Viscosity and boost invariance at RHIC and LHC

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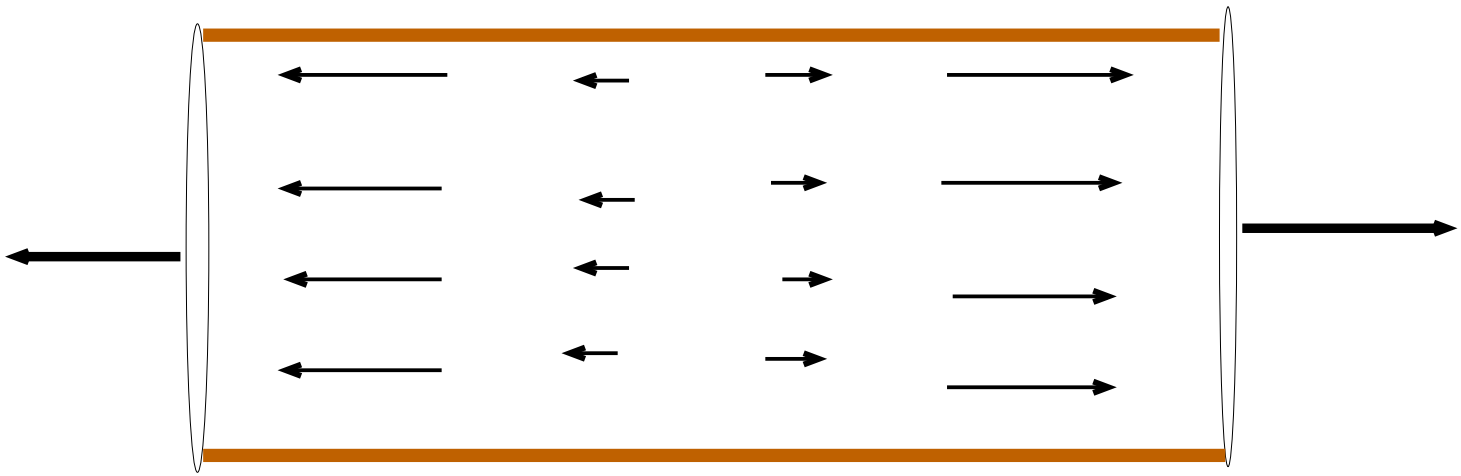
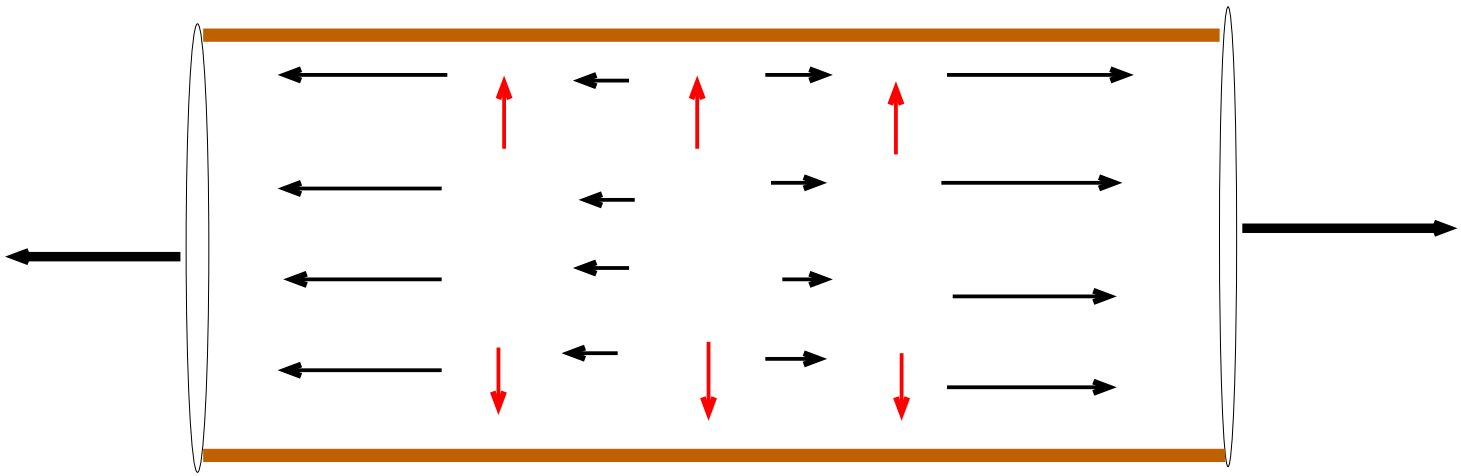
longitudinal expansion



