Early dissipation and viscosity

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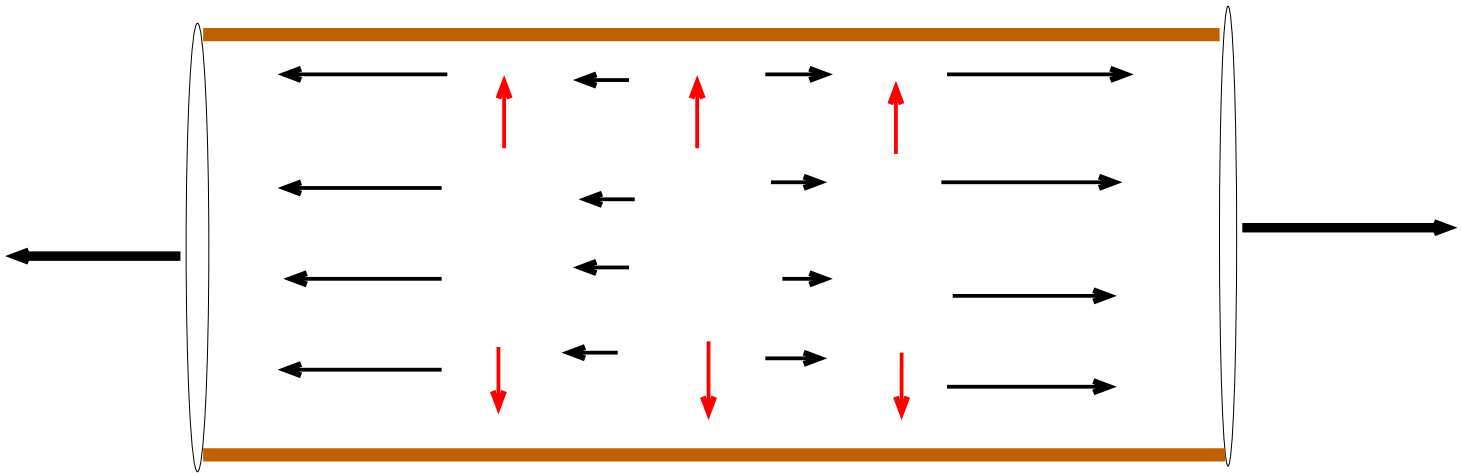
longitudinal+transverse expansion



$$Y = \frac{1}{2}\ln\left(\frac{1+v}{1-v}\right) \;=\; y_s = \ln\left(\frac{t+z}{t-z}\right)$$

Hydrodynamics with viscosity

boost invariance + transverse expansion + viscosity

- build up of transverse flow
- HBT
- elliptic flow - very sensitive!
- slower cooling + entropy production

Teaney, Romatschke, Heinz, Song, Chaudhuri, Muronga, ...

Modified energy-momentum tensor

Bjorken longitudinal flow $\vec{v} = (0, 0, v_z)$

- $T^{\mu\nu} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & p + \Pi/2 & 0 & 0 \\ 0 & 0 & p + \Pi/2 & 0 \\ 0 & 0 & 0 & p - \Pi \end{pmatrix}$
- increased transverse pressure
- $\frac{d\epsilon}{d\tau} = -\frac{\epsilon + p - \Pi}{\tau}$
  less longitudinal work

2-D hydrodynamics

3-D hydro (standard)

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

isotropic pressure
longitudinal work

2-D hydro (Heinz, Wong, Białas, Chojnacki, Florkowski)

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

no longitudinal work, stronger transverse expansion, larger flow, smaller HBT radii

Evolution of the energy-momentum tensor

$$\begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & p_\perp & 0 & 0 \\ 0 & 0 & p_\perp & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \rightarrow \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$$

