Early Thermalization at RHIC ?!

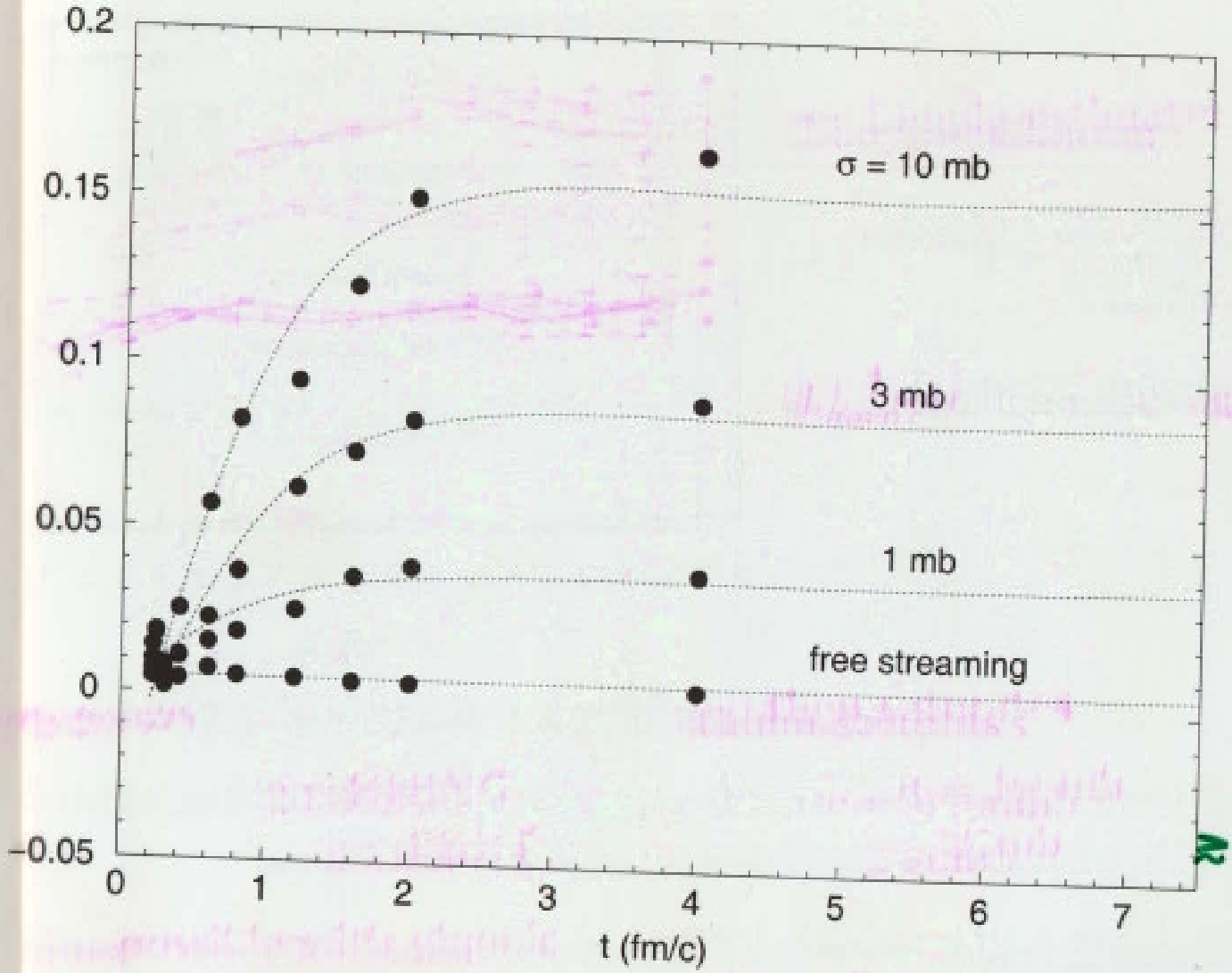
Peter Kolb + U. Heinz, Ohio State U.

in collaboration with P. Huovinen

- Radial and elliptic flow – theoretical characteristics
- RHIC spectra vs. hydrodynamics
- What does this all mean? A challenge for microscopic theories

In fact, a lot of rescattering!

Elliptic flow requires rescattering:



$\gtrsim 30 \times \sigma_{QCD}$!

$\gtrsim 10$ times σ_{QCD} !

B. Zhang, M. Gyulassy, C.M. Ko, PLB 455 (1999) 45

Relativistic Hydrodynamics

Conservation of energy, momentum and baryonnumber

$$\partial_\mu T^{\mu\nu} = 0, \qquad \partial_\mu j^\mu = 0$$

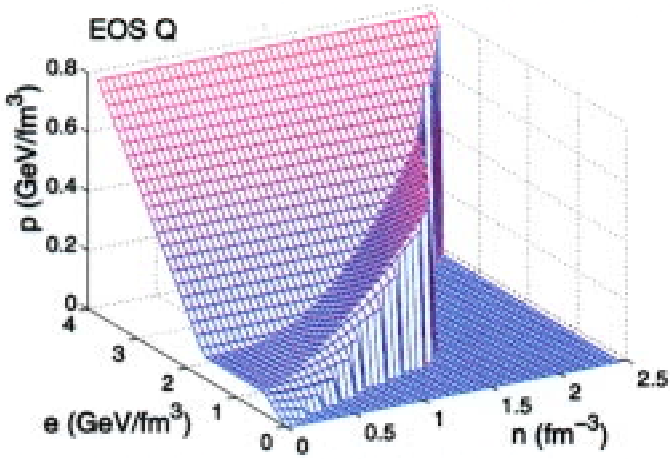
with energy momentum tensor:

