta T}\right)$$

- bulk viscosity

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

- viscosity corrections from velocity gradients
- **initial** stress tensor - pressure anisotropy

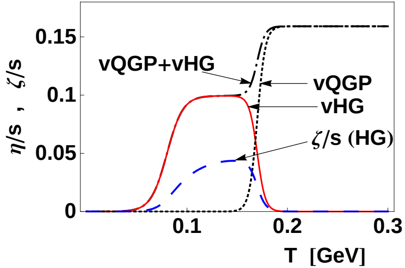


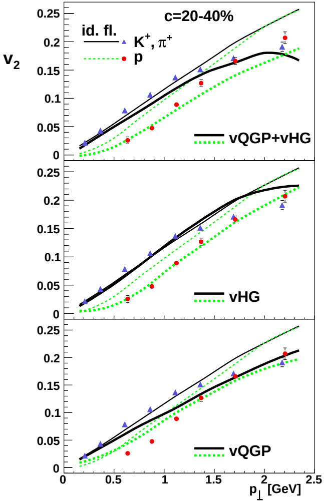


v_2 insensitive to large η/s

$$\frac{\pi}{\epsilon + p} \simeq \frac{\eta}{s}\frac{1}{\tau T}$$

Viscosity in HG vs. viscosity in QGP





$\eta/s \simeq 0.1,\ \zeta/s \simeq 0.03$

Bozek, Phys. Rev. C81, 034909 (2010)

How to test very early dissipation ?

Transverse / Longitudinal Pressure

Non-equilibrium and/or viscosity
Early stage

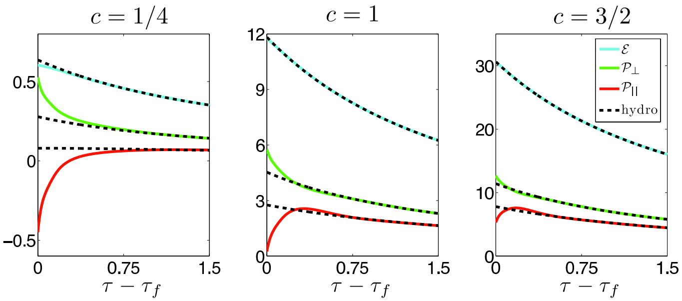
$$T^{\mu\nu} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & p + \pi/2 & 0 & 0 \\ 0 & 0 & p + \pi/2 & 0 \\ 0 & 0 & 0 & p - \pi \end{pmatrix}$$

$$\pi = \frac{4}{3}\frac{\eta}{\tau} \quad \text{Navier-Stokes}$$

more general π possible - (initial value, dynamics, far off-equilibrium)

What signatures of isotropization?

- early non-equilibrium $\neq$ viscosity
- pressure anisotropy
- rescattering, chaotic behavior, strong coupling?



AdS/CFT Chesler, Yaffe, Phys. Rev D82, 026006 (2010)

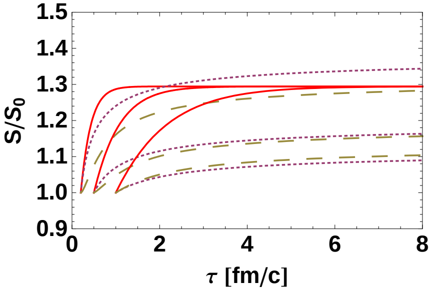
Early dissipation

$$\Pi(t) = \frac{2}{3}(P_\perp - P_\parallel)$$
$$= P_{eq}(\tau_0) exp\left(-\frac{\tau - \tau_0}{\tau_\pi}\right)$$

phenomenological ansatz
relaxation time τ_π

Bozek, Acta Phys. Polon. B39, 1375 (2008)

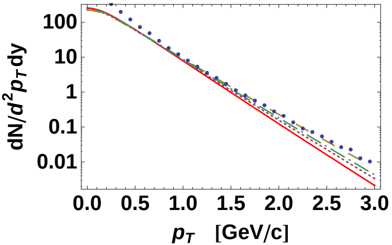
entropy increase



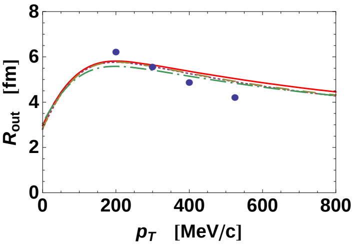
Transverse flow

(various τ_0 and τ_π)