local isotropisation of the pressure
time dependent corrections to the pressure

$$\Pi(\tau_0) = p(\tau_0)$$

relaxation equation

$$\frac{d\Pi}{d\tau} = -\Pi(\tau)/\tau_\pi + \Pi_{NS}/\tau_\pi$$

we drop the NS term ($\eta = 0$)
only initial conditions

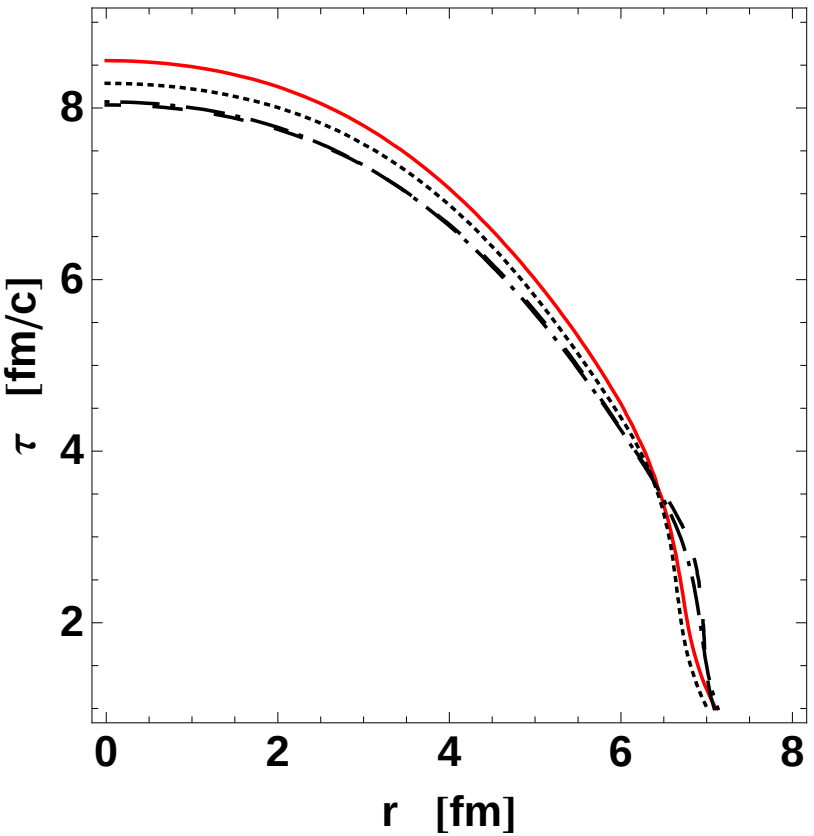
Stages of the evolution

- $\tau_{parton} < \tau \leq \tau_0$
  2-D expansion (if at all) $\Rightarrow$ free-steaming?
- $\tau_0 \leq \tau \leq \tau_0 + \tau_\pi$
  2-D $\longrightarrow$ 3-D, glasma $\longrightarrow$ liquid, $\Rightarrow$ dissipation
- $\tau_0 + \tau_\pi < \tau < \tau_{fr}$
  3-D expansion $\Rightarrow$ almost ideal fluid
- $\tau_{fr} < \tau$
  hadronic rescattering, $\Rightarrow$ viscosity

Transverse expansion with early dissipation

1+1dim calculation in τ-r

freeze-out hypersurface

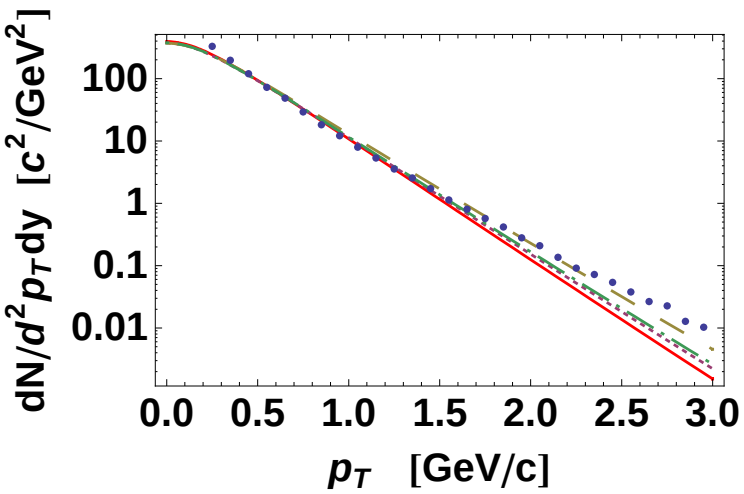


- $\tau_0 = 1\text{fm/c}$,
  - $\tau_\pi = 1\text{fm/c}$
  - ideal fl.
- $\tau_0 = 0.5\text{fm/c}$,
  - $\tau_\pi = 0.5\text{fm/c}$
  - ideal fl.