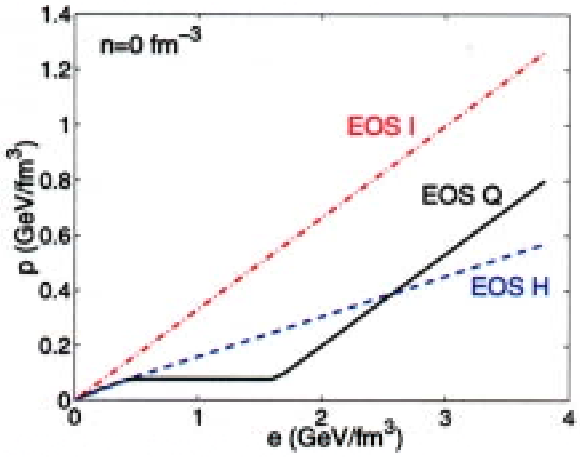
$$T^{\mu\nu}(x) = (e(x) + p(x))\, u^\mu(x) u^\nu(x) - g^{\mu\nu} p(x)$$

and baryon current: $j^\mu(x) = n(x)\, u^\mu(x)$

Equations of state

- EOS I: ultrarelativistic ideal gas, $p = \frac{1}{3}\, e$
- EOS H: massive, interacting gas of hadrons, $p \sim 0.15\, e$
- EOS Q: Maxwell construction between EOS I and EOS H
  - critical temperature $T_{\text{crit}} = 0.16$ GeV
  - bag constant $B^{1/4} = 0.23$ GeV



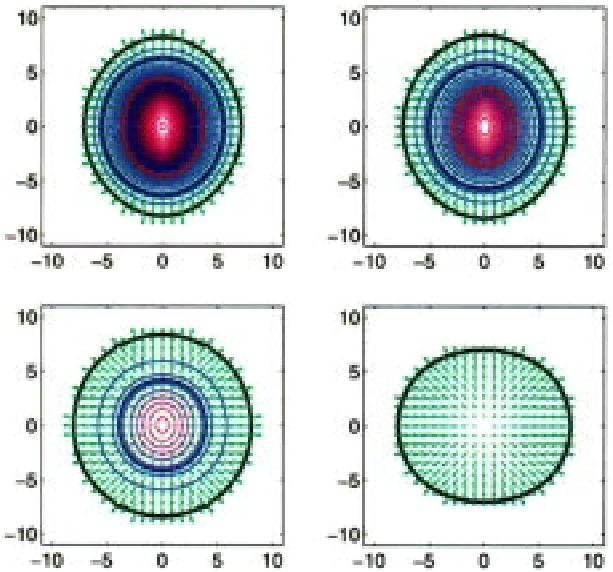


Evolution of energy density,

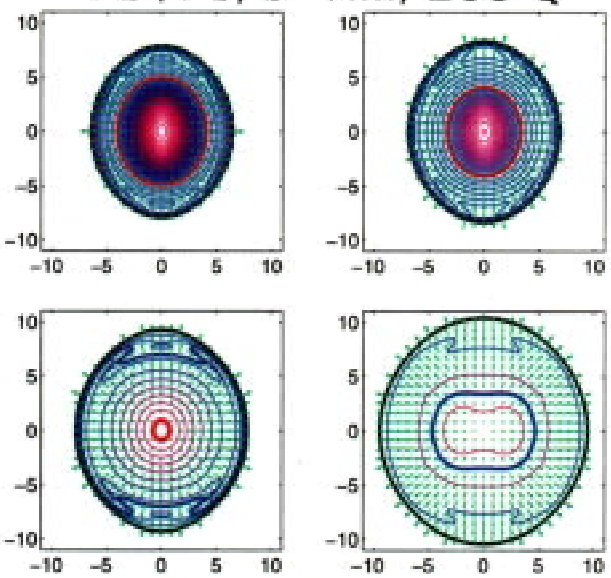
$T_0 \approx 500 MeV$ @ $\tau_{equ} = 0.4$ fm/c

snapshots at τ=3.2, 4.0, 5.6 and 8.0 fm/c after initialization

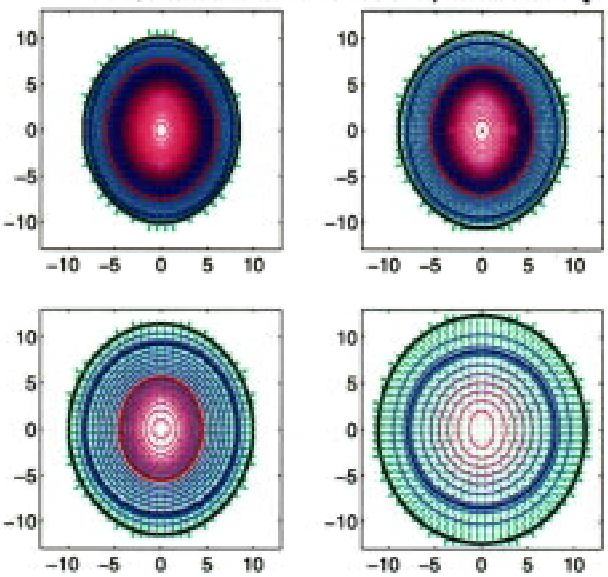
Pb+Pb, b=7 fm, EOS I



Pb+Pb, b=7fm, EOS Q



U+U side-on-side, EOS Q



Initial conditions: $s(\vec{r}, \tau_0) = x\, s_{BC}(\vec{r}, \tau_0) + (1-x)\, s_{WN}(\vec{r}, \tau_0)$

