Rapidity dependence of spectra and v_n and the effect of viscosity at forward rapidities

Björn Schenke
Physics Department, Brookhaven National Laboratory, Upton, NY, USA

June 25 2013

2013 RHIC & AGS
Annual Users' Meeting

BNL, Upton, NY

BROOKHAVEN
NATIONAL LABORATORY

Introduction

Hydrodynamics has proven a powerful effective theory for the description of bulk properties of heavy-ion collisions

Problem was simplified by assuming boost invariance or the ideal limit

Less than 2 years ago, the first viscous 3+1 dimensional simulations became available

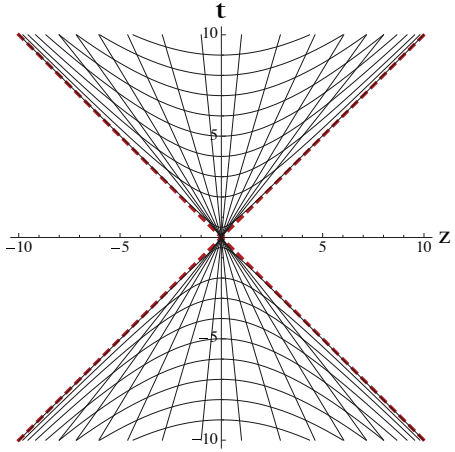
This talk:
I summarize new insights from including
longitudinal dynamics and viscosity

From 3+1 to 0+1 dimensions and back

Reduce dimensions to tackle problem:
High energy $\rightarrow$ approximate boost-invariance of particle production

Hyperbolic coordinates

$$t = \tau \cosh \eta \qquad \tau = \sqrt{t^2 - z^2}$$
$$z = \tau \sinh \eta \qquad \eta = \frac{1}{2} \frac{t+z}{t-z}$$



0+1 dimensions: Bjorken model J. D. Bjorken, Phys. Rev., D27, 140 (1983)
boost invariance and homogeneity in transverse direction
The ideal hydrodynamic equation: $\partial_\tau \varepsilon + \frac{\varepsilon + P}{\tau} = 0$
can be solved analytically (with ideal equation of state)

1+1 dimensions: isotropy in transverse direction and boost-invariance
or no boost-invariance but homogeneity in transverse direction

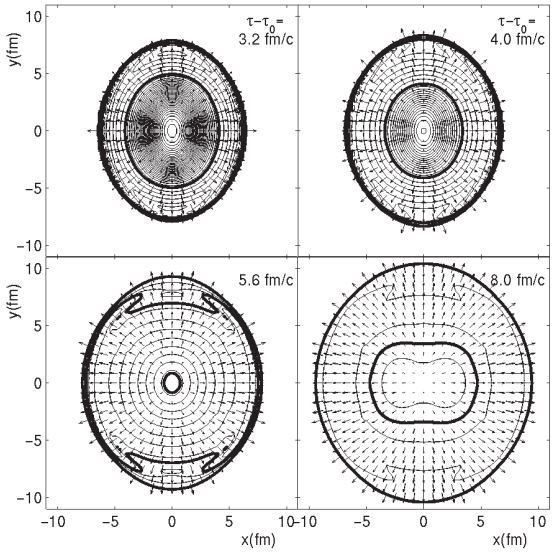
Towards 3+1 dimensional fluid-dynamics

2+1 dimensions: boost-invariance, full transverse dynamics

ideal fluid-dynamics:

P. F. Kolb, J. Sollfrank, and U. W. Heinz, Phys. Lett. B459, 667 (1999)
P. F. Kolb, J. Sollfrank, and U. W. Heinz, Phys. Rev. C62, 054909 (2000)
P. F. Kolb, P. Huovinen, U. W. Heinz, and H. Heiselberg, Phys. Lett. B500, 232 (2001)
T. Hirano and K. Tsuda, Phys. Rev. C66, 054905 (2002)
...

Kolb et al., Phys. Rev. C 62, 054909



viscous fluid-dynamics:

P. Romatschke and U. Romatschke, Phys. Rev. Lett. 99, 172301 (2007)
M. Luzum and P. Romatschke, Phys. Rev. C78, 034915 (2008)
H. Song and U. W. Heinz, Phys. Lett. B658, 279 (2008)
H. Song and U. W. Heinz, Phys. Rev. C78, 024902 (2008)
K. Dusling and D. Teaney, Phys. Rev. C77, 034905 (2008)
...

valid around mid-rapidity, able to describe measured anisotropic flow

Towards 3+1 dimensional fluid-dynamics

3+1 dimensions: full longitudinal and transverse dynamics

ideal fluid-dynamics:

C. Nonaka, E. Honda, and S. Muroya, Eur. Phys. J. C17, 663 (2000)
T. Hirano, Phys. Rev. C65, 011901 (2002)
T. Hirano and K. Tsuda, Phys. Rev. C66, 054905 (2002)
T. Hirano, K. Morita, S. Muroya, and C. Nonaka, Phys. Rev. C65, 061902 (2002)
C. Nonaka and S. A. Bass, Phys. Rev. C75, 014902 (2007)
B. Schenke, S. Jeon, and C. Gale, Phys.Rev. C82, 014903 (2010)
...

viscous fluid-dynamics:

B. Schenke, S. Jeon, and C. Gale, Phys.Rev.Lett.106, 042301 (2011)
B. Schenke, S. Jeon, C. Gale, Phys. Rev. C85, 024901 (2012)
P. Bozek, Phys.Rev. C85, 034901 (2012)
J. Vredevoogd, S. Pratt, Phys.Rev. C85, 044908 (2012)
C. Nonaka, Y. Akamatsu, M. Takamoto, Nucl.Phys. A904-905, 405c-408c (2013)
...

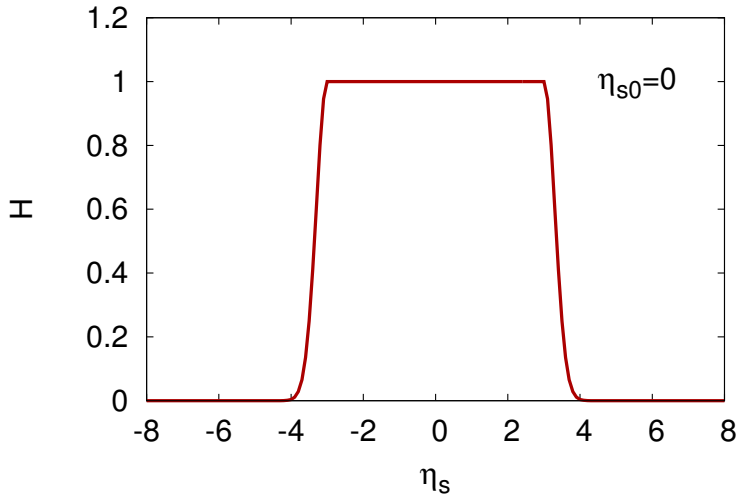
The third dimension: space-time rapidity

No first principles understanding of longitudinal initial conditions

Simple ansatz:

$$\varepsilon(\eta_s) \propto H(\eta_s) = \exp\left[-\frac{(|\eta_s - \eta_{s0}| - \eta_{\rm flat}/2)^2}{2\sigma_\eta^2}\theta(|\eta_s - \eta_{s0}| - \eta_{\rm flat}/2)\right]$$

while transverse direction can be described by anything:
smooth, fluctuating Glauber or MC-KLN, IP-Glasma



$\eta_{\rm flat} = 6$
$\sigma_\eta = 0.3$

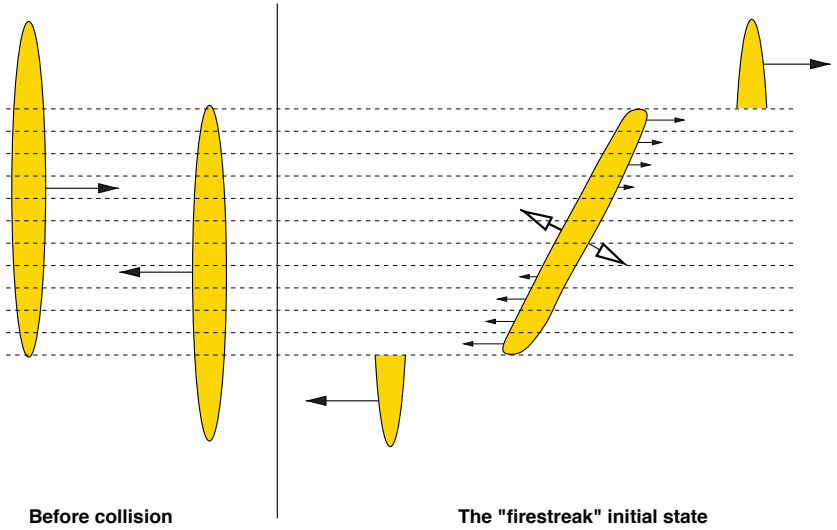
String models and Color Glass Condensate
can give longitudinal structure directly

The third dimension: space-time rapidity

For non-central collisions one can use $\eta_{s0}(x, y, b) \neq 0$

T. Hirano and K. Tsuda, Phys. Rev. C66, 054905 (2002)
J. Sollfrank, P. Huovinen, and P. V. Ruuskanen, Eur. Phys. J. C6, 525 (1999)

