RHIC/INT Workshop
LBL 1/99

Flow at RHIC and QCD Phase transition

- **Longitudinal Flow:**
  NOT Hydrodynamics but governed by Regge / string dynamics
  + stopping, strange baryon production, junction dynamics
- **Transverse flows:**
  sensitivity to the "softest point of the Equation of State"
  + "kinky" centrality dependence of elliptic flow,
  + EOS w./ phase transition in RQMD

HS: nucl-th/9812057

HS, N. Xu: in preparation

Time scale of Entropy production:

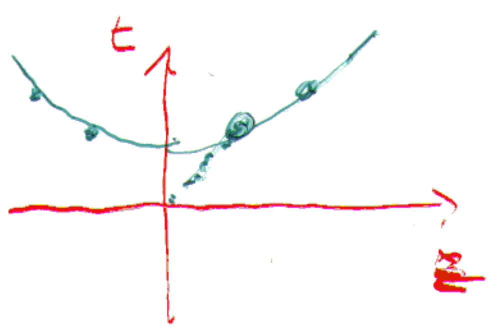
+ Bjørken scenario
+ strings, ropes
+ inside-outside cascade (empirical)
+ coherent production

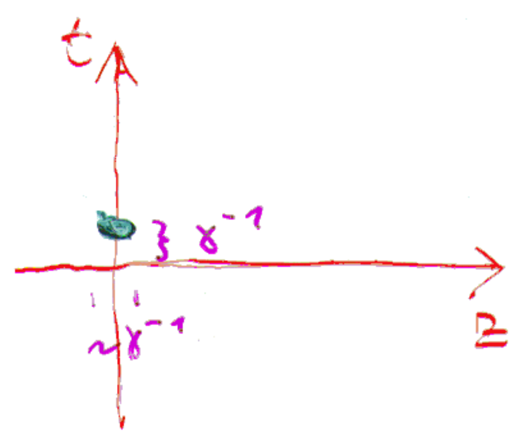
$$t_{Form} \sim \gamma$$

↑ Lorentz factor of produced particle

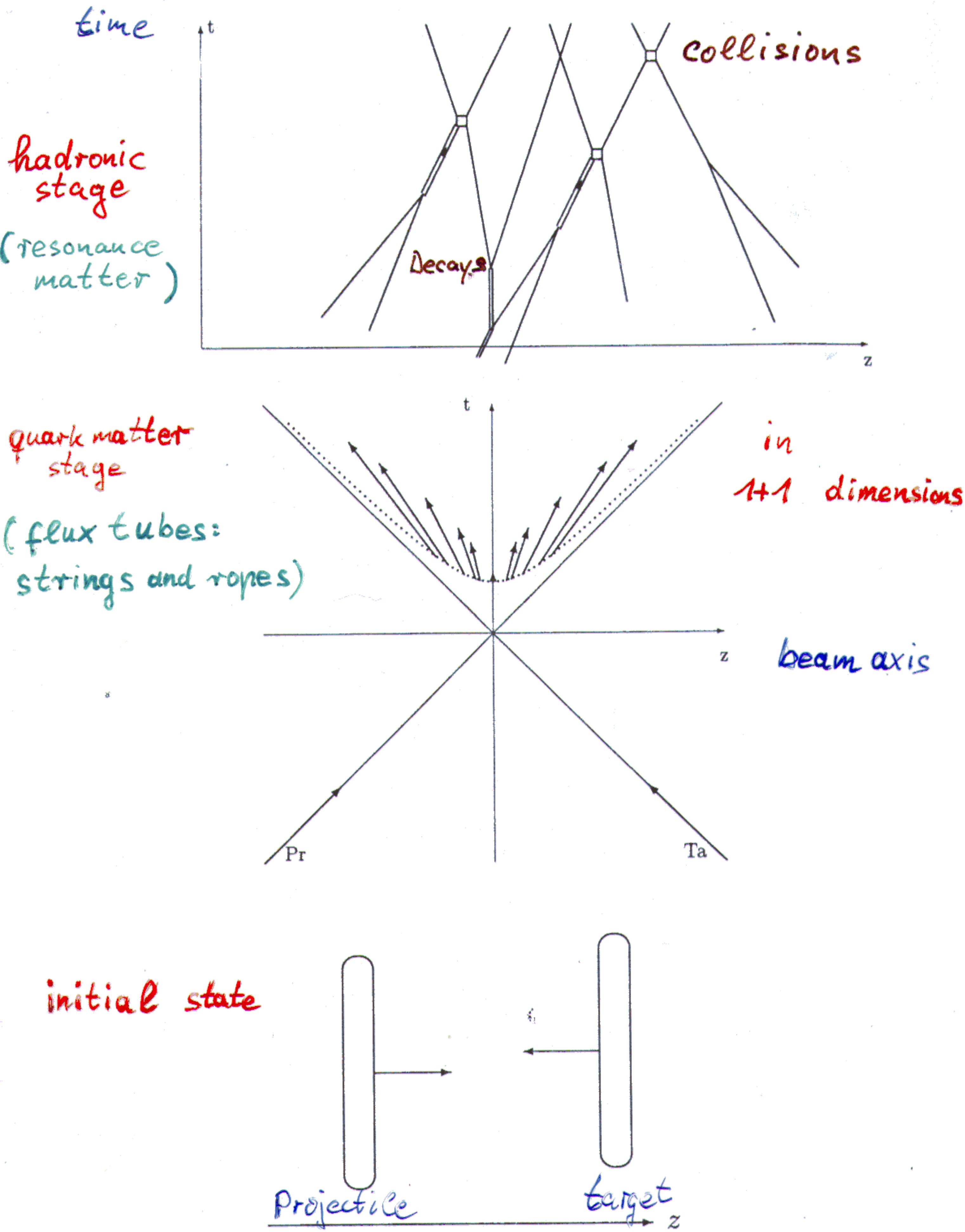
+ Landau-type Hydrodynamics
+ Parton cascade model (KKG)