$x = 0.25$

$\tau_0 = 0.6$ fm/c

$\varepsilon_0 = \varepsilon(\vec{r}=0, \tau_0) = 21.4$ GeV/fm^3 at $b=0$

$n_0 = 0.2$ fm^{-3} $\Rightarrow$ $\bar{p}/p = 0.6$ @ T_{had}

$T_0 = 323$ MeV @ $b=0$

Decoupling conditions: $T_{dec} = 128$ MeV

$\langle v_\perp \rangle \approx 0.6c$ @ $b=0$

$\mu_B \approx 70$ MeV

$\gamma_p = \gamma_{\bar{p}} = 2.55 = e^{120\text{ MeV}/128\text{ MeV}}$

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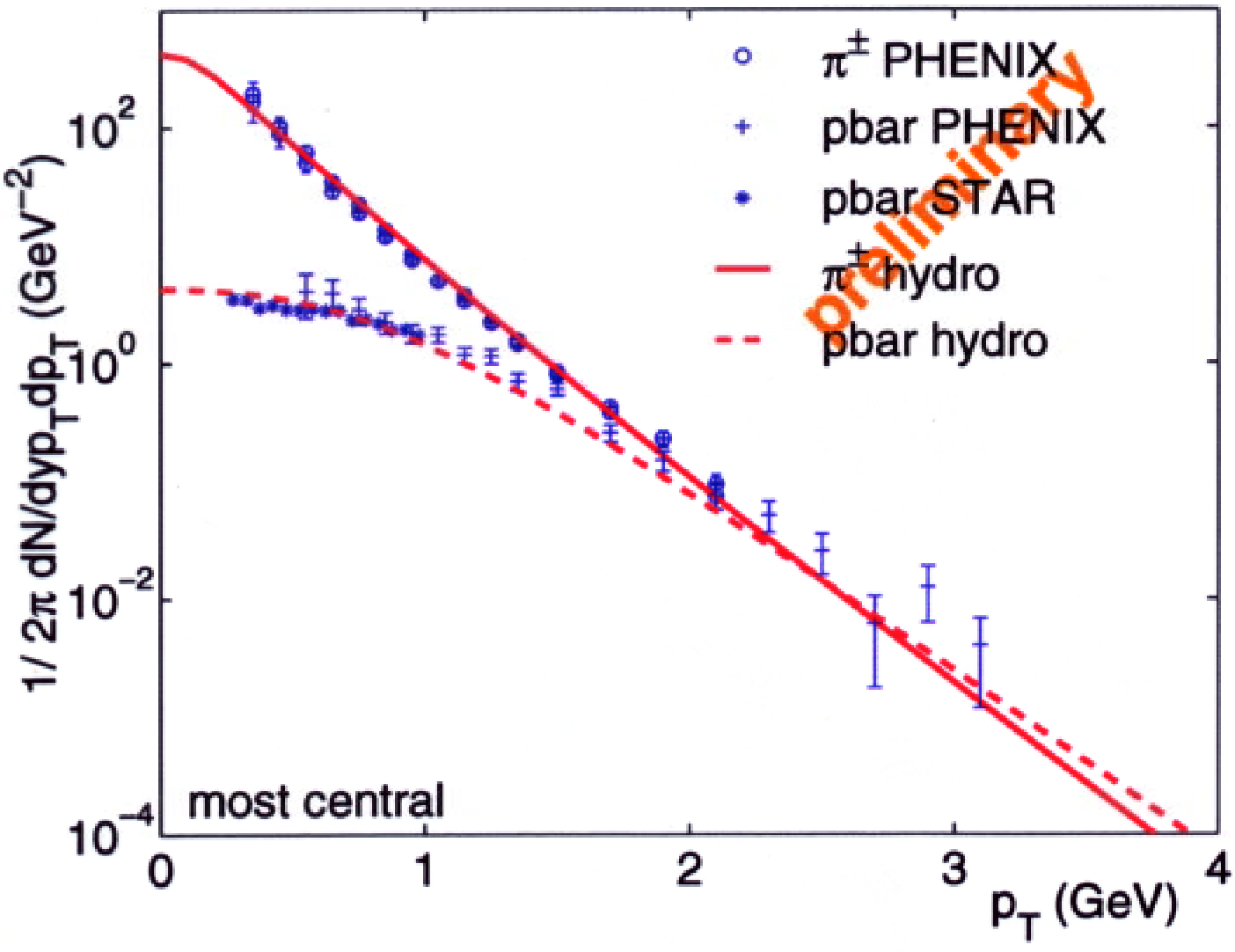
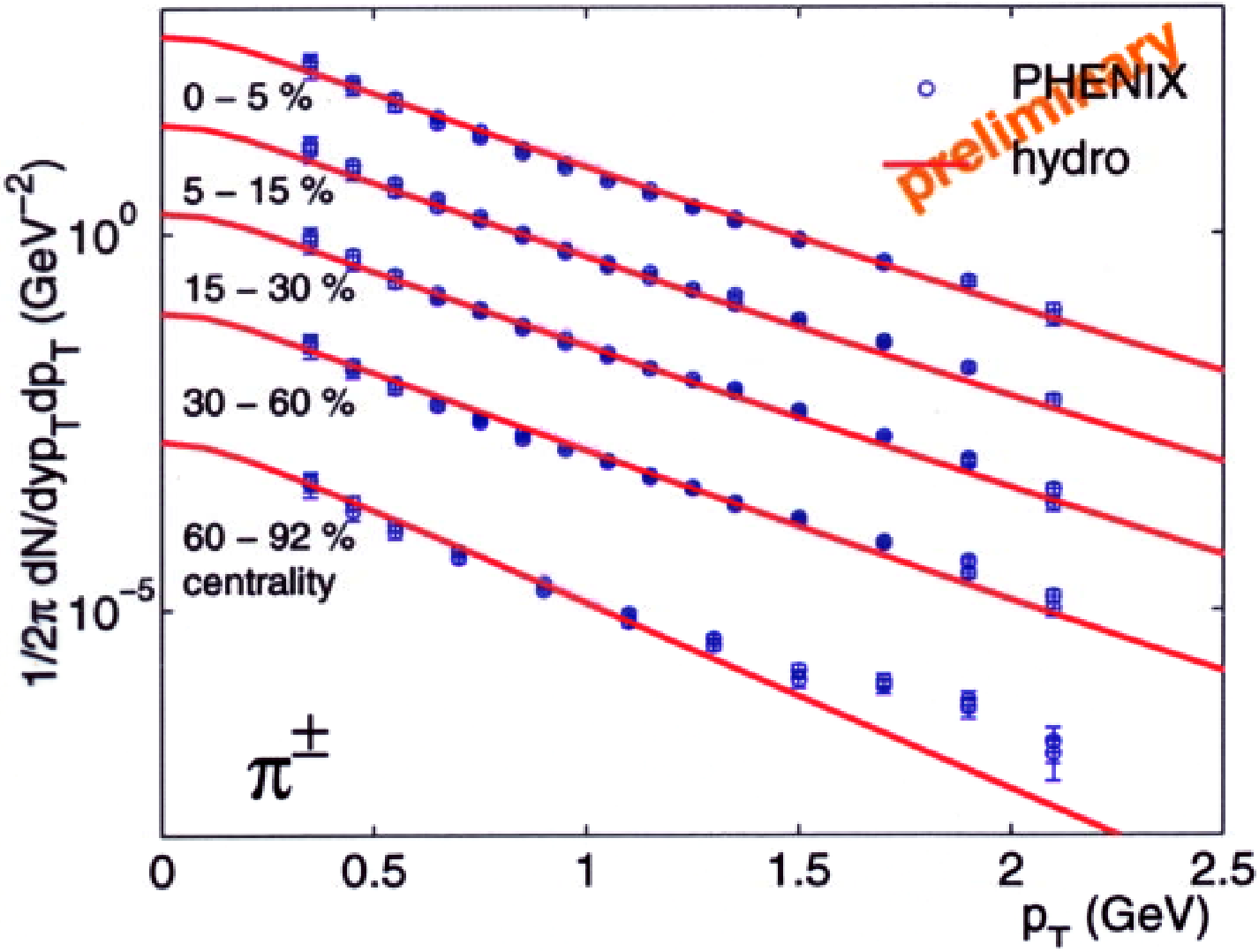