$\rightarrow$ center of rapidity shifts with transverse position leading to a tilted fireball as in the firestreak model



J. Gosset, Joseph I. Kapusta, G.D. Westfall, Phys.Rev. C18, 844-855 (1978)
V.K. Magas, L.P.Csernai, D. Strottman, Nucl.Phys. A712, 167-204 (2002)

Leads to rotation, possibly Kelvin-Helmholtz instability
L.P. Csernai, D.D. Strottman, Cs. Anderlik, Phys.Rev. C85, 054901 (2012)

3+1 dimensional hydrodynamics

The equations of hydrodynamics in hyperbolic coordinates are

$$\partial_\tau(\tau J^\tau) + \partial_{\eta_s} J^{\eta_s} + \partial_v(\tau J^v) = 0$$

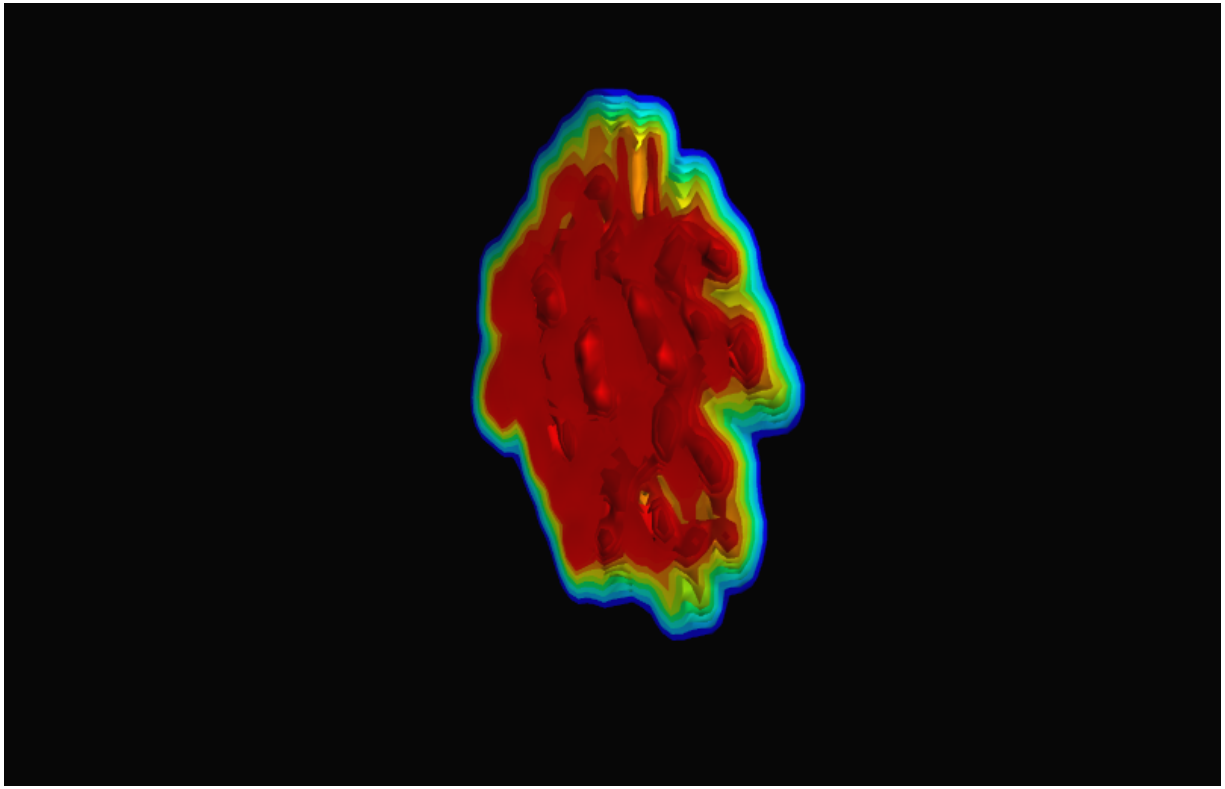
for the net baryon current J^μ and

$$\begin{aligned}
\partial_\tau(\tau T^{\tau\tau}) + \partial_{\eta_s}(T^{\eta_s\tau}) + \partial_v(\tau T^{v\tau}) + T^{\eta_s\eta_s} &= 0 \\
\partial_\tau(\tau T^{\tau\eta_s}) + \partial_{\eta_s}(T^{\eta_s\eta_s}) + \partial_v(\tau T^{v\eta_s}) + T^{\tau\eta_s} &= 0 \\
\partial_\tau(\tau T^{\tau v}) + \partial_{\eta_s}(T^{\eta_s v}) + \partial_w(\tau T^{wv}) &= 0
\end{aligned}$$

for the energy-momentum tensor

The terms $T^{\eta_s\eta_s}$ and $T^{\tau\eta_s}$ come from the coordinate transformation

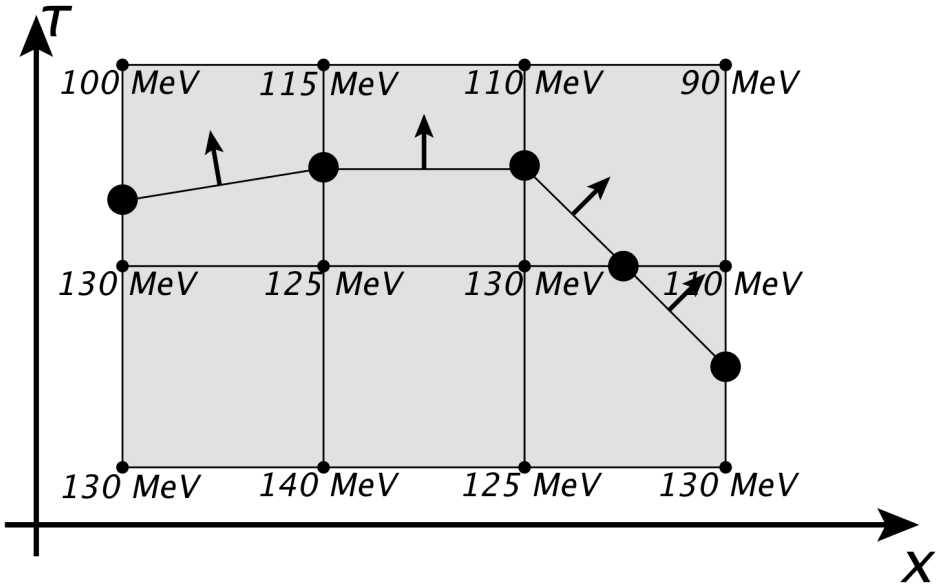
Hydrodynamic evolution in 3+1 dimensions