$$t_{Form} \sim \frac{1}{\gamma}$$

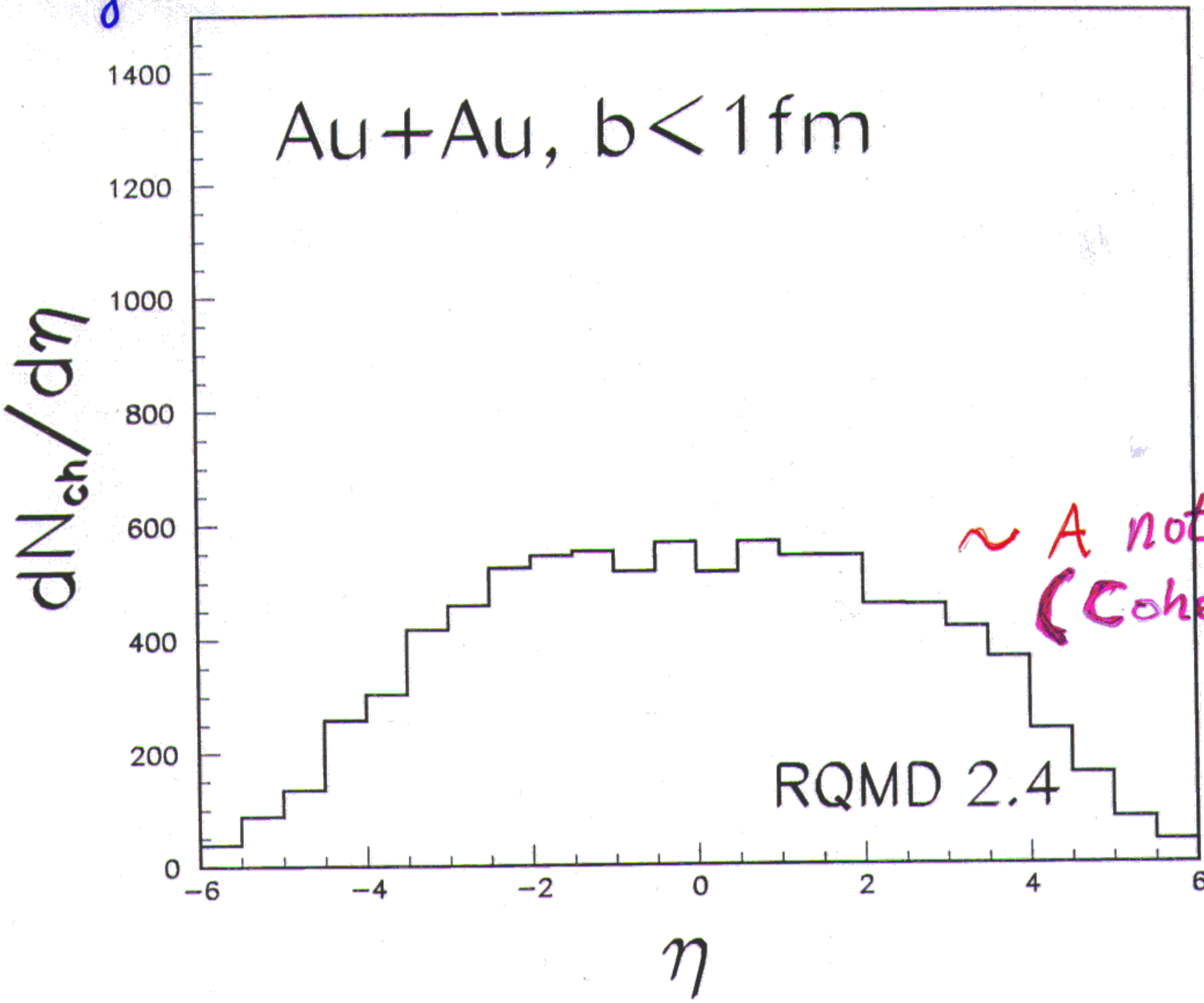




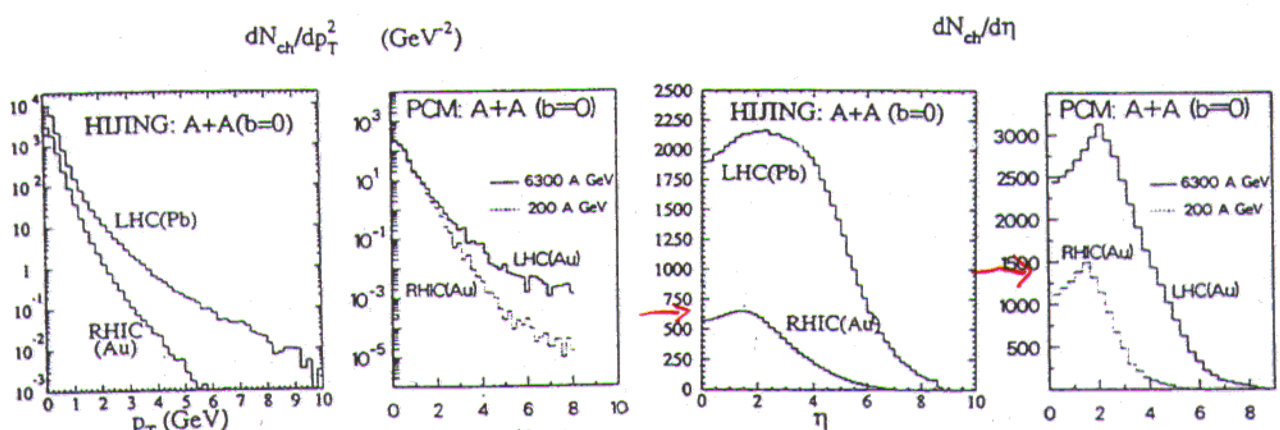
Transport calculation with RQMD