longitudinal+transverse expansion



Modified energy-momentum tensor

Bjorken longitudinal flow $\vec{v} = (0, 0, z/t)$

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

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- increased transverse pressure
- $\frac{d\epsilon}{d\tau} = -\frac{\epsilon + p - \Pi}{\tau}$
  less longitudinal work

boost invariance + transverse expansion + viscosity

- build up of transverse flow
- HBT
- elliptic flow
- slower cooling and entropy production

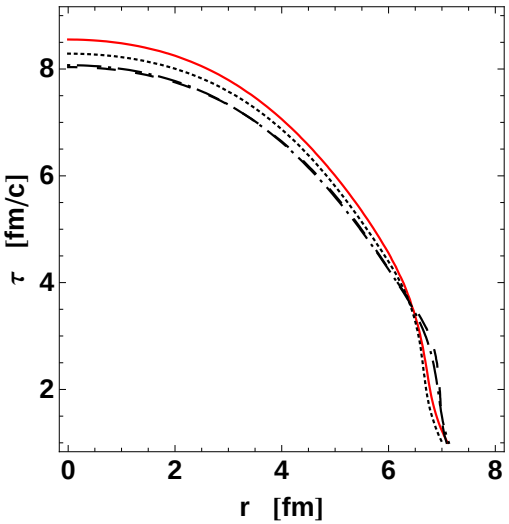
Cooper-Frye formula

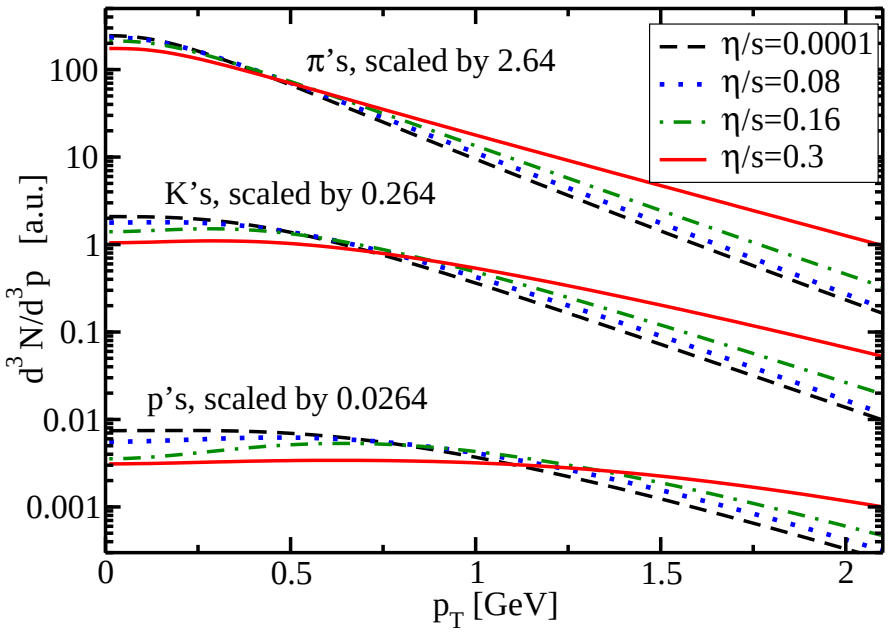
$$E\frac{d^3N}{d^3p} = \int d\Sigma_\mu p^\mu \left[f(p_\nu u^\nu) + \delta f(p_\nu u^\nu)\right]$$