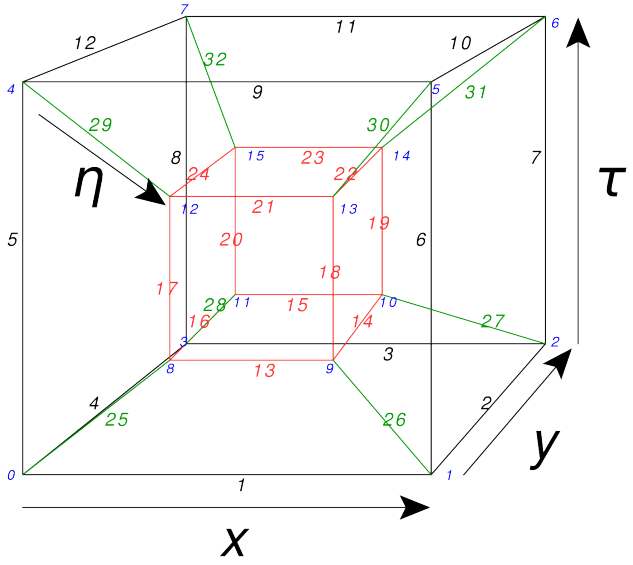
beam direction z

Freeze-out in 3+1 dimensions

Freeze-out surface
in 2 dimensions: easy



Freeze-out surface
in 4 dimensions: difficult



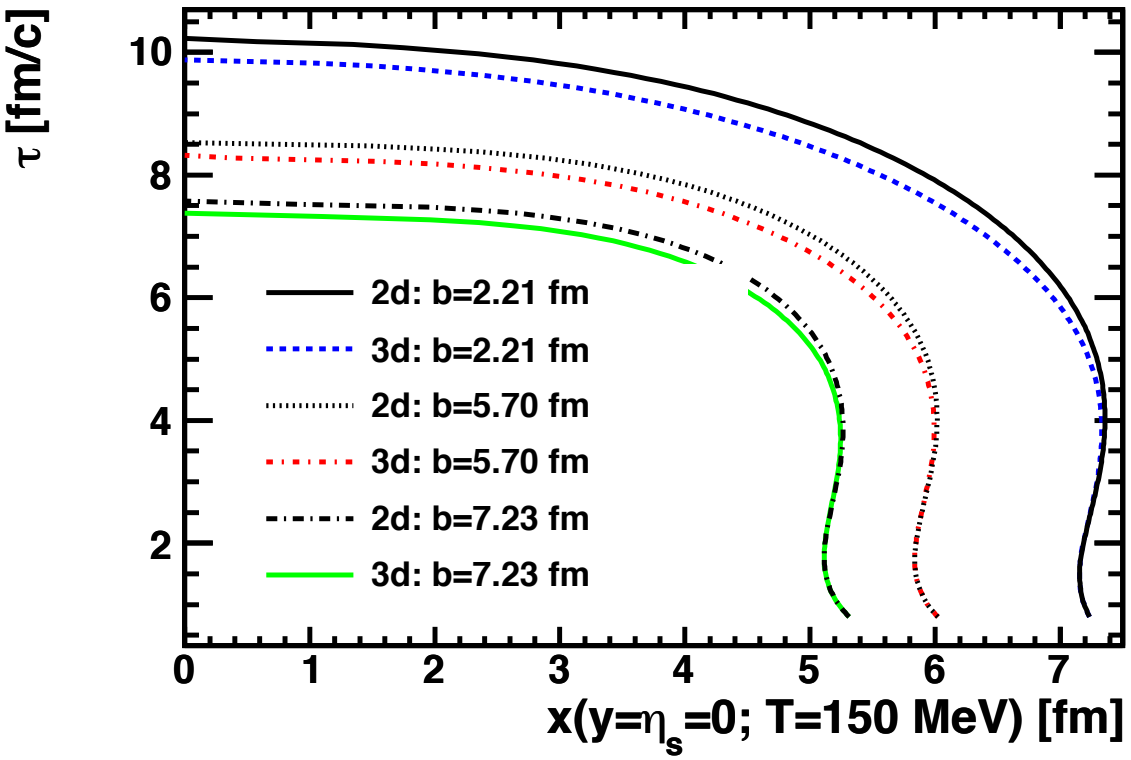
with the surface Σ_μ we get the thermal particle spectra

$$E\frac{dN}{d^3p} = \int_\Sigma d\Sigma_\mu p^\mu f(x, \partial_\mu u^\mu)$$

Cooper and Frye, Phys.Rev.D10, 186 (1974)

then do resonance decays or feed into hadron-cascade

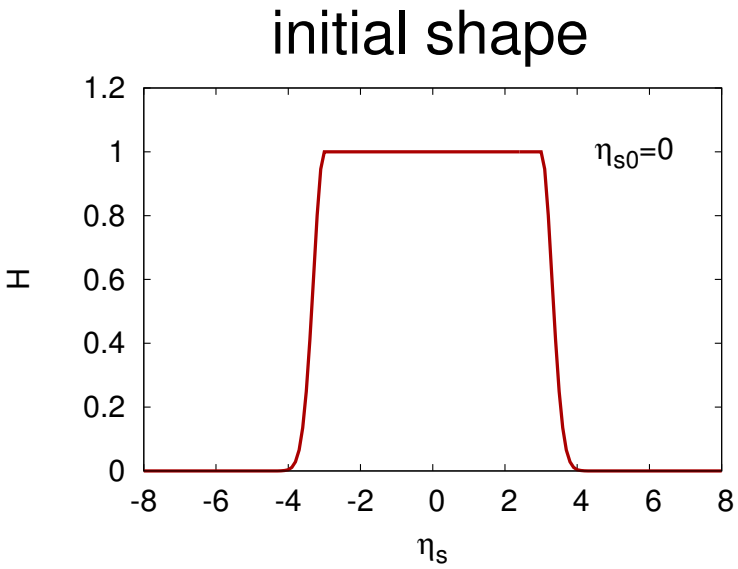
Freeze-out in 3+1 dimensions

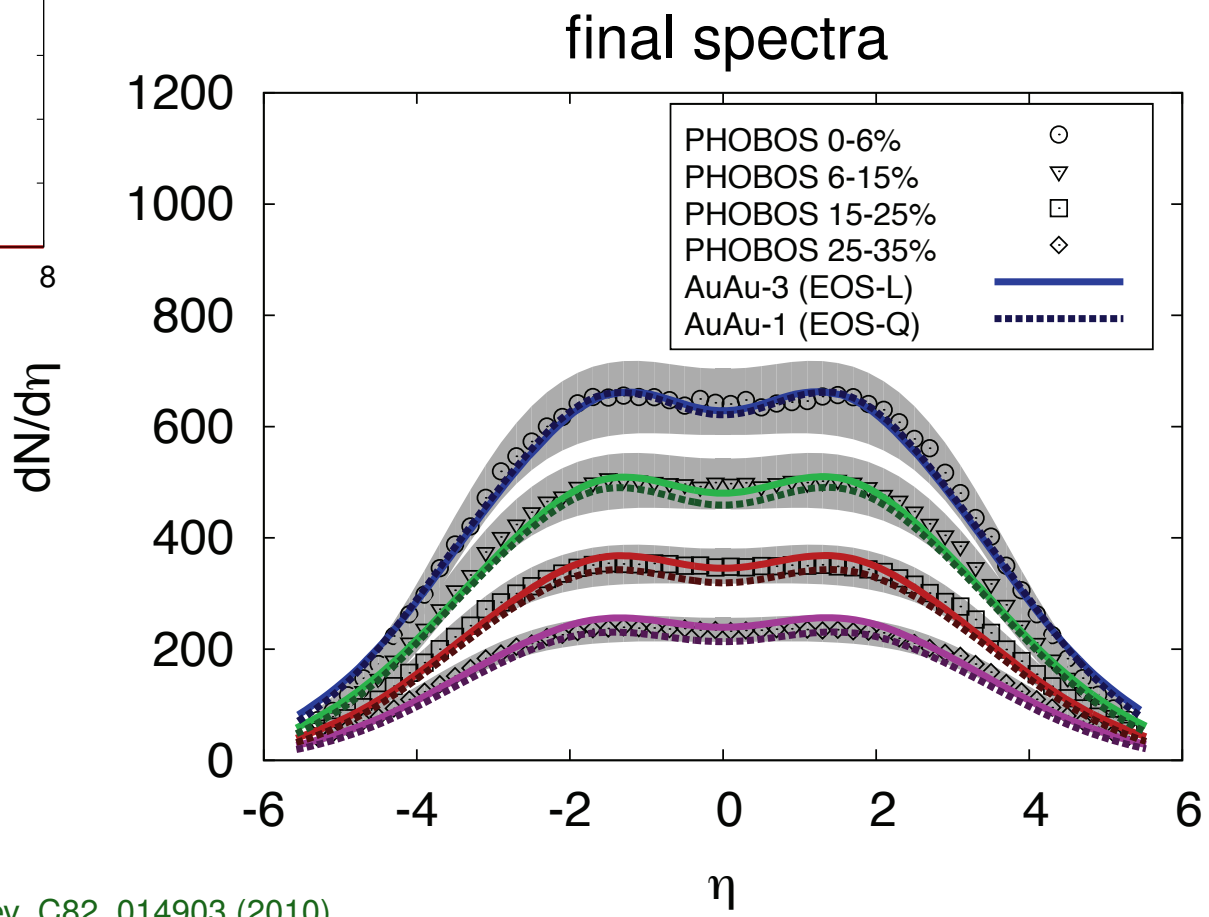


Lifetime reduced by $\sim 5\%$ in the full 3+1 dimensional case (due to increased longitudinal velocity gradient)