$\pi^{\pm}$ PHENIX
pbar PHENIX
pbar STAR
$\pi^{\pm}$ hydro
pbar hydro
preliminary
most central
$1/2\pi\, dN/dyp_T dp_T$ (GeV^{-2})
p_T (GeV)
10^2
10^0
10^{-2}
10^{-4}
0
1
2
3
4


PHENIX
hydro
preliminary
0 – 5 %
5 – 15 %
15 – 30 %
30 – 60 %
60 – 92 %
centrality
$\pi^{\pm}$
$1/2\pi\ dN/dyp_T dp_T\ (GeV^{-2})$
10^0
10^{-5}
0
0.5
1
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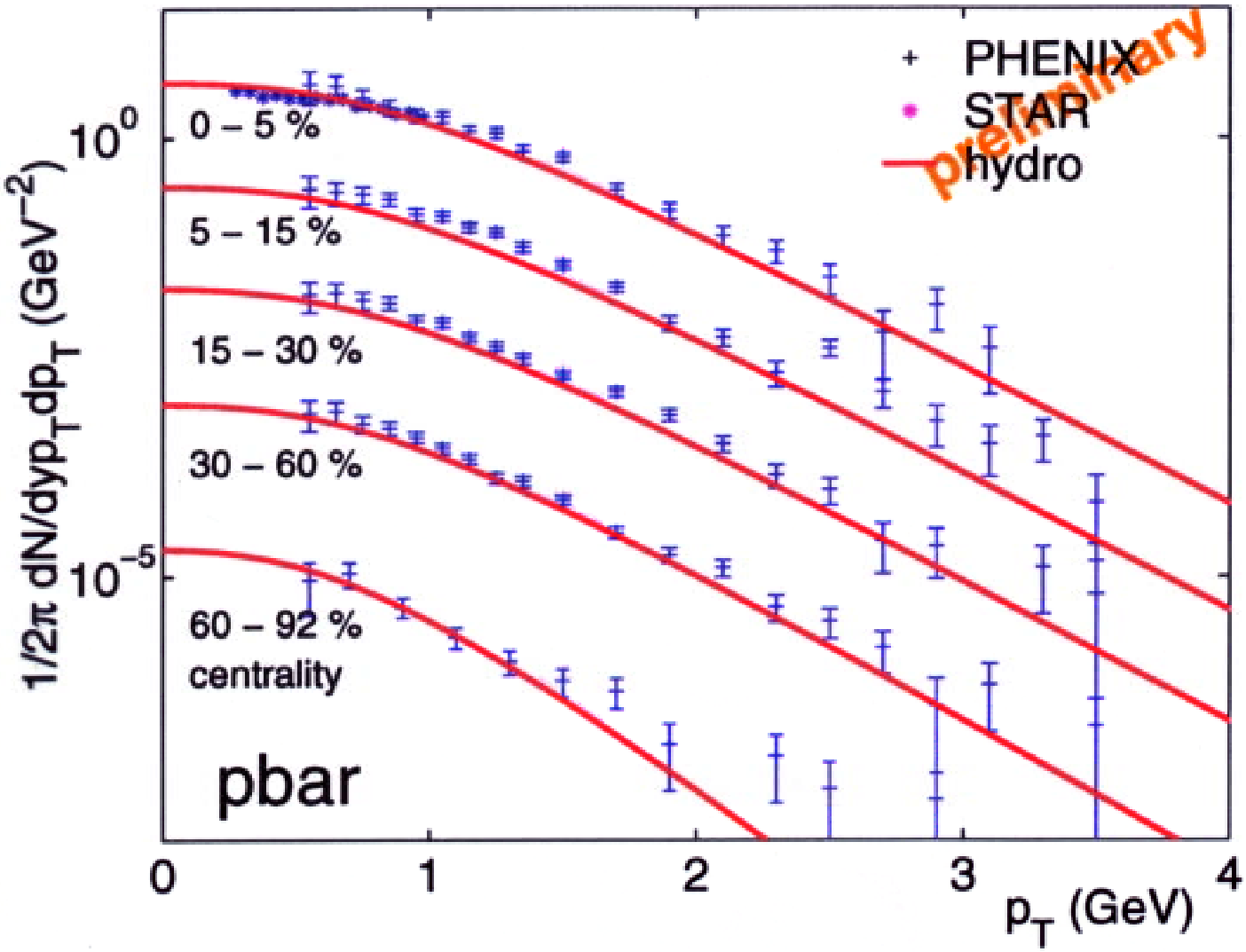
2
2.5
p_T (GeV)


PHENIX
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hydro
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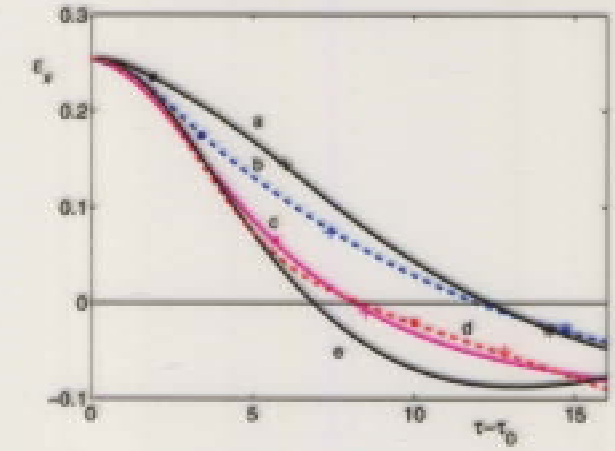
10^0
10^{-5}
0
1
2
3
4
p_T (GeV)