π^+ spectra



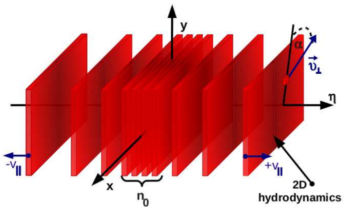
HBT



Bozek, Acta Phys. Polon. B39, 1375 (2008)

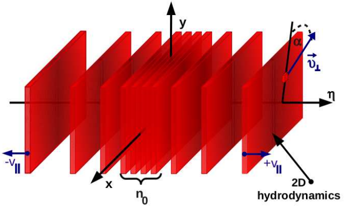
No sensitivity of transverse flow to early dissipation !

Transverse expansion scenarios

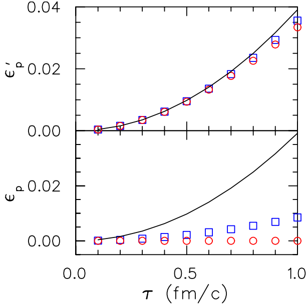


- 2D hydro
- Early dissipation
- Shear viscosity
- Free streaming
- Color fields

Transverse expansion scenarios



BUT
Universal flow



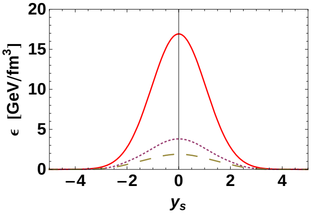
(Vredevoogd Pratt)

- 2D hydro
- Early dissipation
- Shear viscosity
- Free streaming
- Color fields

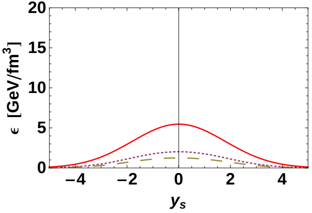
Small effect of early transverse pressure

Longitudinal expansion - cooling

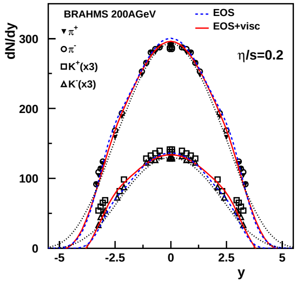
Ideal hydro



Viscous hydro $\eta/s = 0.2$



Bozek, Phys. Rev. C77, 034977 (2008)



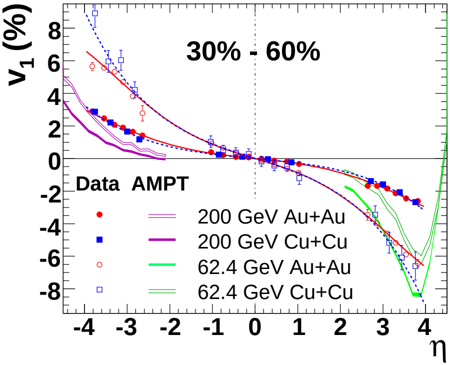
Cannot be observed in final distributions !

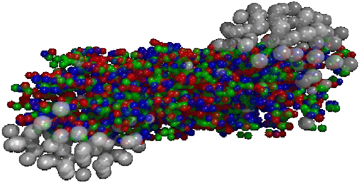
Standard observables are not sensitive to early non-equilibrium

transverse or longitudinal expansion alone is insufficient

Directed flow - v_1

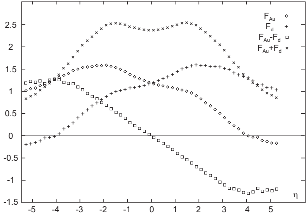
URQMD





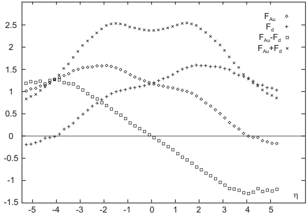
- large flow at 200GeV
- anti-flow
- Au-Au similar to Cu-Cu
- Dynamics: early, 3D

$$\frac{dN}{d^2p\,dy} = \frac{dN}{2\pi\,p\,dp}dy\left(1 + v_1\cos\phi + v_2\cos 2\phi + \dots\right)$$