J. Vredevoogd, S. Pratt, Phys.Rev. C85, 044908 (2012)

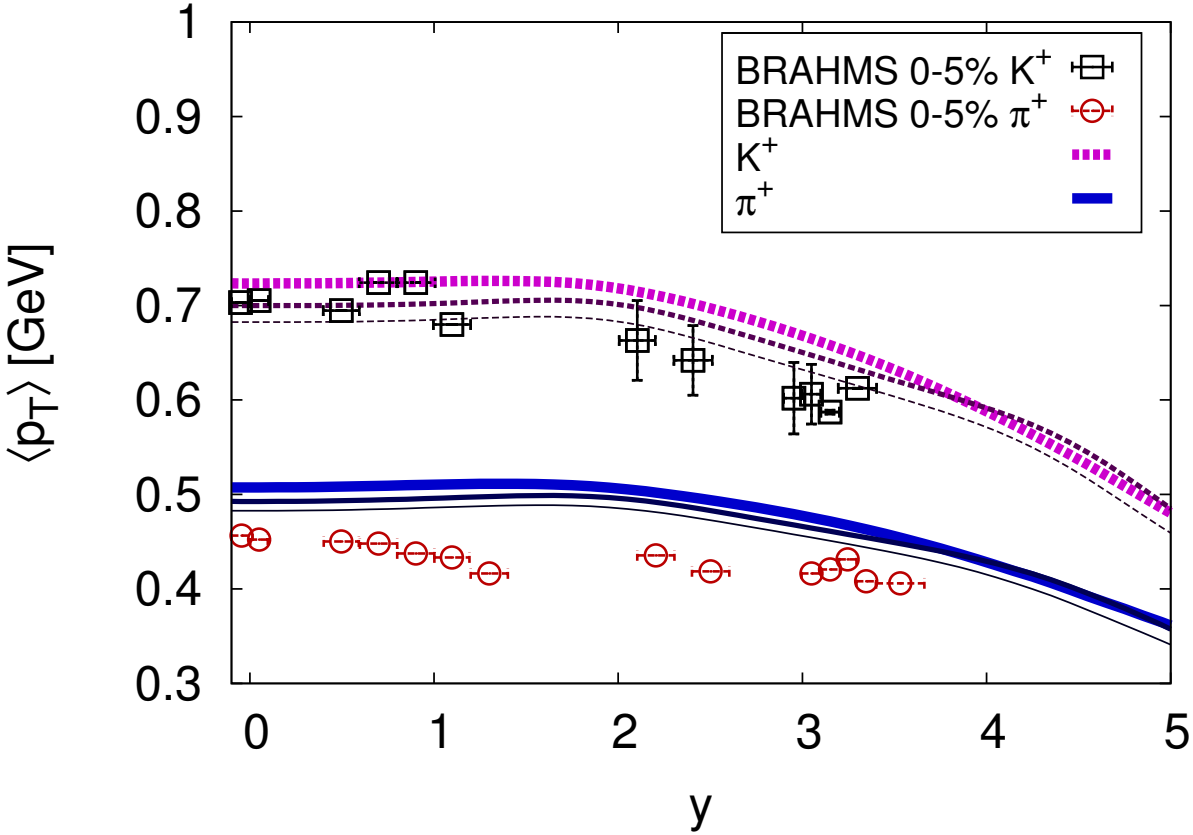
Ideal case: Multiplicity distribution





B. Schenke, S. Jeon, and C. Gale, Phys.Rev. C82, 014903 (2010)
Experimental data: B. B. Back et al., Phys. Rev. Lett. 91, 052303 (2003)

Ideal case: Mean transverse momentum



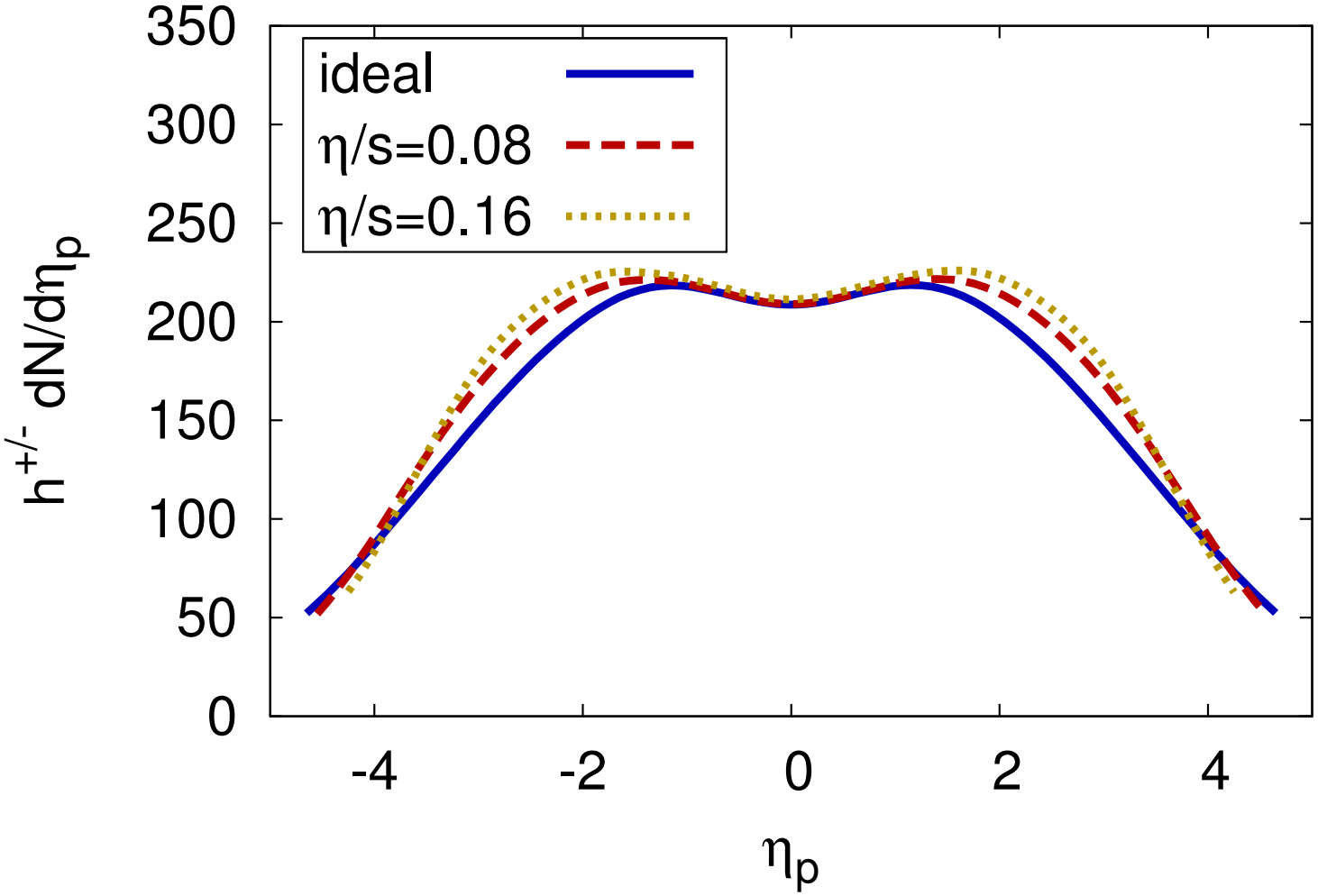
Different lines correspond to different parameters

Top line: lattice EoS, Bottom lines: first order phase transition

B. Schenke, S. Jeon, and C. Gale, Phys.Rev. C82, 014903 (2010)

Experimental data: I. G. Bearden et al. (BRAHMS), Phys. Rev. Lett. 94, 162301 (2005)

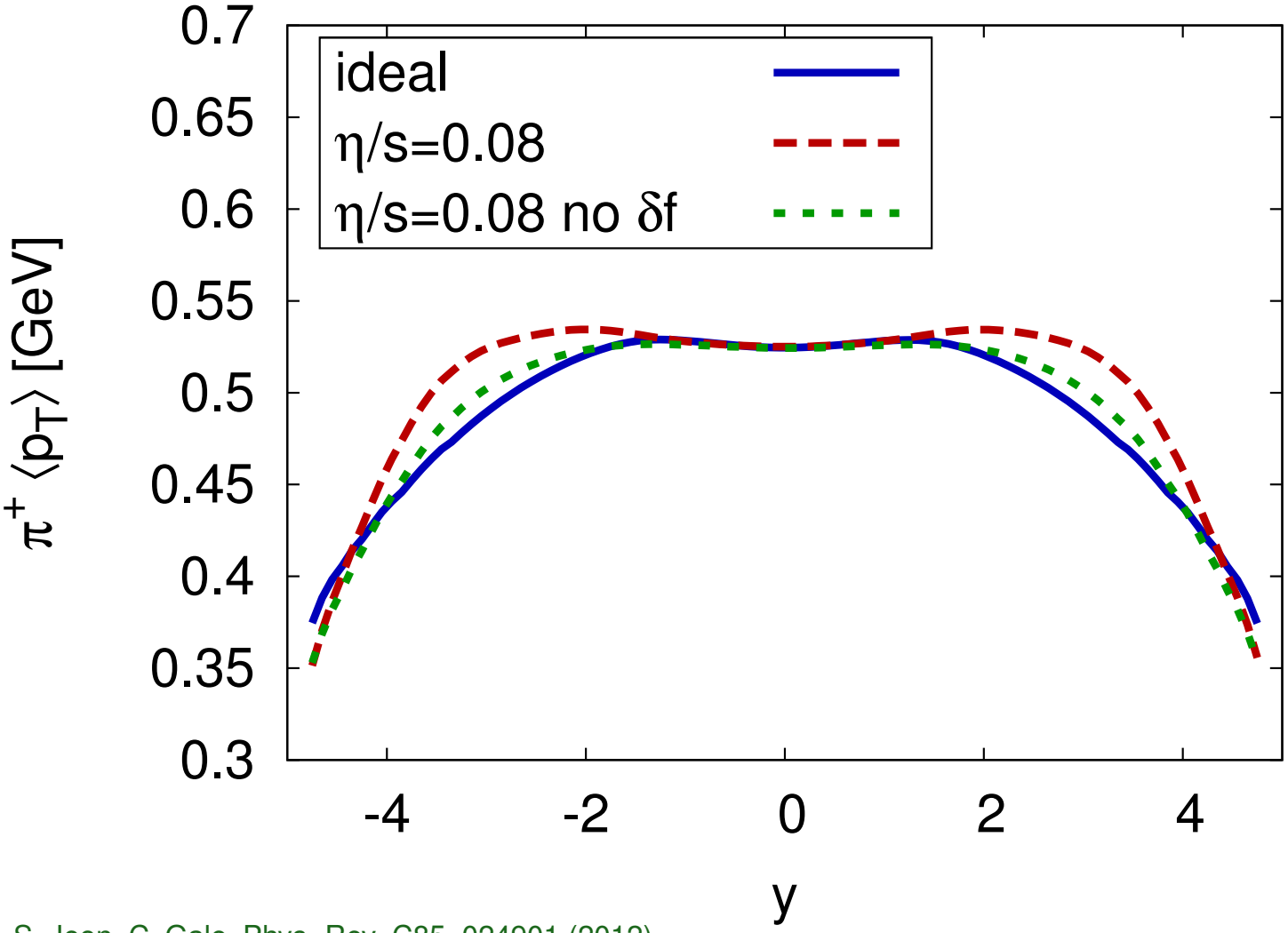
Multiplicity distribution: Effect of shear viscosity