nonequilibrium corrections

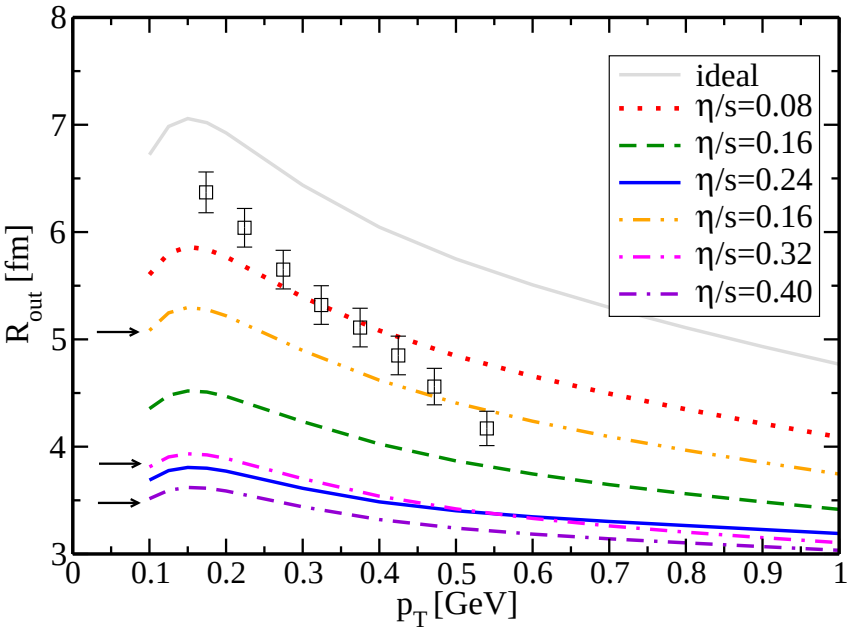
$$\delta f(p) \simeq \frac{p_\mu p_\nu \pi^{\mu\nu}}{2T^2(\epsilon + p)} f(p)$$

spectra, HBT, elliptic flow

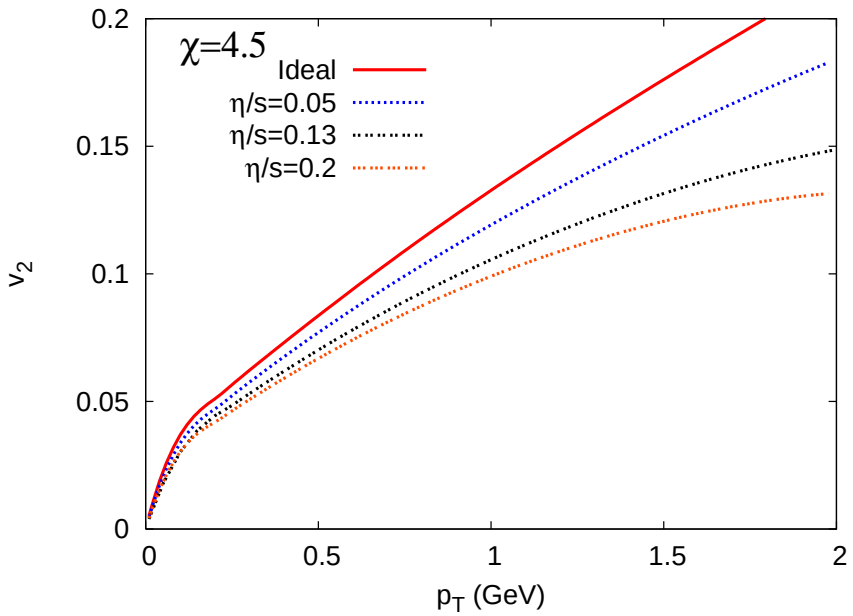




harder spectra (Baier, Romatschke)