Evolution of Pb+Pb, b=7 fm

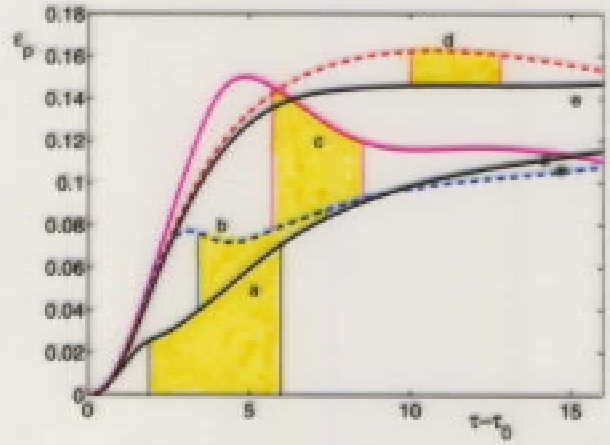
for various initial energies

a ≙ 9.0, b ≙ 25, c ≙ 175, d ≙ 25000 GeV/fm^3; e ≙ ideal gas limit



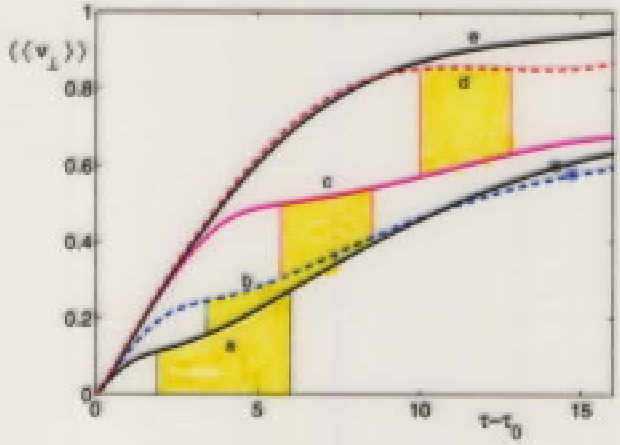
spatial asymmetry

$$\epsilon_x = \frac{\langle\langle y^2 - x^2\rangle\rangle}{\langle\langle y^2 + x^2\rangle\rangle}$$



momentum anisotropy

$$\epsilon_p = \frac{\langle\langle T^{xx} - T^{yy}\rangle\rangle}{\langle\langle T^{xx} + T^{yy}\rangle\rangle}$$



radial flow

$$\langle\langle v_\perp\rangle\rangle = \frac{\left\langle\left\langle \sqrt{v_x^2 + v_y^2}\right\rangle\right\rangle}{\langle\langle\gamma\rangle\rangle}$$

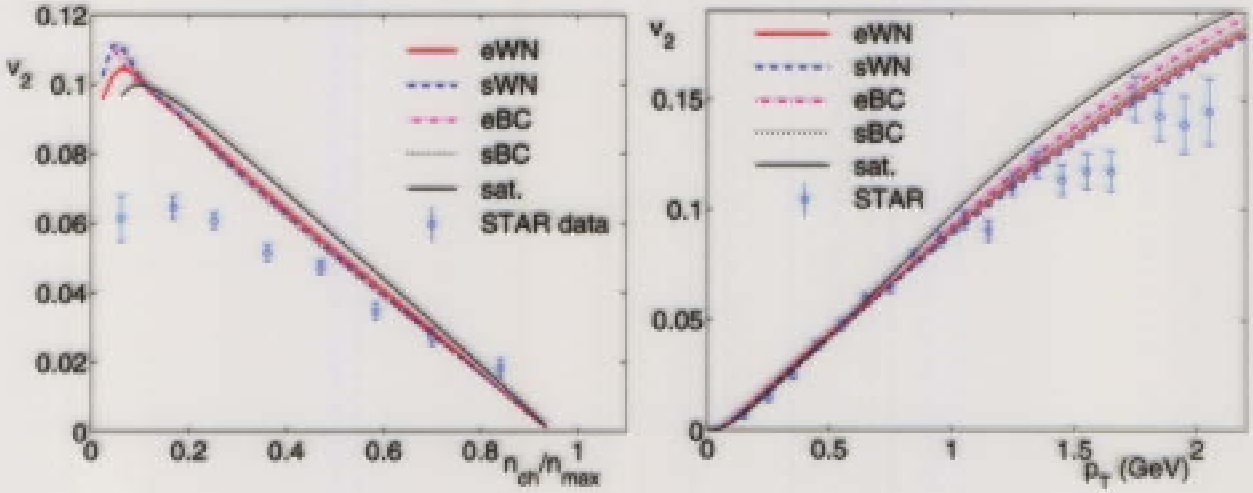
P. Kolb et al., PRC 62, 054909 (2000)

Elliptic flow

STAR-collaboration, K.H. Ackermann et al., Phys. Rev. Lett. 86 (2001) 402

$$v_2(p_t;\, b) = \frac{\int d\phi \cos(2\phi) \frac{dN}{dy\, d\phi\, p_t dp_t}(p_t, \phi; b)}{\int d\phi \frac{dN}{dy\, d\phi\, p_t dp_t}(p_t, \phi; b)}$$

over centrality over momentum



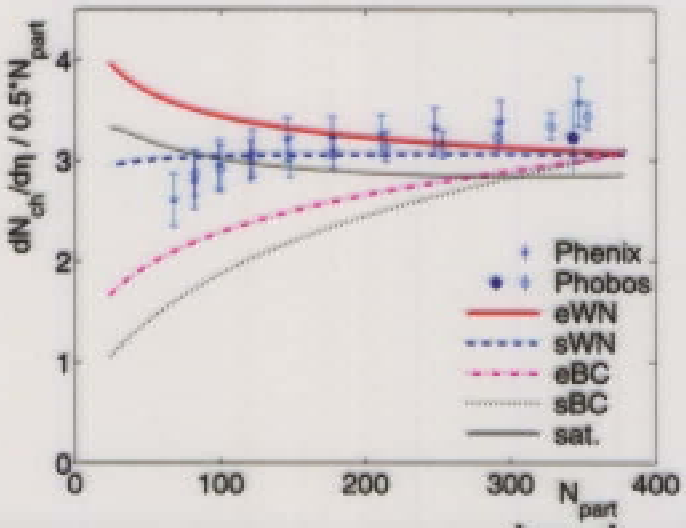
→ hydrodynamics is in good agreement with the data at central and semicentral collisions ($b < 7 - 8$ fm) and transverse momenta up to $p_T < 1.5 - 2.0$ GeV.