Normalization adjusted to obtain same multiplicity at midrapidity

B. Schenke, S. Jeon, C. Gale, Phys. Rev. C85, 024901 (2012)

Mean transverse momentum



B. Schenke, S. Jeon, C. Gale, Phys. Rev. C85, 024901 (2012)

Discussion I

Effect at large rapidities:
Take 1D Bjorken expansion
Navier-Stokes stress:

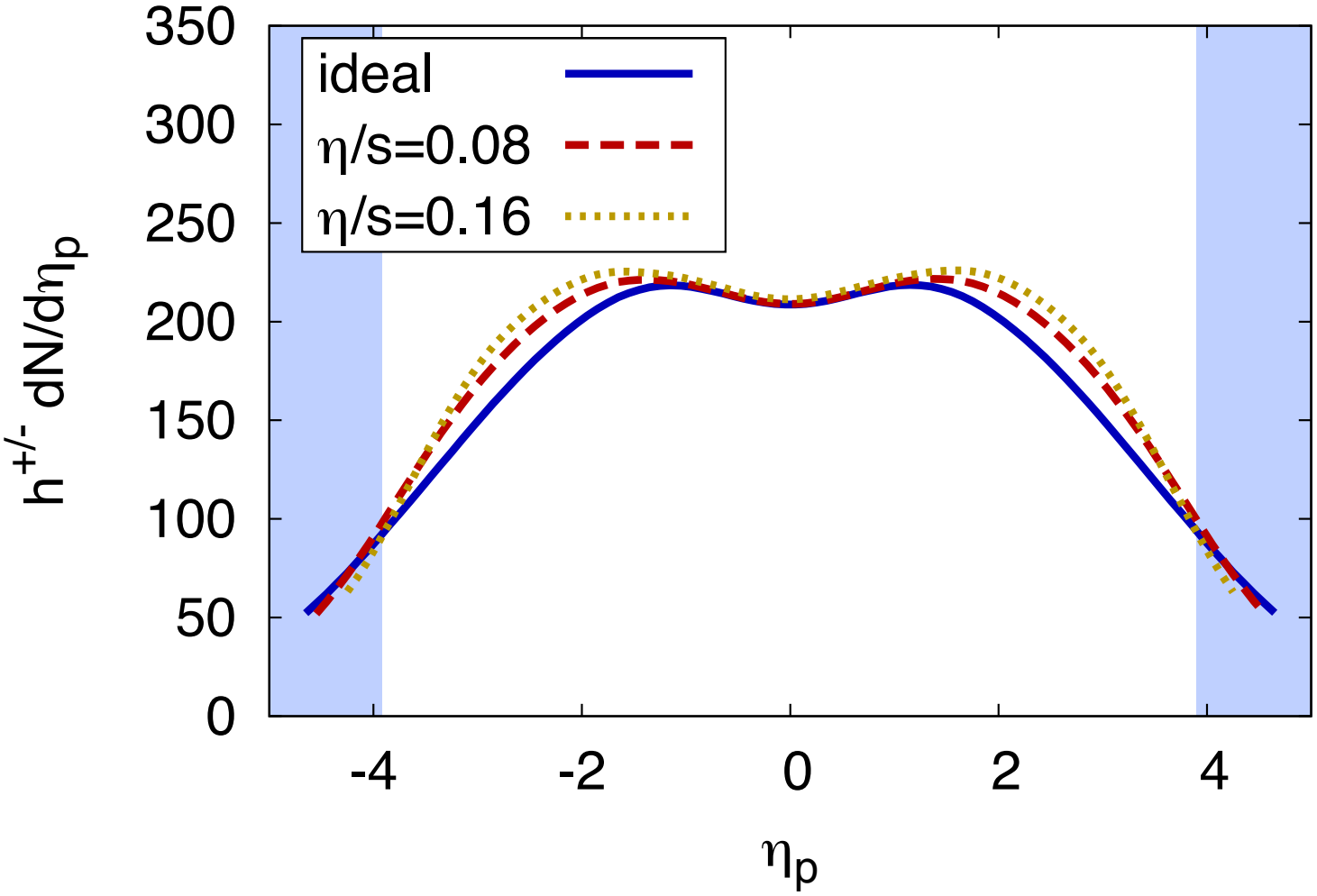
$$\pi^{\mu\nu} = 2\eta\nabla^{<\mu}u^{\nu>} = \mathrm{diag}\left(0, \frac{2\eta}{3\tau}, \frac{2\eta}{3\tau}, -\frac{4\eta}{3\tau}\right)$$
$$T^{\mu\nu} = \mathrm{diag}\left(\varepsilon, P - \frac{\pi_L}{2}, P - \frac{\pi_L}{2}, P + \pi_L\right)$$

with $\pi_L = \pi^{\eta\eta} = -\frac{4\eta}{3\tau}$.

- Effective longitudinal pressure $P - \frac{4\eta}{3\tau} < P$
- Effective transverse pressure $P + \frac{2\eta}{3\tau} > P$

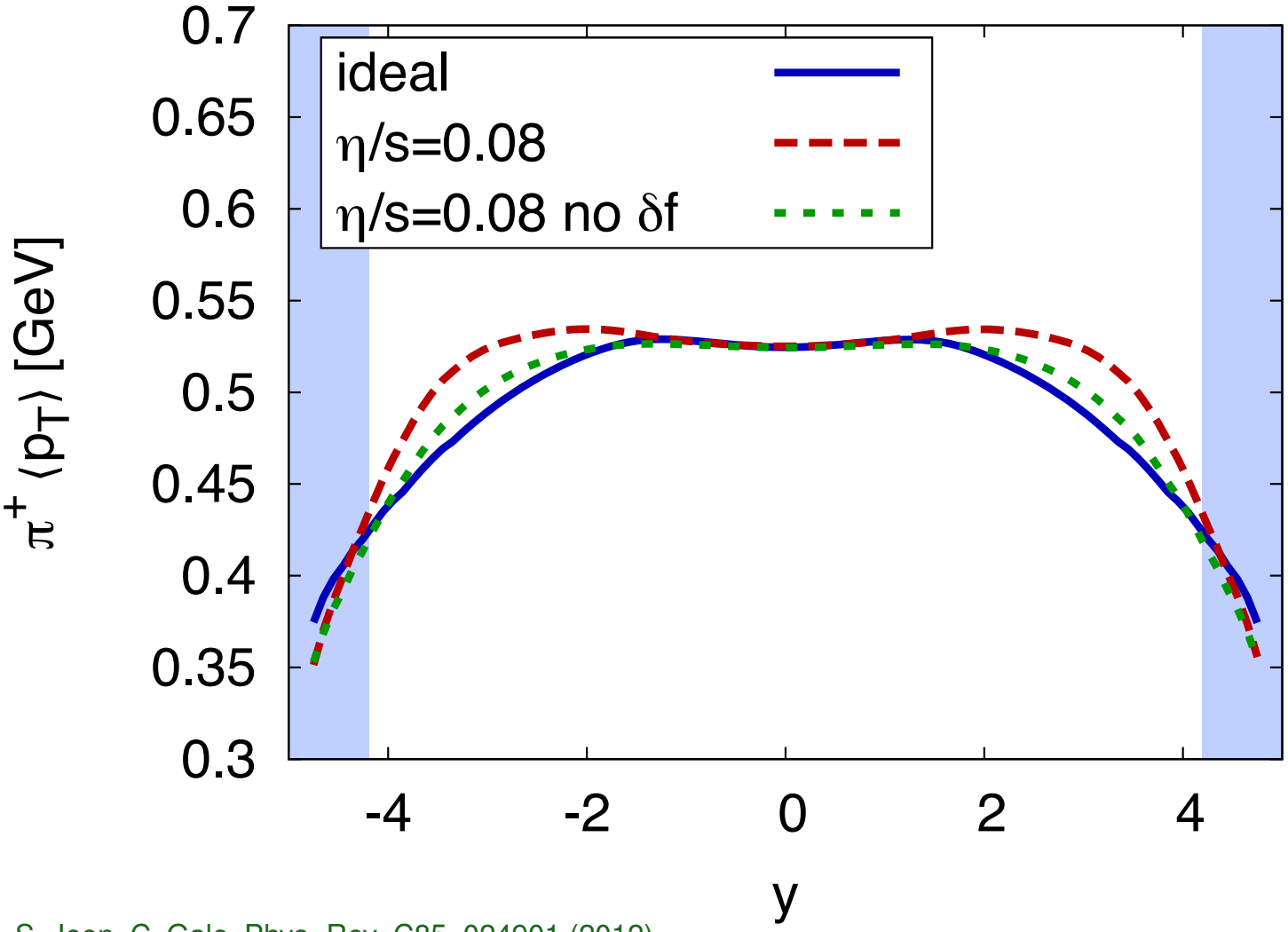
Shear slows down longitudinal expansion
$\rightarrow$ lower multiplicity at most forward rapidities
System is smaller $\rightarrow$ freezes out earlier $\rightarrow$ smaller $\langle p_T \rangle$