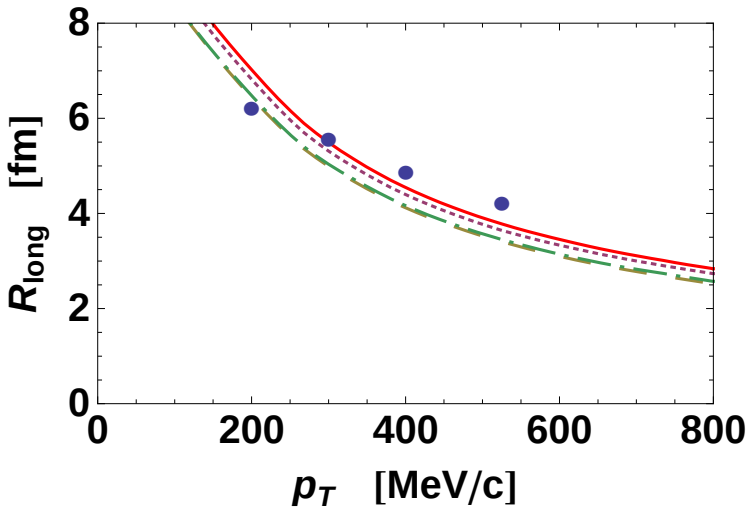
viscous and ideal hydro - same freeze-out

retuning of initial conditions

π^+ spectra

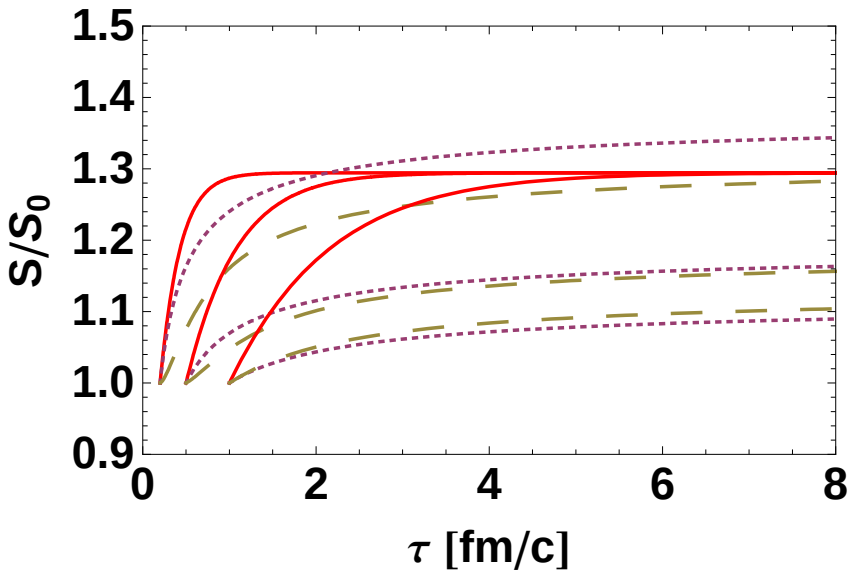


HBT



retuning of initial conditions

Entropy production



30% increase of entropy

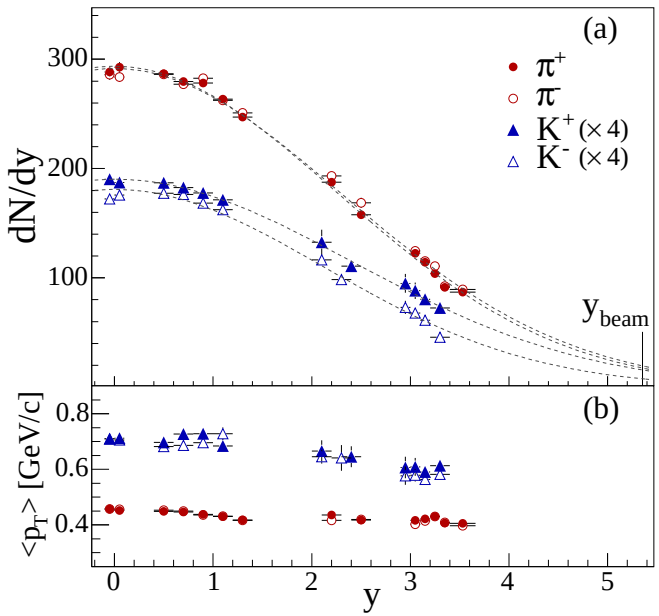
Experimental limits on entropy production :