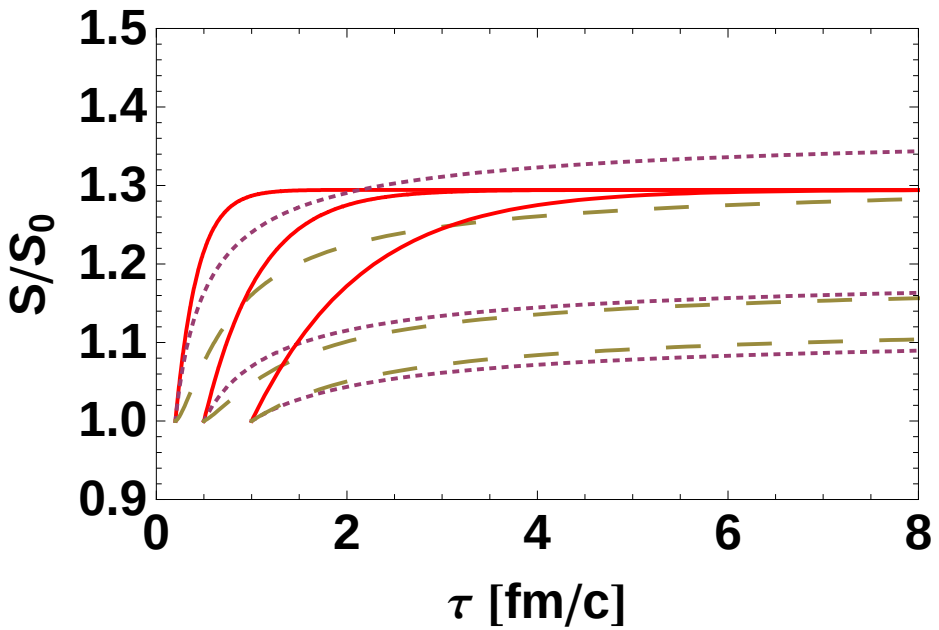
stress tensor at freeze-out $\Rightarrow$ modified HBT (Romatschke)



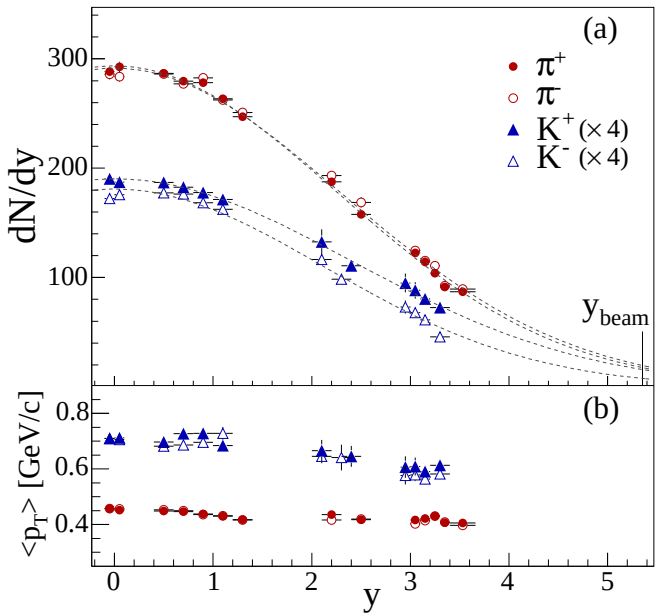
Elliptic flow (Dusling, Teaney)