Multiplicity distribution: Effect of shear viscosity



B. Schenke, S. Jeon, C. Gale, Phys. Rev. C85, 024901 (2012)

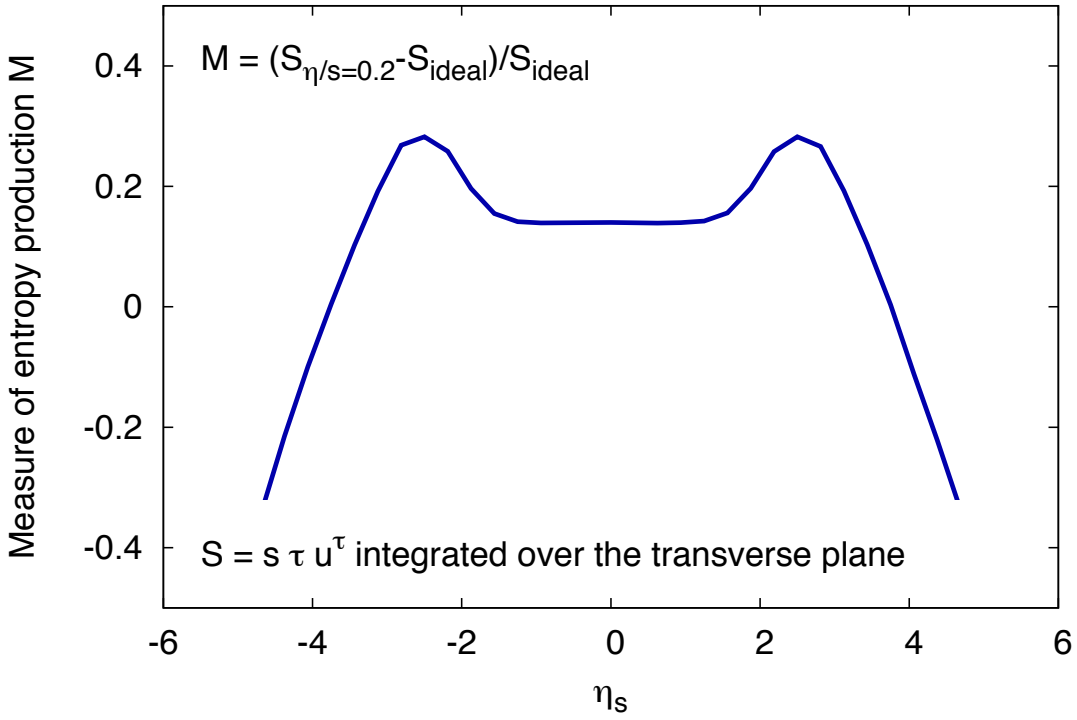
Mean transverse momentum



B. Schenke, S. Jeon, C. Gale, Phys. Rev. C85, 024901 (2012)

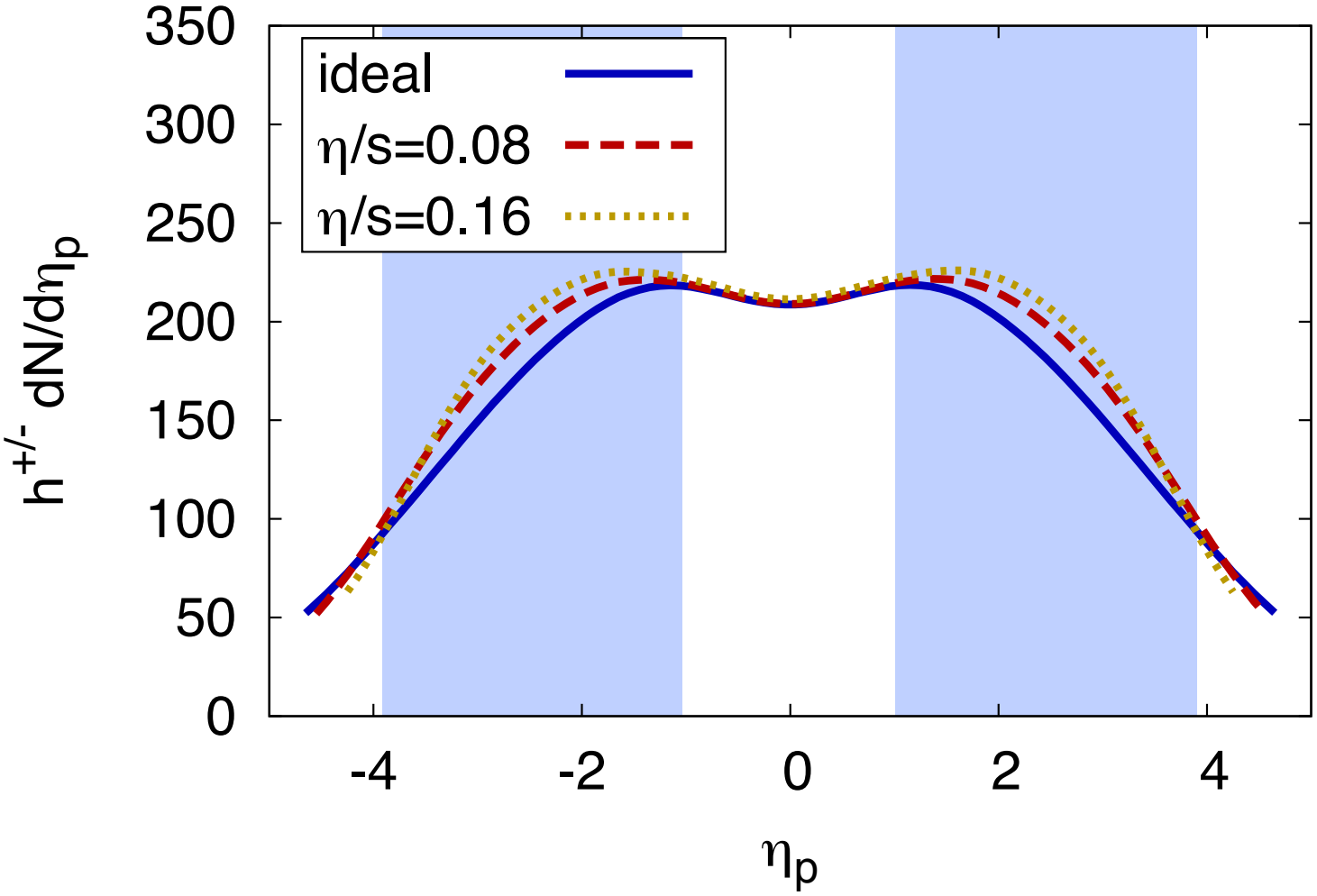
Discussion II

At intermediate rapidities: largest gradients in rapidity direction
Strongest longitudinal expansion in that region
Shear $\propto$ difference between transverse and longitudinal expansion
$\rightarrow$ strongest entropy production in that region