charged hadrons RHIC

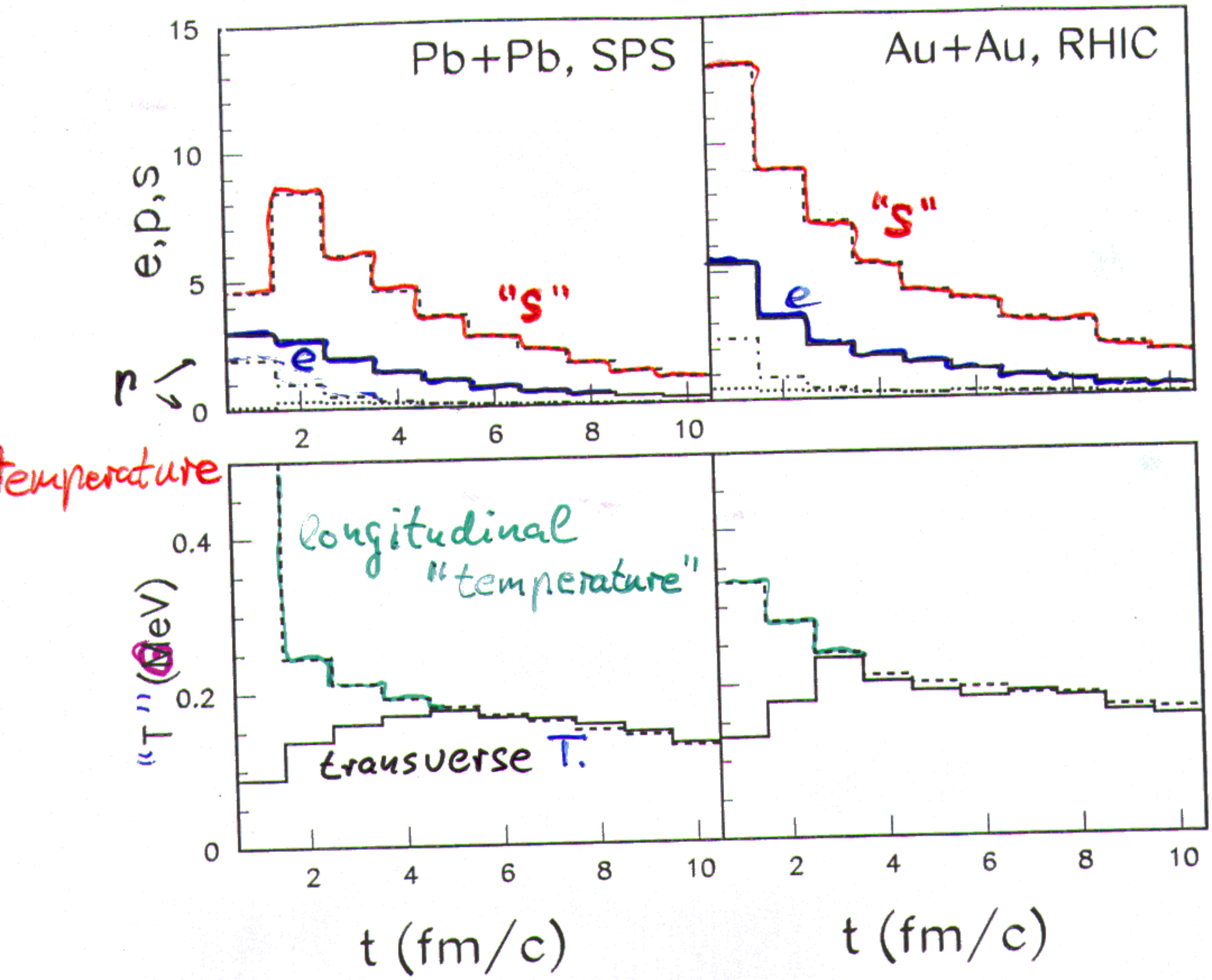


~ A not $A^{4/3}$
(Coherence)



HIJING (X.N. Wang) PCM (K. Geiger)
B. Mueller

RQMD



e energy density

p pressure, long. + tr.

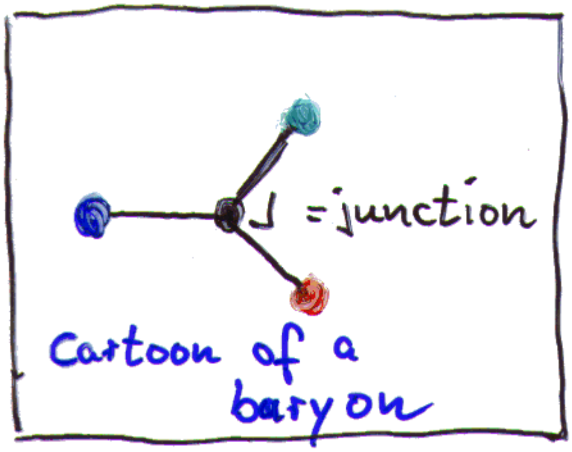
s "entropy" density (≃ 4 · ρ_h)

T "temperature" (≃ p/ρ), long. + tr.