dissipation $\longrightarrow$ entropy production

$$\frac{d(s\tau)}{d\tau} = \frac{\Pi}{T}$$



No boost-invariance at RHIC



Bjorken solution

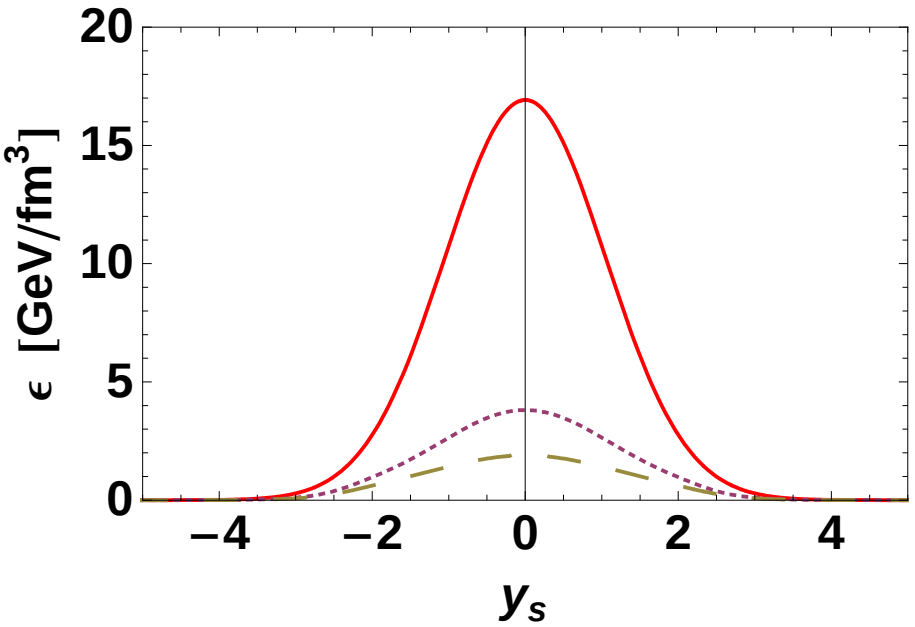
- $Y = y_s$
- $\epsilon(\tau, y_s) = \epsilon(\tau) \propto \tau^{-(1+c_s^2)}$

Freeze-out !!

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

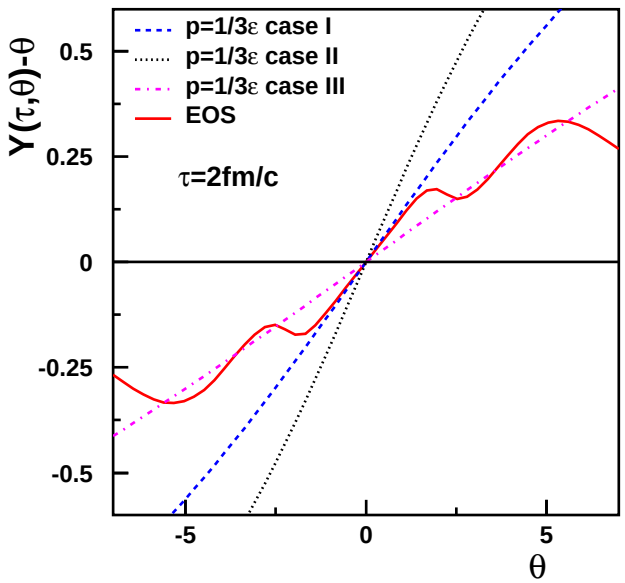
expansion

$\tau = 1,\ 3,\ 5\text{fm/c}$



stronger flow!