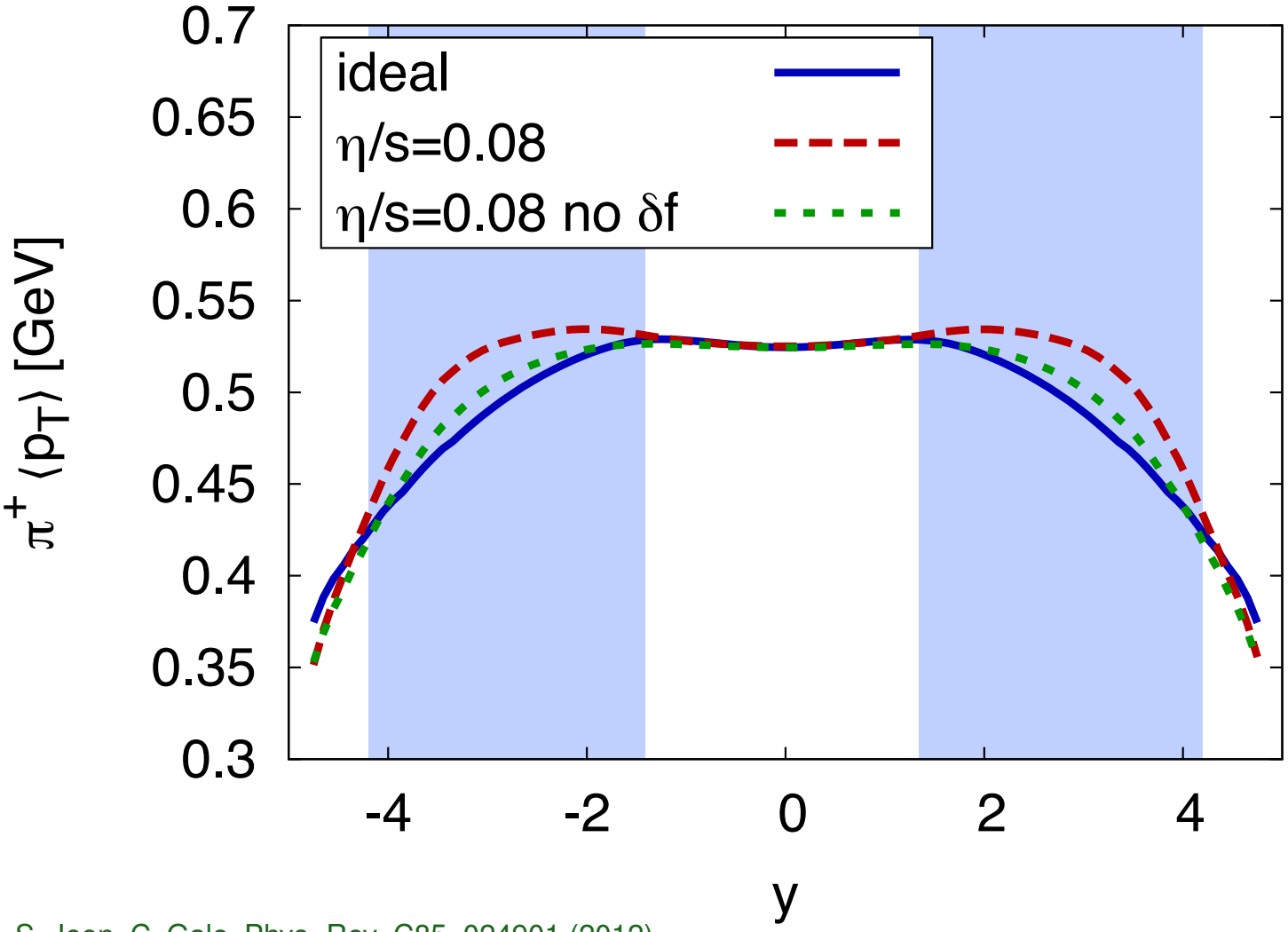
large shear $\rightarrow$ large transverse pressure $\rightarrow$ larger $\langle p_T \rangle$

Multiplicity distribution: Effect of shear viscosity



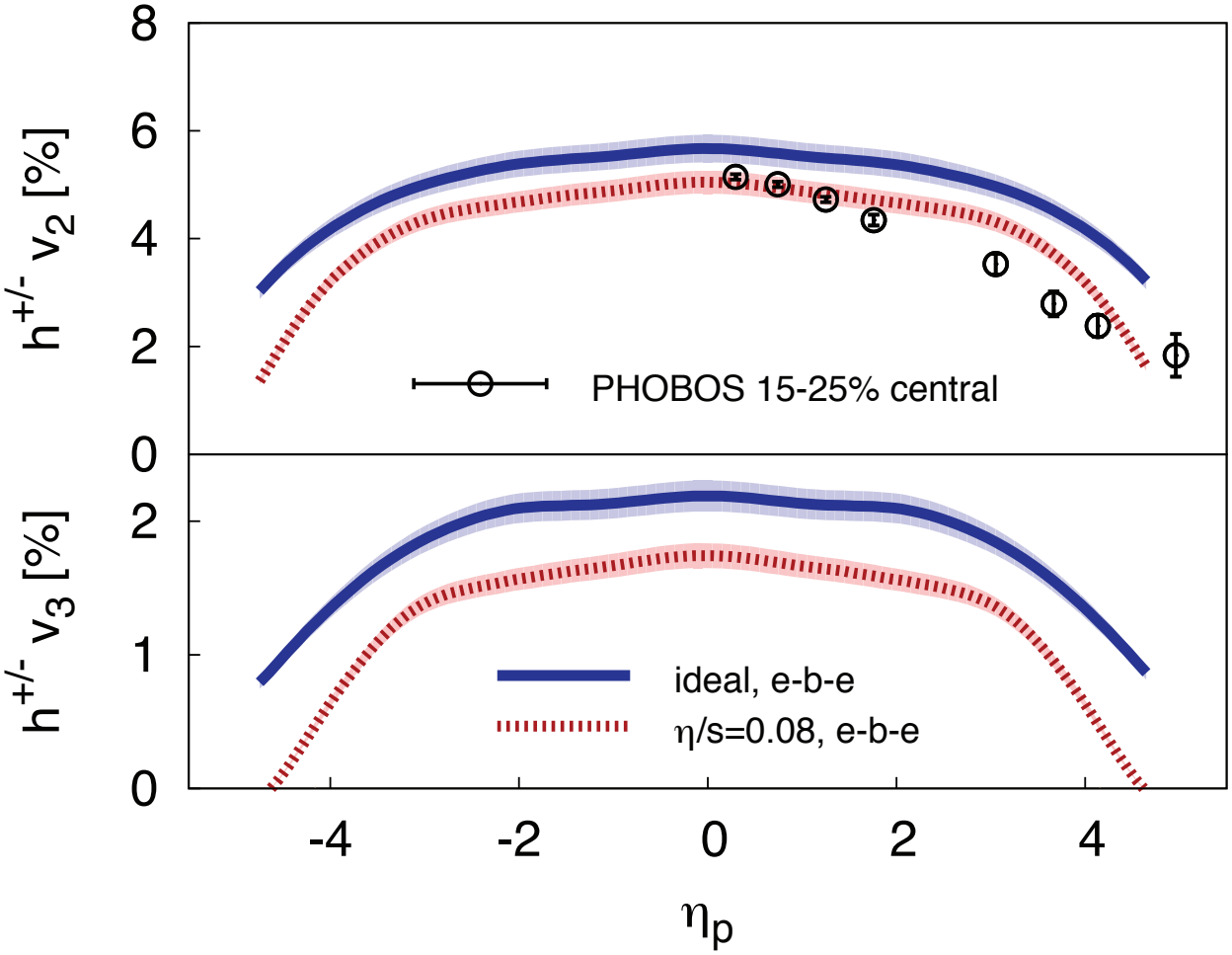
B. Schenke, S. Jeon, C. Gale, Phys. Rev. C85, 024901 (2012)

Mean transverse momentum



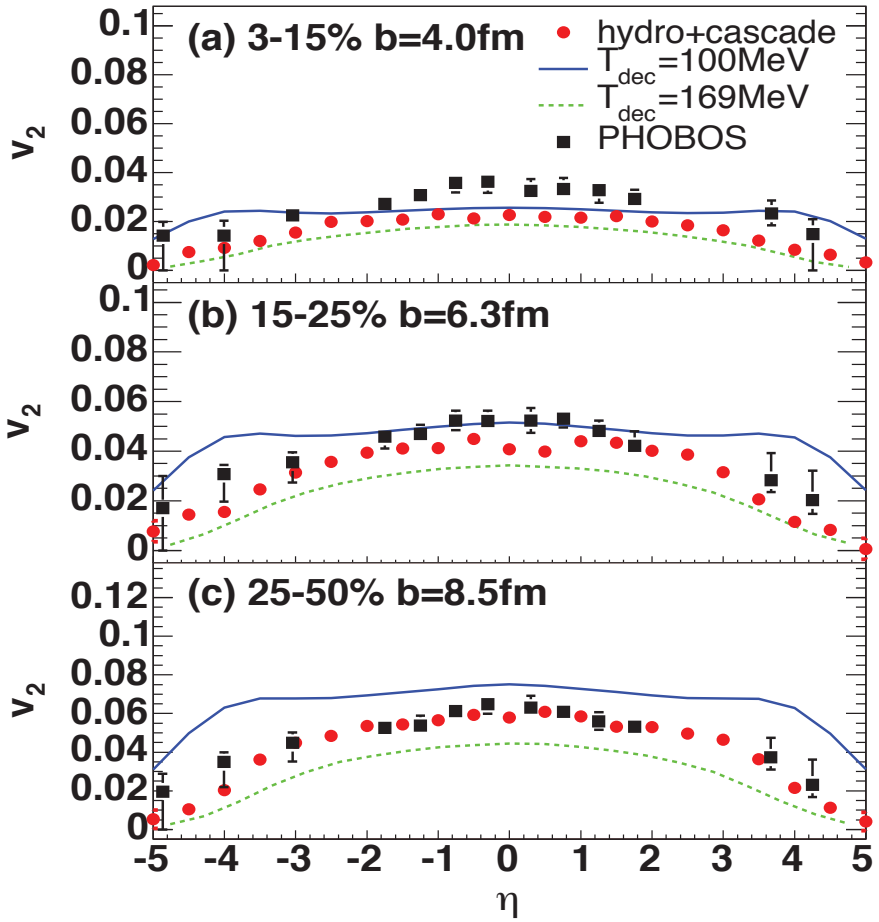
B. Schenke, S. Jeon, C. Gale, Phys. Rev. C85, 024901 (2012)