- 0% - CGC or diquark initial conditions
- 60% - wounded nucleons initial conditions

Effect of viscosity on longitudinal expansion

1+1dim calculation in t-z

No boost-invariance at RHIC



Bjorken solution

- $Y = y_s$
- $\epsilon(\tau, y_s) = \epsilon(\tau) \propto \tau^{-(1+c_s^2)}$

Freeze-out !!

$$\epsilon(y_s) \leftrightarrow \frac{dN}{dy}$$

Viscous hydro equations 1+1 dimensions

- cooling

$$D\epsilon = -(\epsilon + p - \Pi)\mathcal{K}Y$$

- acceleration

$$(\epsilon + p - \Pi)DY = -\mathcal{K}p + \mathcal{K}\Pi$$

- relaxation

$$D\Pi = -\frac{\Pi - \Pi_{Navier-Stokes}}{\tau_\pi}$$

derivative operators

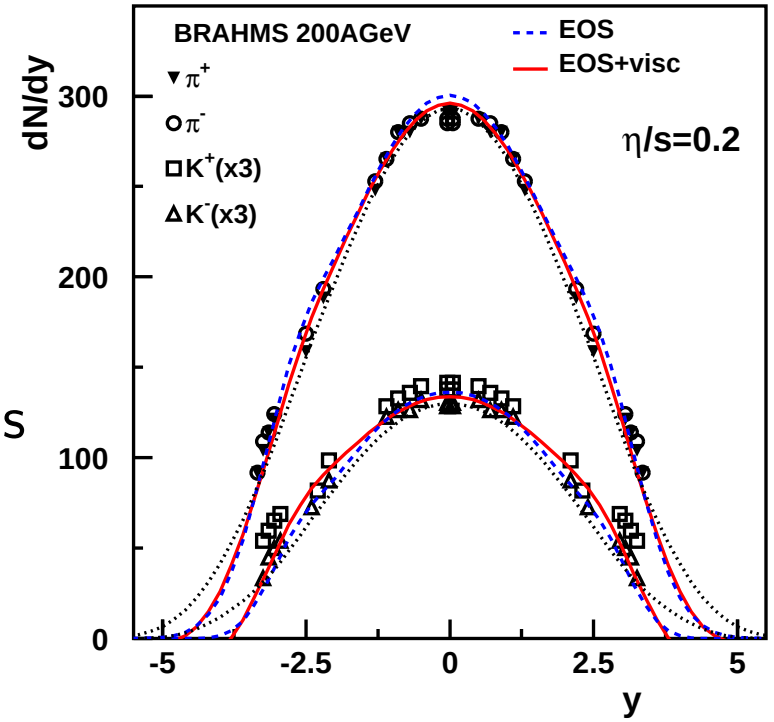
"time"

$D = \cosh(Y - y_s)\partial_\tau + \sinh(Y - y_s)/\tau\partial_{y_s}$

"spatial"

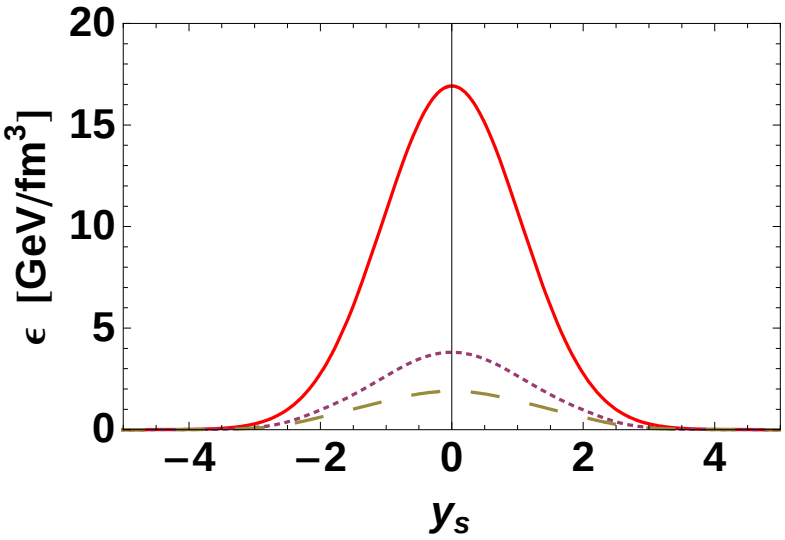
$K = \sinh(Y - y_s)\partial_\tau + \cosh(Y - y_s)/\tau\partial_{y_s}$