In string models, Regge theory based approaches:

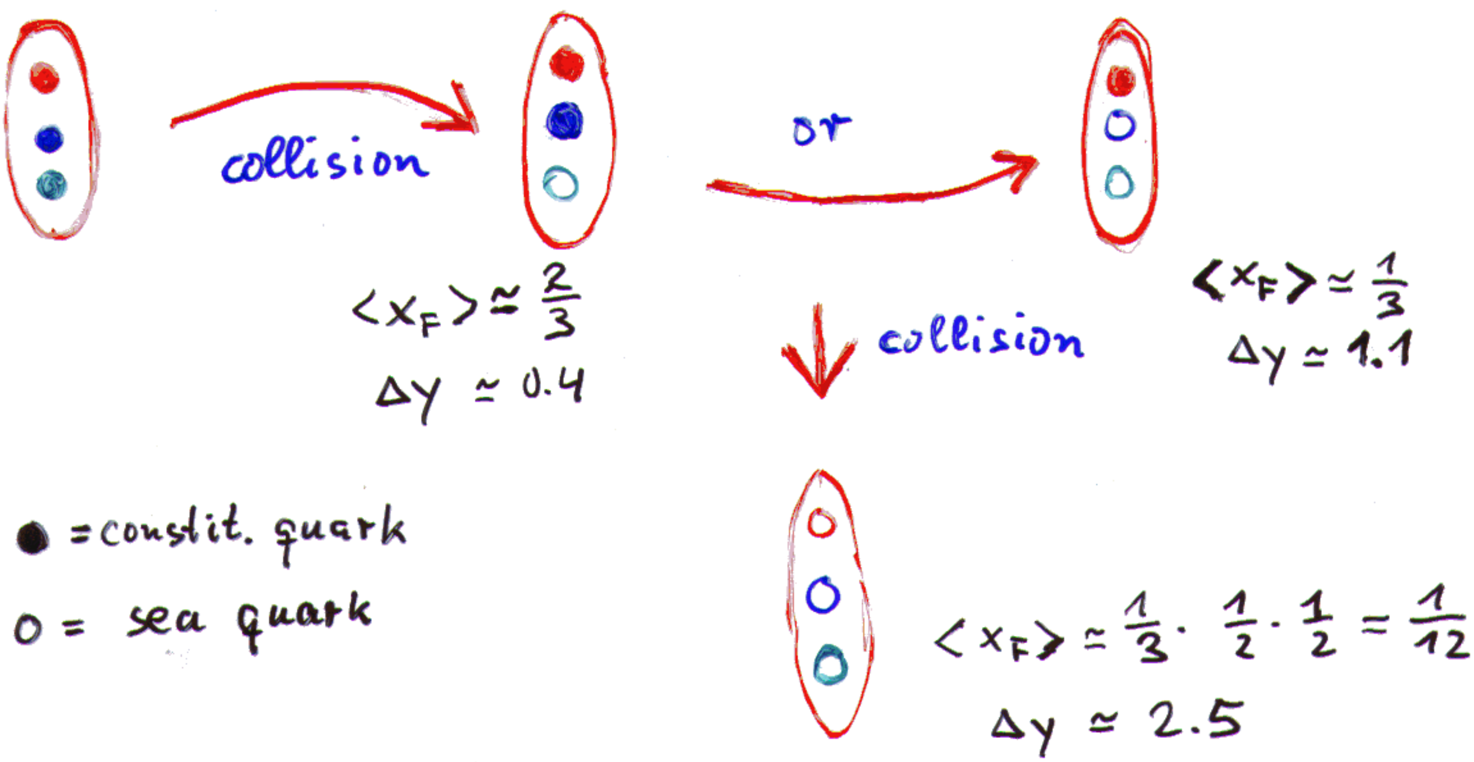
BARYON STOPPING ≠ ENERGY STOPPING ≠ ≠ CHARGE STOPPING

RQMD: shift of baryon number caused by constituent quark stripping off the B junction

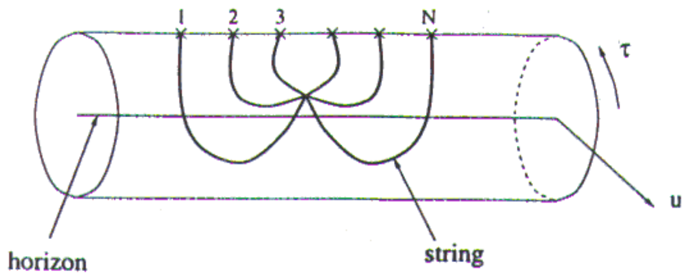


Refs.:
HS et al.: ZfP C59 (1993) 85.
HS: PR C52 (1995) 3291.