Anisotropic flow



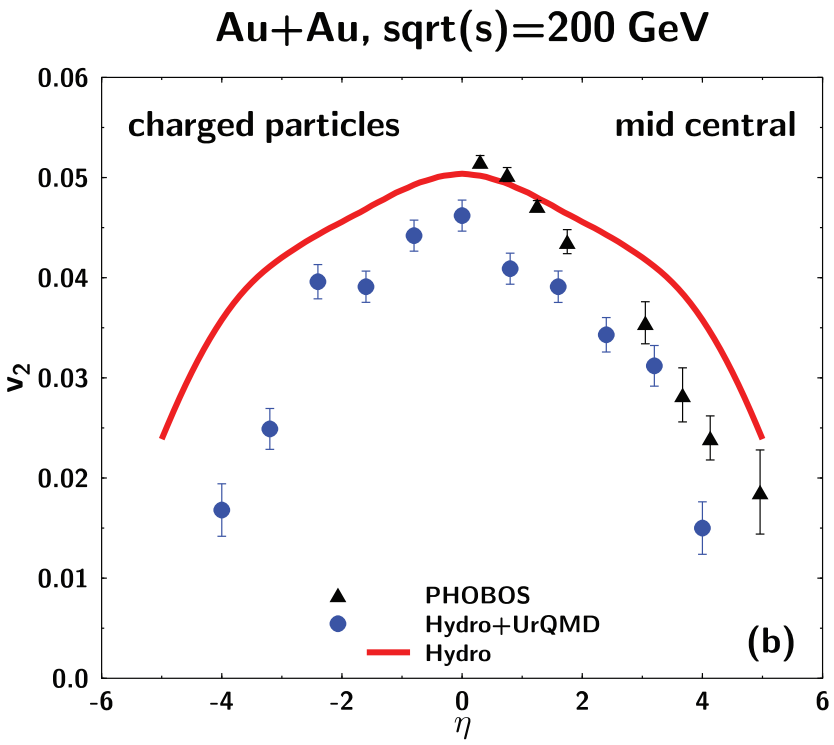
B. Schenke, S. Jeon, and C. Gale, PRL 106, 042301 (2011)
Experimental data: B. B. Back et al. (PHOBOS), Phys. Rev. C72, 051901 (2005)

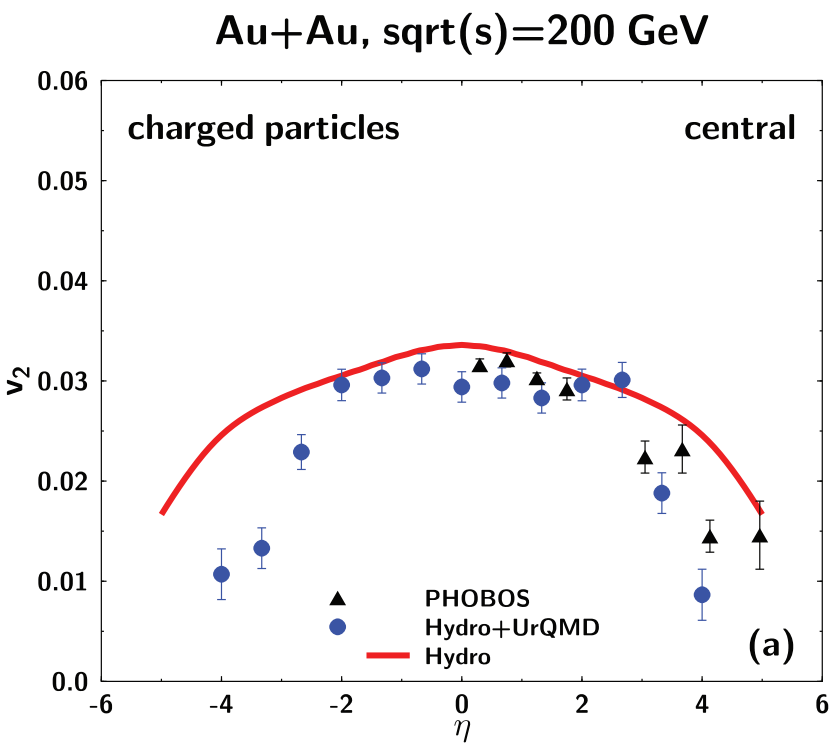
Anisotropic flow - ideal hydro + hadron transport



T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara, Phys.Lett. B636, 299-304 (2006)

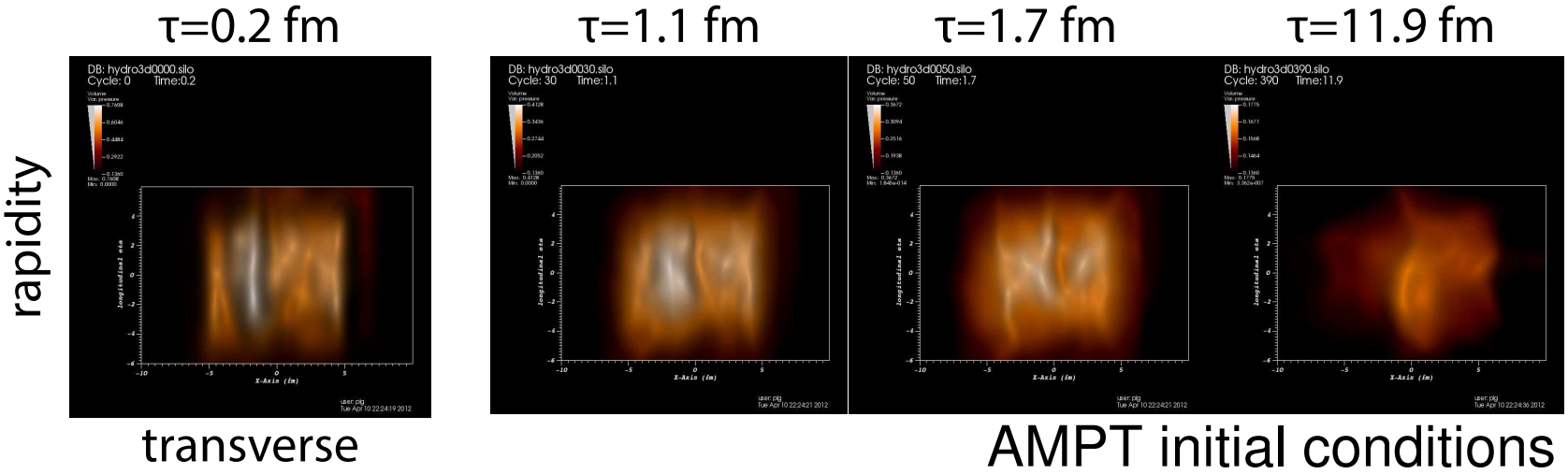
Anisotropic flow - ideal hydro + UrQMD



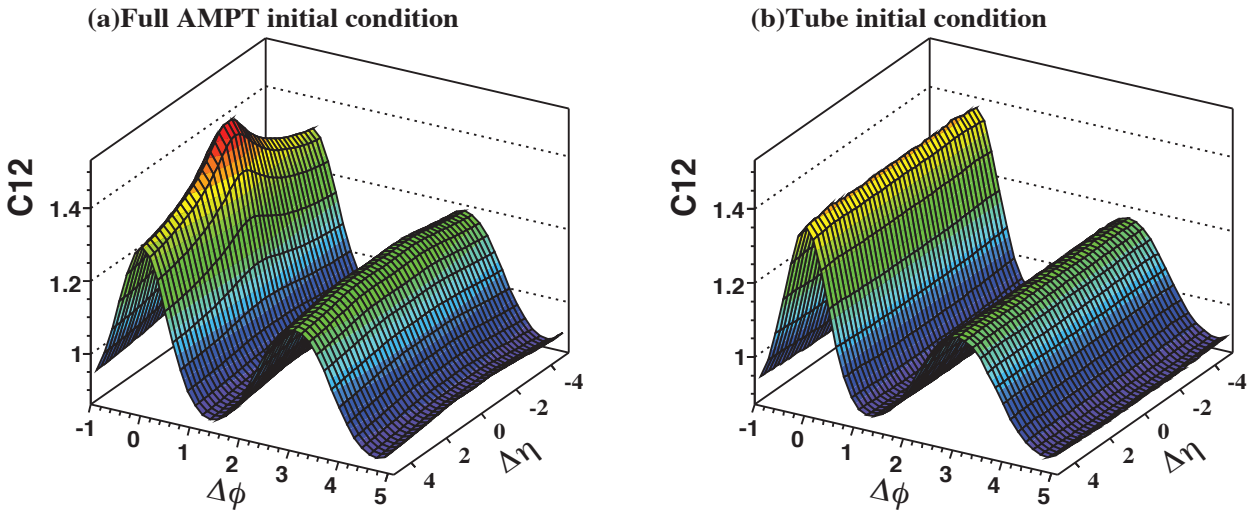


C. Nonaka and S. A. Bass, Phys. Rev. C75, 014902 (2007)

Fluctuations in the rapidity direction (ideal hydro)



AuAu 200 GeV/n Centrality $30-40\%$



Longgang Pang, Qun Wang, Xin-Nian Wang, Nucl.Phys.A904-905, 811c-814c (2013)

Summary and conclusions

- 3+1 dimensional fluid-dynamics for heavy-ions available in ideal and viscous versions
- Initial longitudinal profile usually tuned to describe multiplicity distributions
- Viscosity has interesting effects at intermediate and large rapidities
- Hadronic rescattering seems necessary to describe v_n at large rapidities
- Fluctuations in the longitudinal direction could be as important as those in the transverse