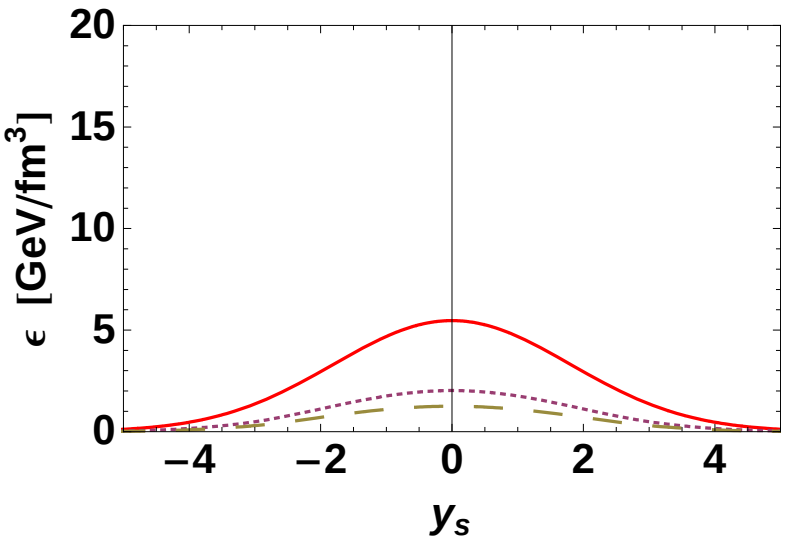
Particle emission
Cooper-Frye formula
retuning the initial conditions