Deviations are due to lack of thermalization in peripheral collisions ('free streaming' → reduction of initial spacial anisotropy) and for high p_T particles (escape without equilibration).

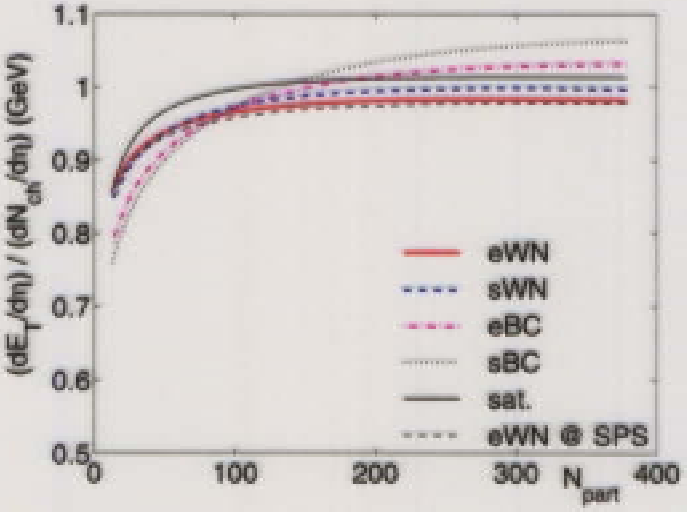
Multiplicities and transverse energy

PHENIX-collaboration, K. Adcox et al., Phys. Rev. Lett. 86 (2001) 3500
G. Roland for the PHOBOS-collaboration at QM 2001