Asymmetric emission

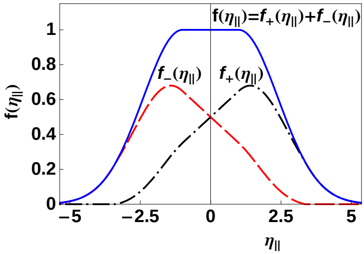
(Białas, Czyż, Acta Phys.Polon.B36, 905 (2005)

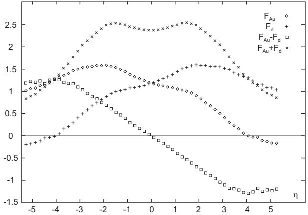


Asymmetric emission

(Białas, Czyż, Acta Phys.Polon.B36, 905 (2005))

$$\rho(\eta, x, y) \quad \propto \quad f_+(\eta) N_+(x, y) + f_-(\eta) N_-(x, y)$$

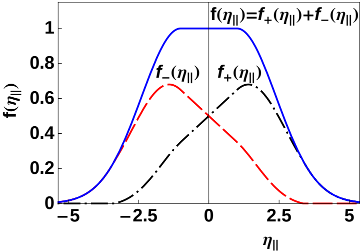


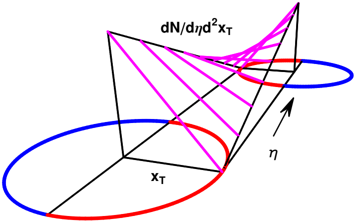


Asymmetric emission

(Białas, Czyż, Acta Phys.Polon.B36, 905 (2005))

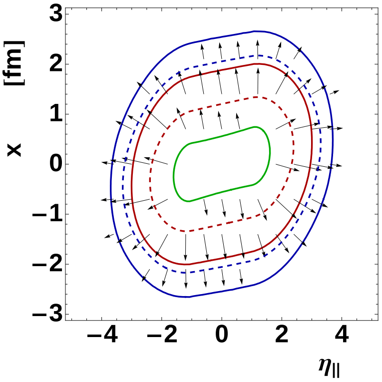
$$\rho(\eta, x, y) \quad \propto \quad f_+(\eta)N_+(x, y) + f_-(\eta)N_-(x, y)$$





bremsstrahlung (Adil Gyulassy, Phys. Rev. C72, 034907 (2005))

Tilted source



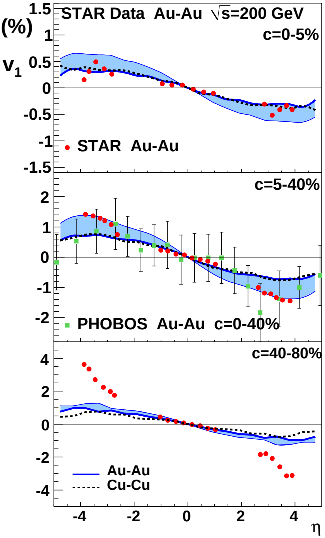
$$\partial_\tau u_x = -\frac{\partial_x p_\perp}{p+\epsilon}$$

$$\partial_\tau Y = -\frac{\partial_\eta p_\parallel}{\tau(p+\epsilon)}$$

Bozek, Wyskiel, Phys. Rev. C81, 054902 (2010)

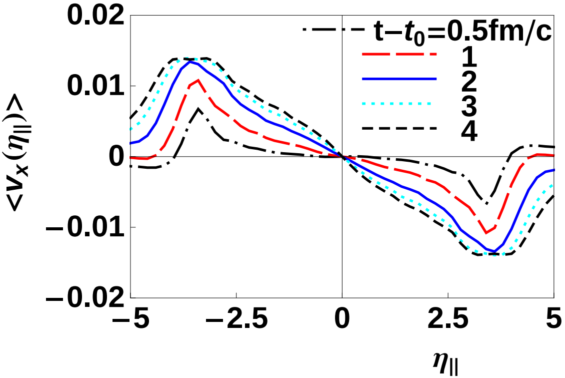
tilted source $\rightarrow$ transverse pressure + longitudinal pressure