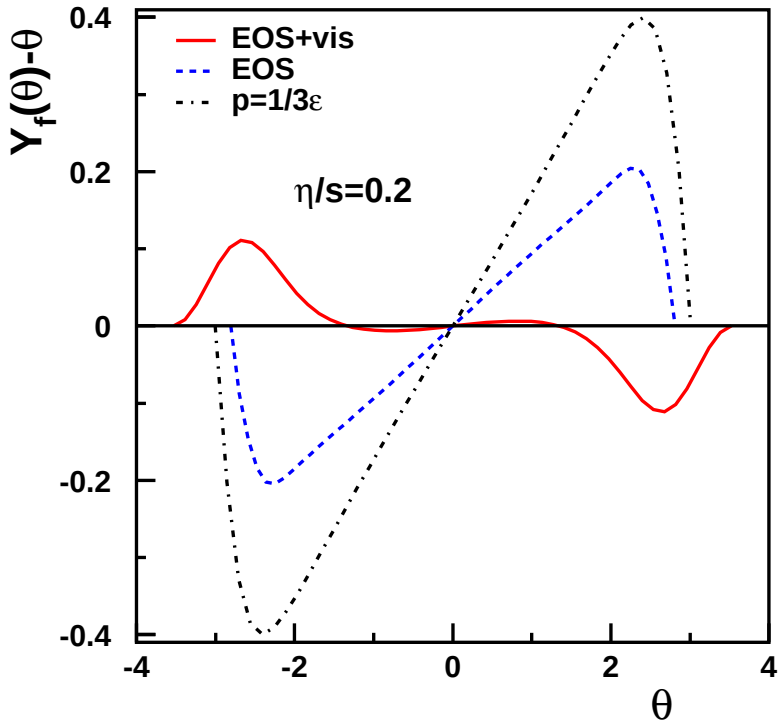


$\tau = 1, 3, 5$**fm/c**

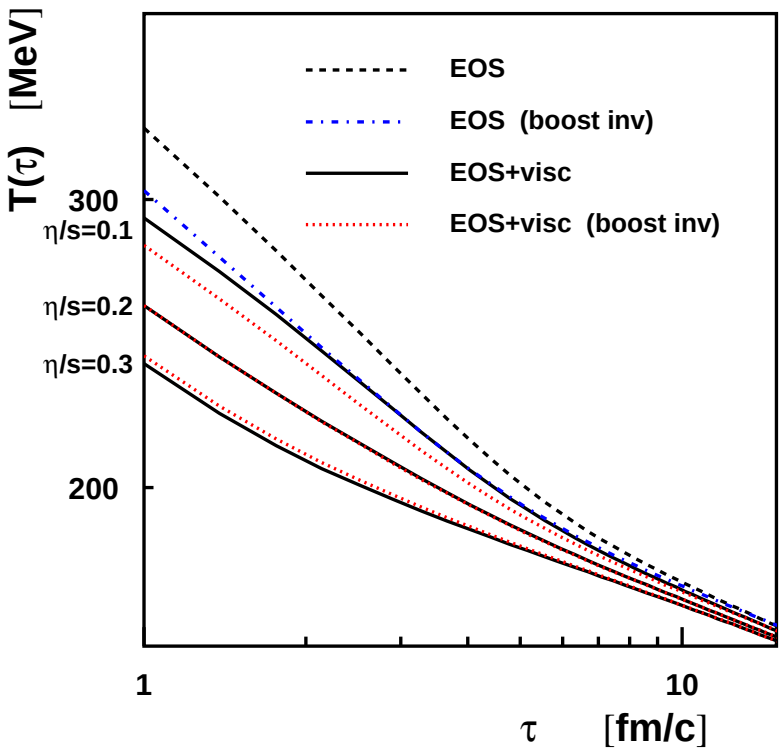
ideal fluid **viscous fluid** $\eta/s = 02.$







viscous hydro
conserves Bjorken flow

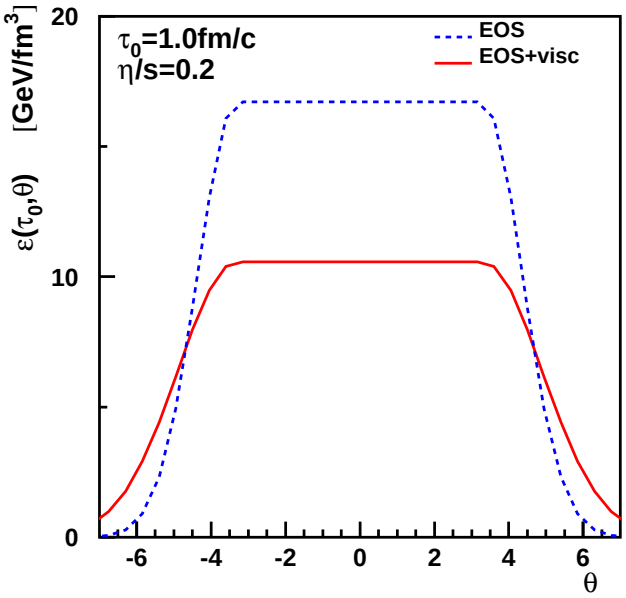


rapidity gradients $\longrightarrow$ faster cooling

viscosity $\longrightarrow$ slower cooling + slower expansion

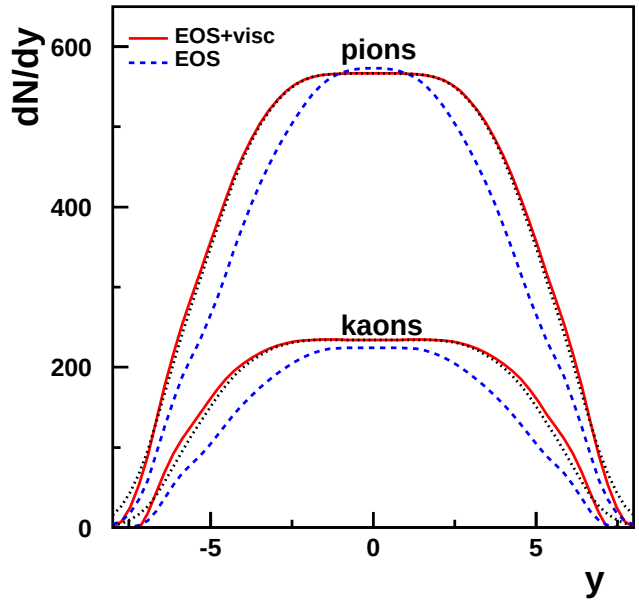
LHC plateau?

initial density



Bjorken plateau

final dn/dy



wider dN/dy plateau !

Effects of early dissipation

- entropy production $\longrightarrow$ reduction of the initial temperature
- slightly harder spectra
- no effect on HBT

Viscosity changes global event dynamics

- helps to conserve Bjorken flow
- slower cooling
- entropy production

Early dissipation + viscous hadronic stage, not around T_c

P.B. arXiv:0711.2889 [nucl-th] and arXiv:0712.3498 [nucl-th]