$Y > y_s$



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

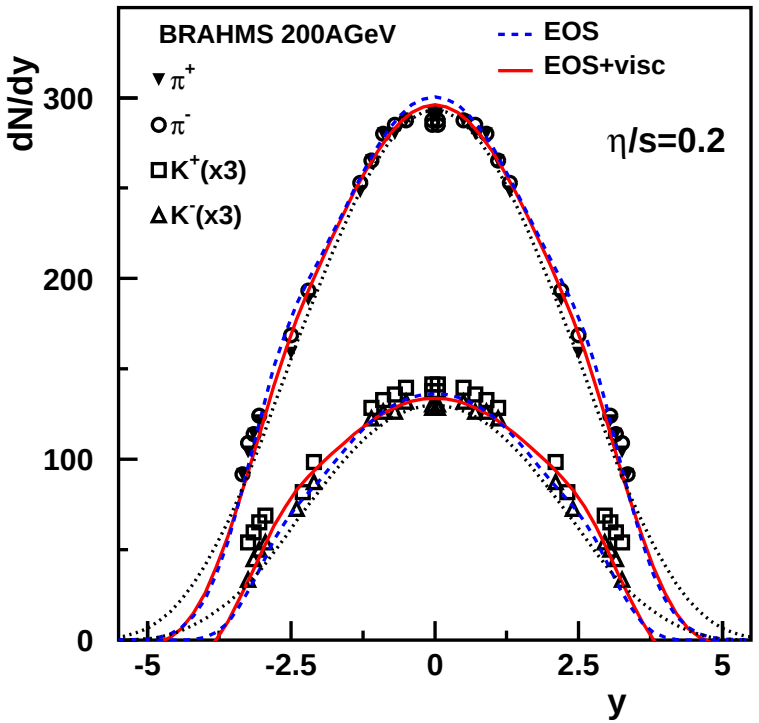
"time"

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

"spatial"

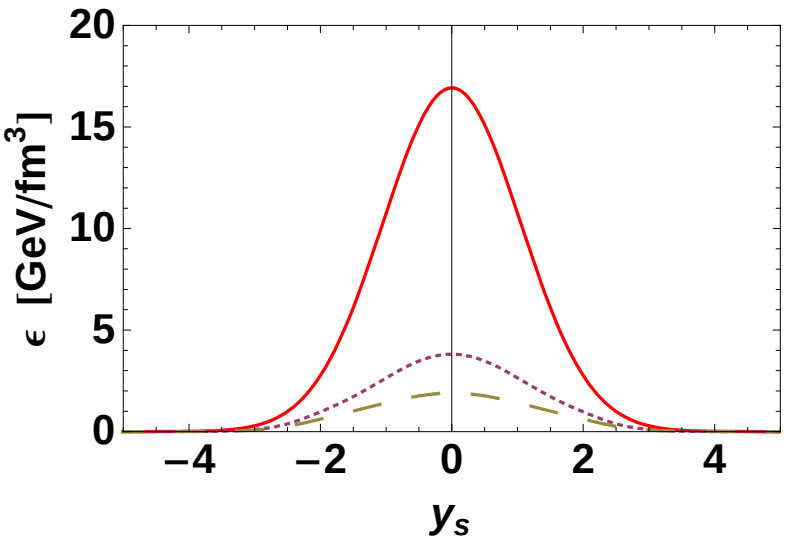
$K = \sinh(Y - y_s)\partial_\tau + \cosh(Y - y_s)/\tau\partial_{y_s}$

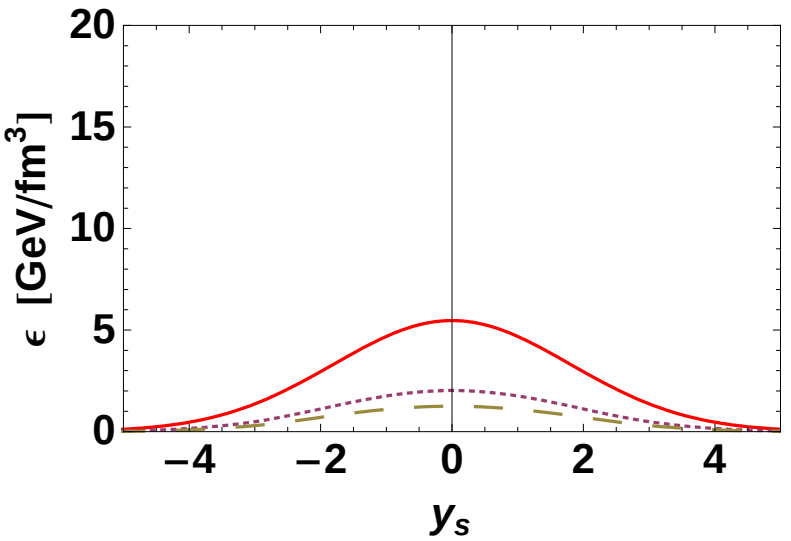
Particle emission
Cooper-Frye formula
tuning initial conditions