Glauber model



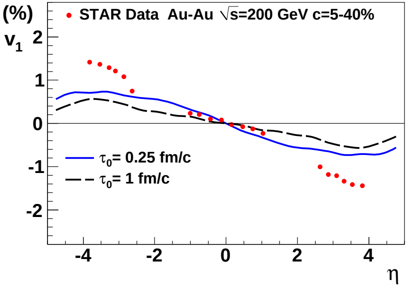
- Anti-flow explained!
- System size dependence
- Consistent with asymmetric emission

Early collectivity



v_1 develops before v_2

Transverse + Longitudinal Expansion = Directed Flow



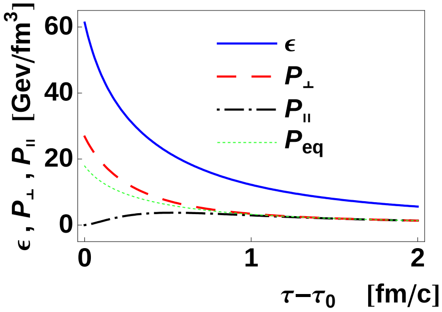
longitudinal pressure appears before 1fm/c
fast isotropization

3+1D expansion with off-equilibrium pressure

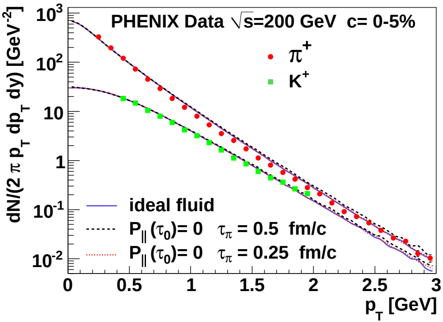
$$T^{\mu\nu} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & p_\perp & 0 & 0 \\ 0 & 0 & p_\perp & 0 \\ 0 & 0 & 0 & p_\parallel \end{pmatrix}$$

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

in $3+1$D

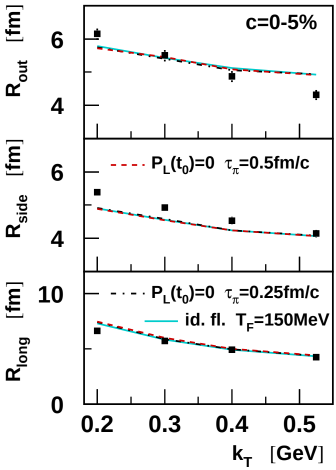


Central collisions - **spectra**



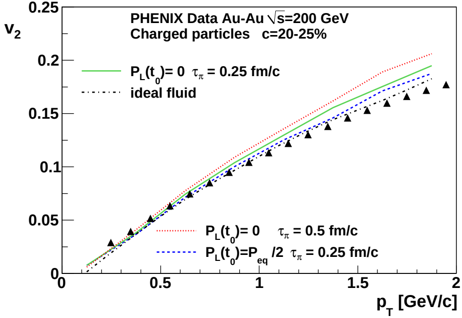
No sensitivity to off-equilibrium pressure

Central collisions - **HBT**



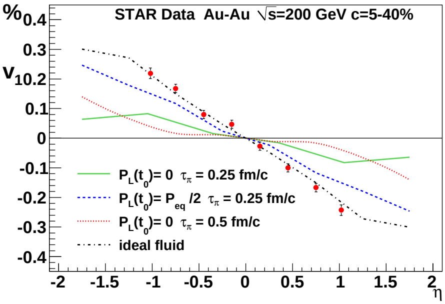
No sensitivity to off-equilibrium pressure

Mid-peripheral collisions - **elliptic flow**



No sensitivity to off-equilibrium pressure

Mid-peripheral collisions - **directed flow**



- **Sensitive to off-equilibrium pressure**
- **RHIC data indicate early thermalization**