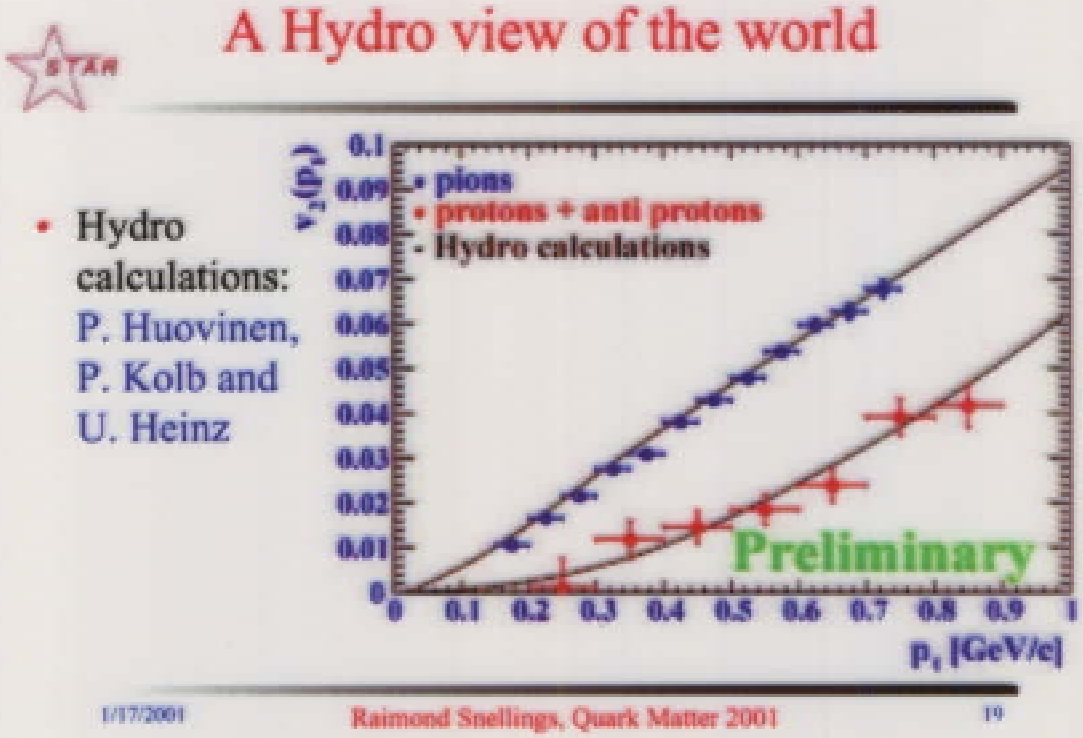
particle yield per participant pair



transverse energy per emitted particle

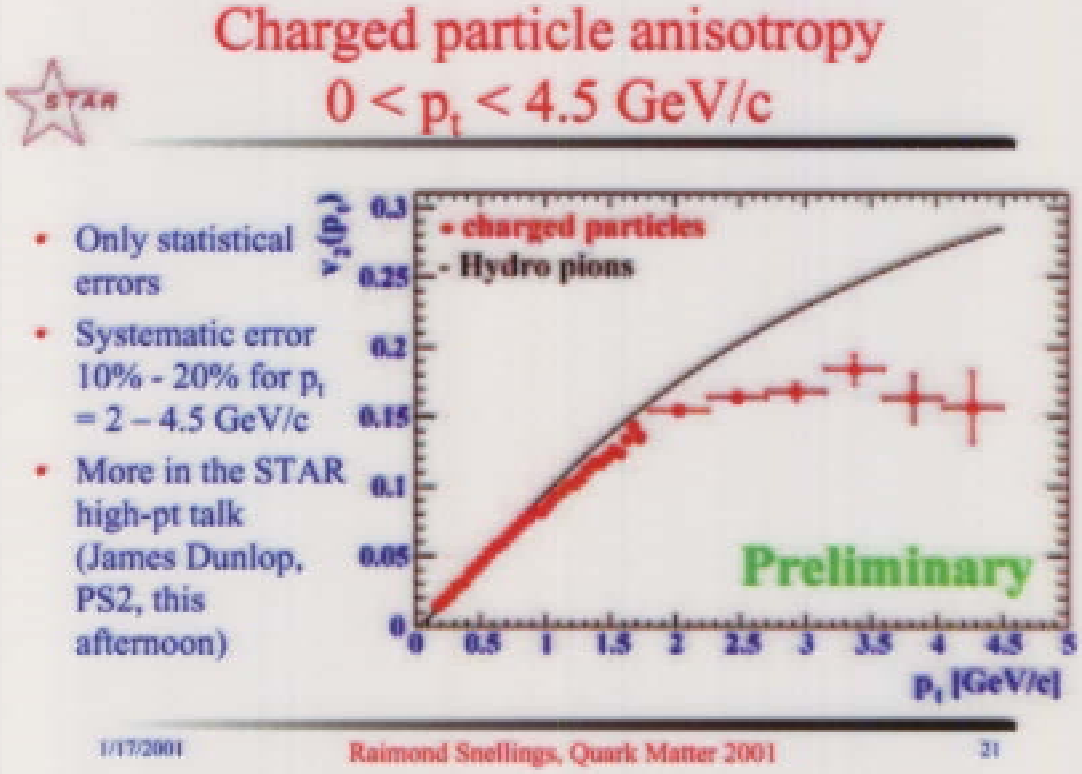


Elliptic flow for different particle species



- Pions and protons in agreement with hydrodynamic results
- Higher mass of the particles under investigation lead to a more gradual rise of $v_2(p_T)$

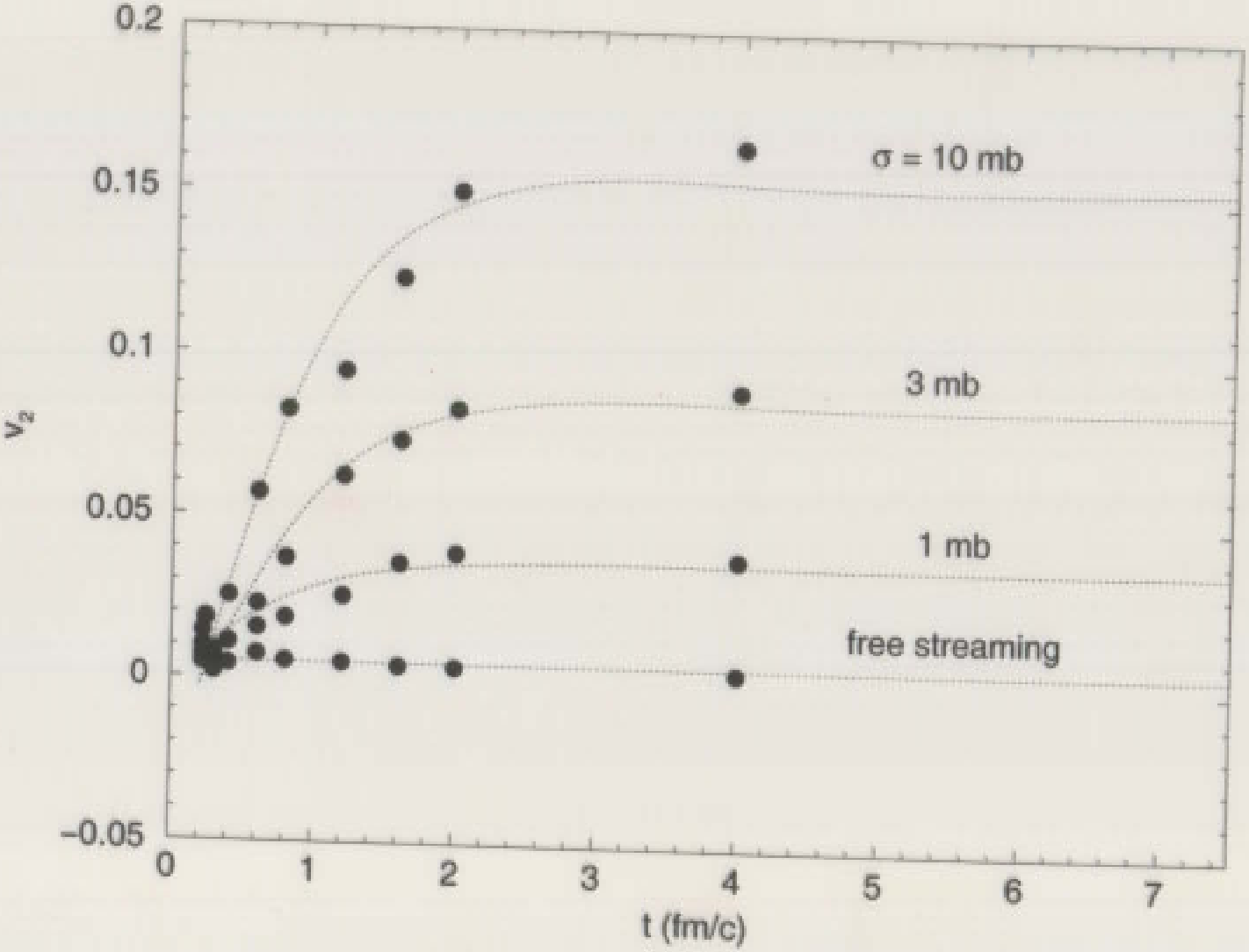
Elliptic flow at high p_T



- Insufficient equilibration of high p_T particles
- Elliptic flow results from different pathlengths and energy loss (jet quenching)

X.N.Wang, nucl-th/0009019

Elliptic flow requires rescattering:



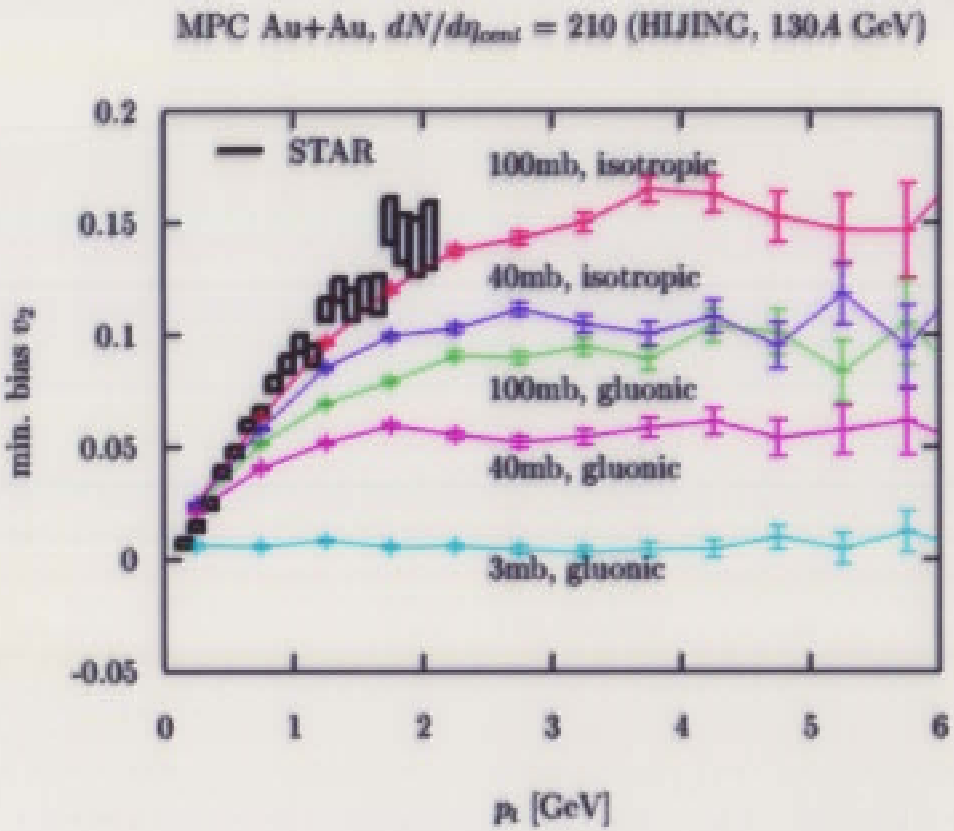
B. Zhang, M. Gyulassy, C.M. Ko, PLB 455 (1999) 45

In fact, a lot of rescattering!

$\gtrsim 30 \times \sigma_{acs}$

$\gtrsim 10$ times σ_{acs}!

Minimum bias v2



Simple estimate:

$$v_2^{minbias} = \frac{2\pi}{\pi b_{max}^2} \int_0^{b_{max}} v_2(b)\, b\, db$$

b_{max} **not known → take 12fm**

- v_2 **grows with** p_t **until** $\sim 2-3$**GeV, then saturates**
- **data supports: HIJING** $dN/dy_{cent} = 210$, $\sigma = 100$**mb isotropic,**
  or EKRT $dN/dy_{cent} = 1000$, **21mb isotropic**
- **also possible with gluonic but needs higher cross sections or densities**
  NOTE: 3mb gluonic requires $dN/dy > 7000$**(!)**

Why is this so interesting?

- Initial momentum distribution is locally isotropic
  $\rightarrow v_2^{init} = 0$ even if $\langle p_\perp^2 \rangle (\vec{r})$ initially anisotropic in $\vec{r}$.

- $\rightarrow$ $v_2 \neq 0$ requires "rescattering".

- $v_2 \neq 0$ also requires spatial anisotropy ε_x.
  ε_x is diluted by free-streaming:

$$\frac{\varepsilon_x(\tau_0 + \delta\tau)}{\varepsilon_x(\tau_0)} = \frac{1}{1 + \frac{(c\,\delta\tau)^2}{R^2(1+\delta^2)}}$$

  In Pb+Pb @ $b = 7$ fm, $\delta\tau = \begin{Bmatrix} 1 \text{ fm/c} \\ 2 \text{ fm/c} \end{Bmatrix}$ dilutes ε_x by $\begin{Bmatrix} 10\% \\ 25\% \end{Bmatrix}$

- $\rightarrow$ v_2 must be built up early

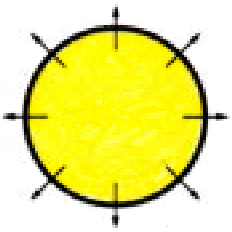
- For given ε_x, ideal (non-viscous) hydrodynamics gives largest possible v_2 response. For $b \lesssim 7$ fm and $p_\perp \lesssim 1.5-2$ GeV, RHIC data saturate this upper limit!

- $\rightarrow$ data require very strong rescattering and $\approx$ local thermalisation ($T^{\mu\nu} \approx T^{\mu\nu}_{\text{ideal fluid}}$) at a very early stage! How?? $\rightarrow$ next talks

- elliptic flow is self-quenching
  $\rightarrow$ sensitive to EOS before hadronisation.

Transverse Flow Patterns

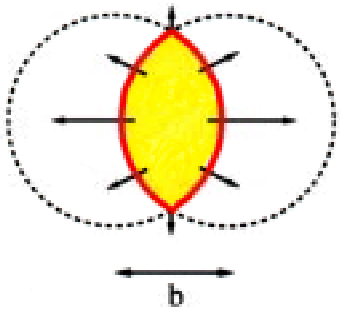
Radial flow:



→ Only type of transverse flow in $b = 0$, $A = B$ collisions (A spherical)

→ Integrates pressure history over complete expansion stage

Anisotropic flow:



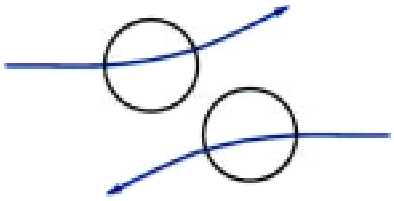
→ from deformed initial overlap region

→ peaks at $y = 0$

→ anisotropic flow reduces spatial deformation, → shuts itself off

→ more weigth towards early stage of expansion (H. Sorge)

Directed transverse flow:



→ only in $b \neq 0$ collisions

→ probes the earliest collision stages (pre-equilibrium)