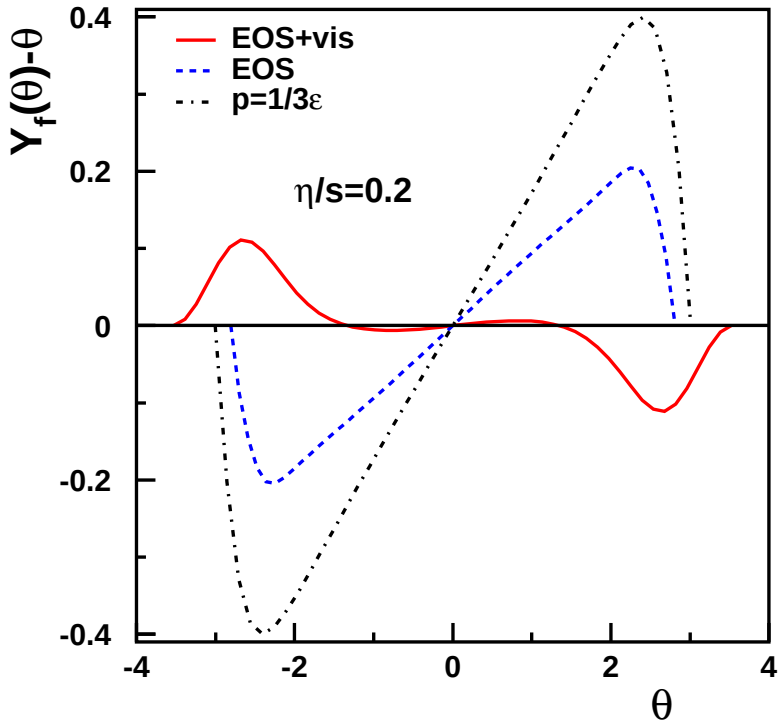


$$\tau = 1, 3, 5 \mathbf{fm/c}$$

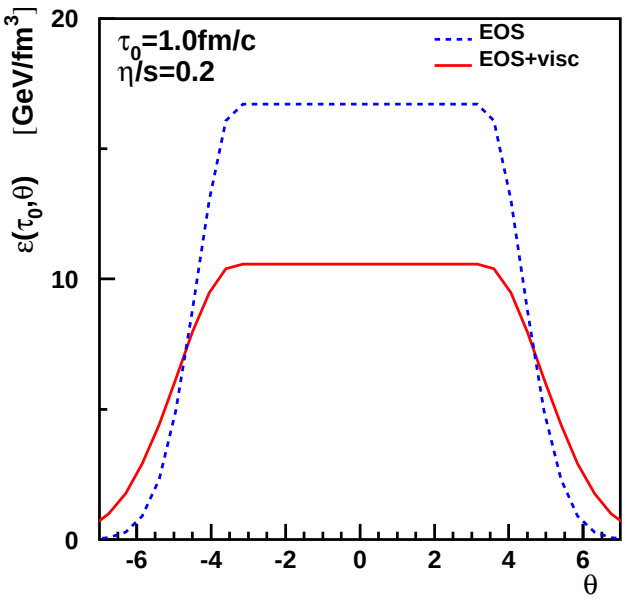
ideal fluid **viscous fluid**



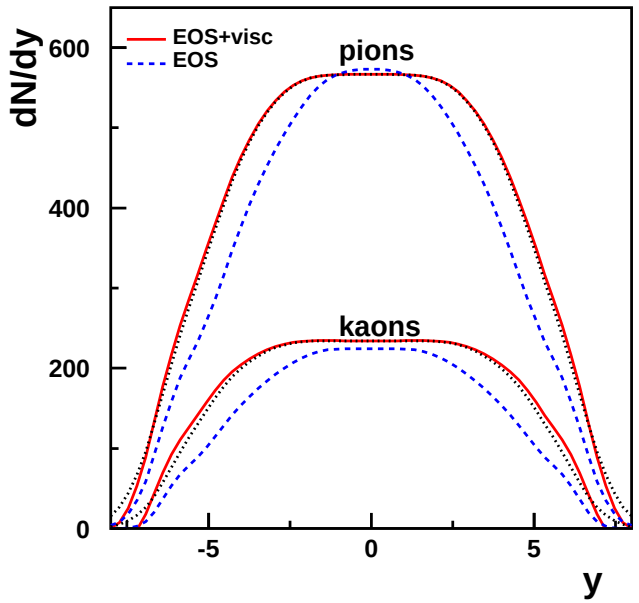




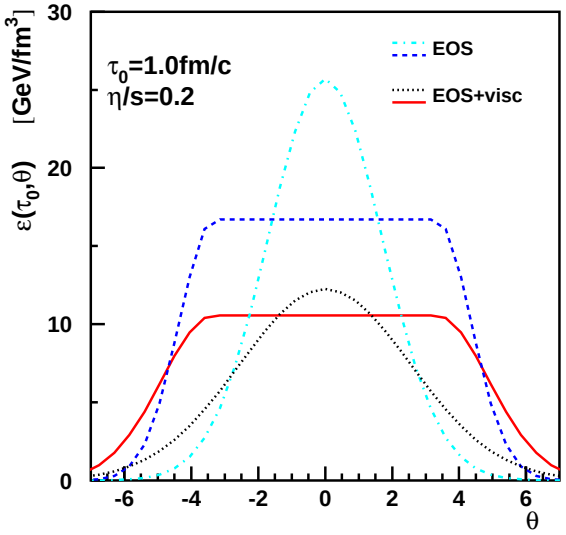
viscous hydro
conserves Bjorken flow



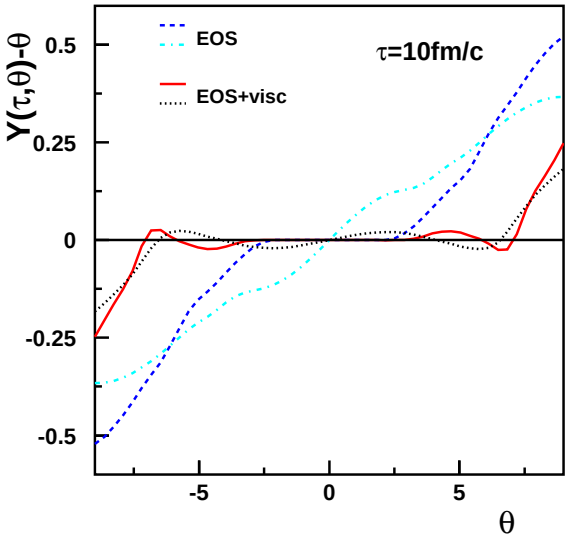
Bjorken plateau



wider dN/dy plateau !



Gaussian initial distribution



Bjorken flow

RHIC

- no boost-invariance in ϵ
- Bjorken flow only with viscosity
- no plateau in dN/dy

LHC

- boost-invariance in ϵ
- Bjorken flow
- plateau in dN/dy in viscous hydro

Viscosity changes global event dynamics

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