New observable for early stages

- η/s in QGP masked by later stages (elliptic flow)
- Directed flow sensitive to longitudinal and transverse pressure
- Directed flow develops early
- Need 3+1D model

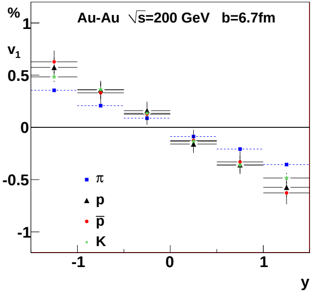
New observable for early stages

- η/s in QGP masked by later stages (elliptic flow)
- Directed flow sensitive to longitudinal and transverse pressure
- Directed flow develops early
- Need 3+1D model

Conclusions

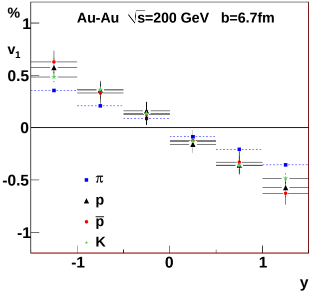
- No room for early pressure anisotropy
- Very fast thermalization

PID v_1

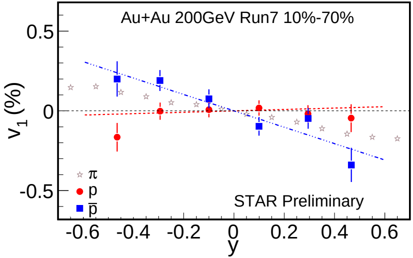


Hydro : mass scaling

PID v_1



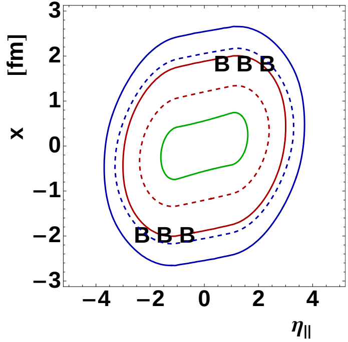
Hydro : mass scaling



Zero baryon flow! (STAR)

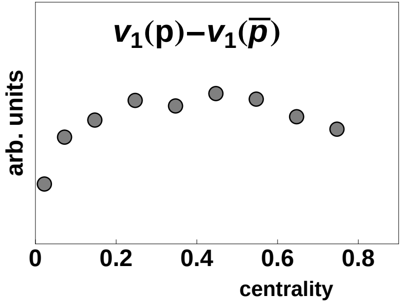
Baryon asymmetry!

fragmenting nucleons

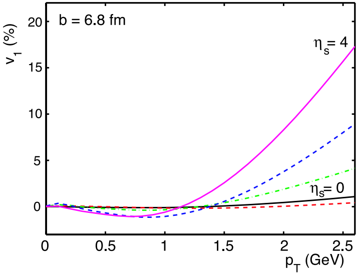


baryons pushed to $v_1 > 0$

$$\Delta v_1 \propto \frac{\mu}{T}\frac{N_+ - N_-}{N_+ + N_-}$$



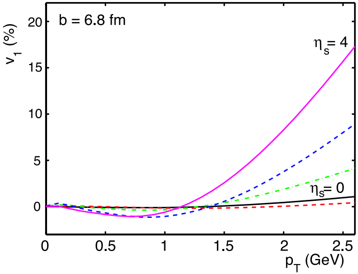
$p_\perp$ dependence



deformed source
(Kolb Heinz)

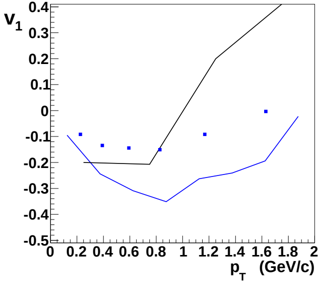
$< p_x >= 0$

$p_\perp$ dependence



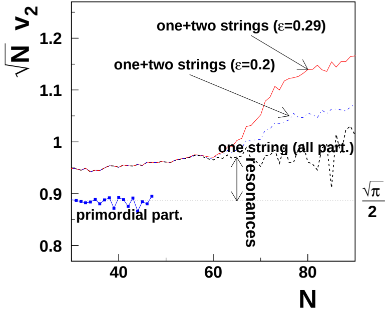
deformed source
(Kolb Heinz)

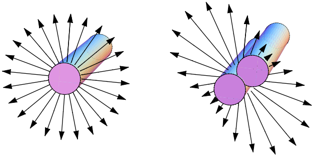
$< p_x >= 0$



3+1D $\rightarrow$ shift to $v_1 < 0$

Collective flow in pp





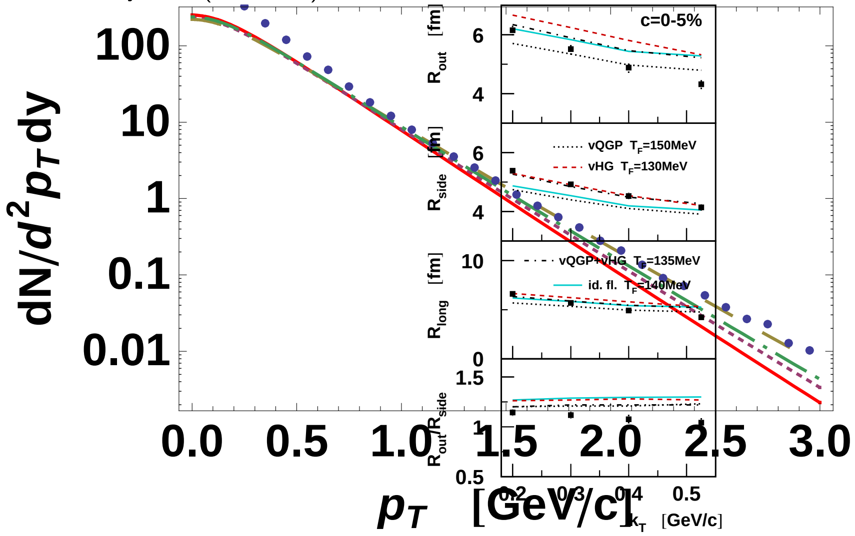
Bozek, 0911.2397;

Casalderrey-Solana, Wiedemann, 0911.4400

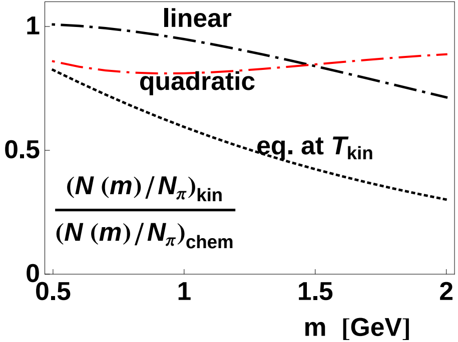
- Asymmetry, flux tubes
- Lifetime$<$ 2fm/c, early flow
- Density?

Probe of early thermalization?

Hubble early flow (Gaussian) Flow from Glauber i.c.

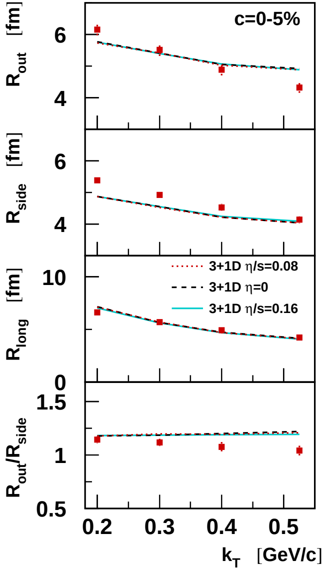


Bulk $\rightarrow$ chemical non-equilibrium
$T_{chem} = 155 MeV \;\; T_{fr} = 140 MeV$



bulk correction shift particles ratios
to temperatures $10 - 15$MeV higher

HBT and δf



HBT insensitive
to viscosity corrections

Bozek, Wyskiel PoS (EPS-HEP), 39 (2009)