K. Werner
D. Kharzeev
S. Vance, M. Gyulassy
V. Kopeliovich, A. Capella



D.J. Gross, H. Ooguri: hep-th/9805129



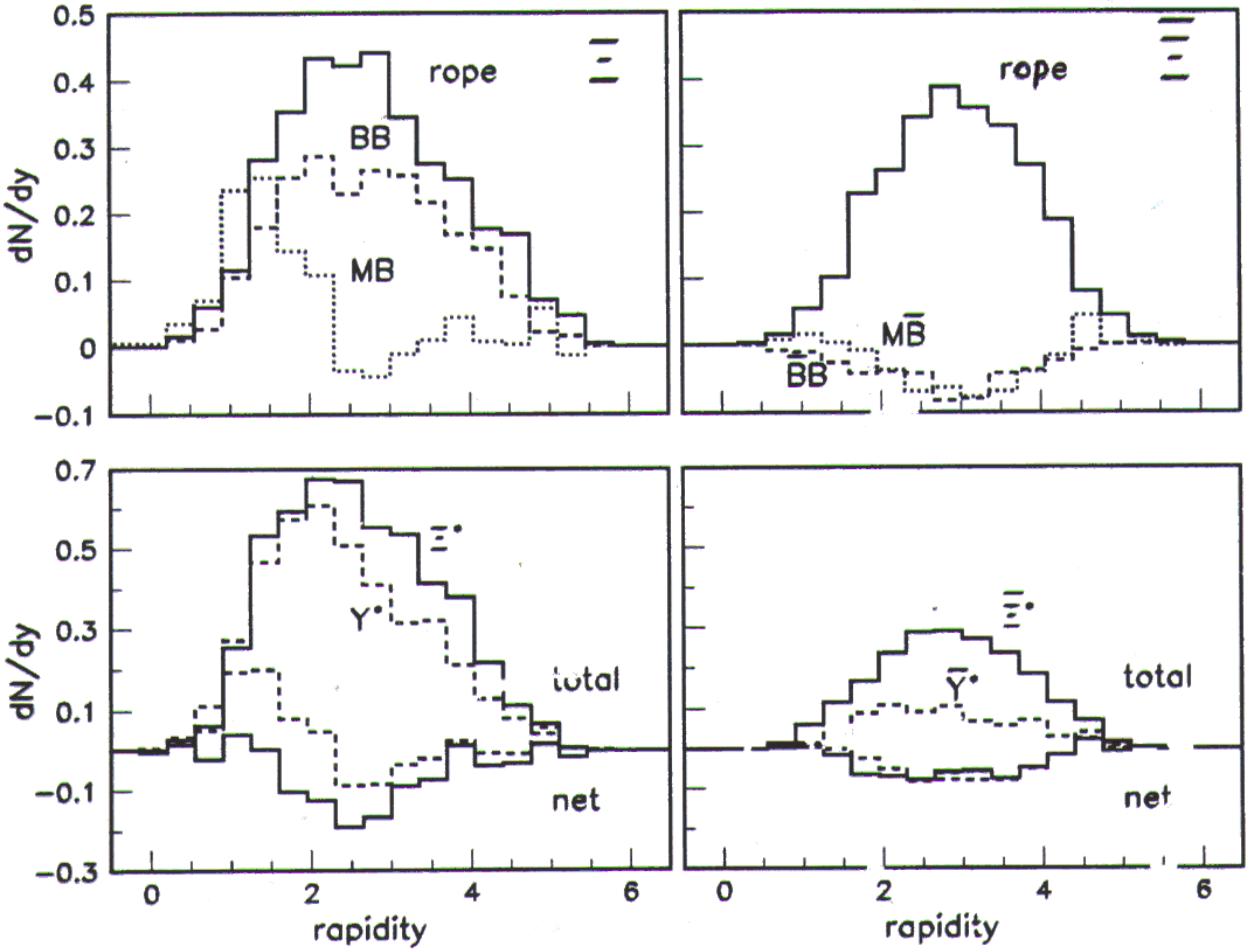
This is graphical representation of a solution in supergravity where N strings join at a point in AdS 5.

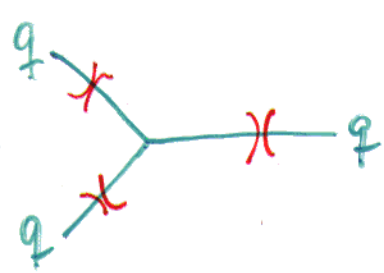
Gauge Theory (large N_c) $\overset{\text{conjectured}}{\Longleftrightarrow}$ string theory

Maldacena
Witten

HS, PLB 344 (1995) 35

(Anti–) Ξ sources in S+W





B =

Figure 2:

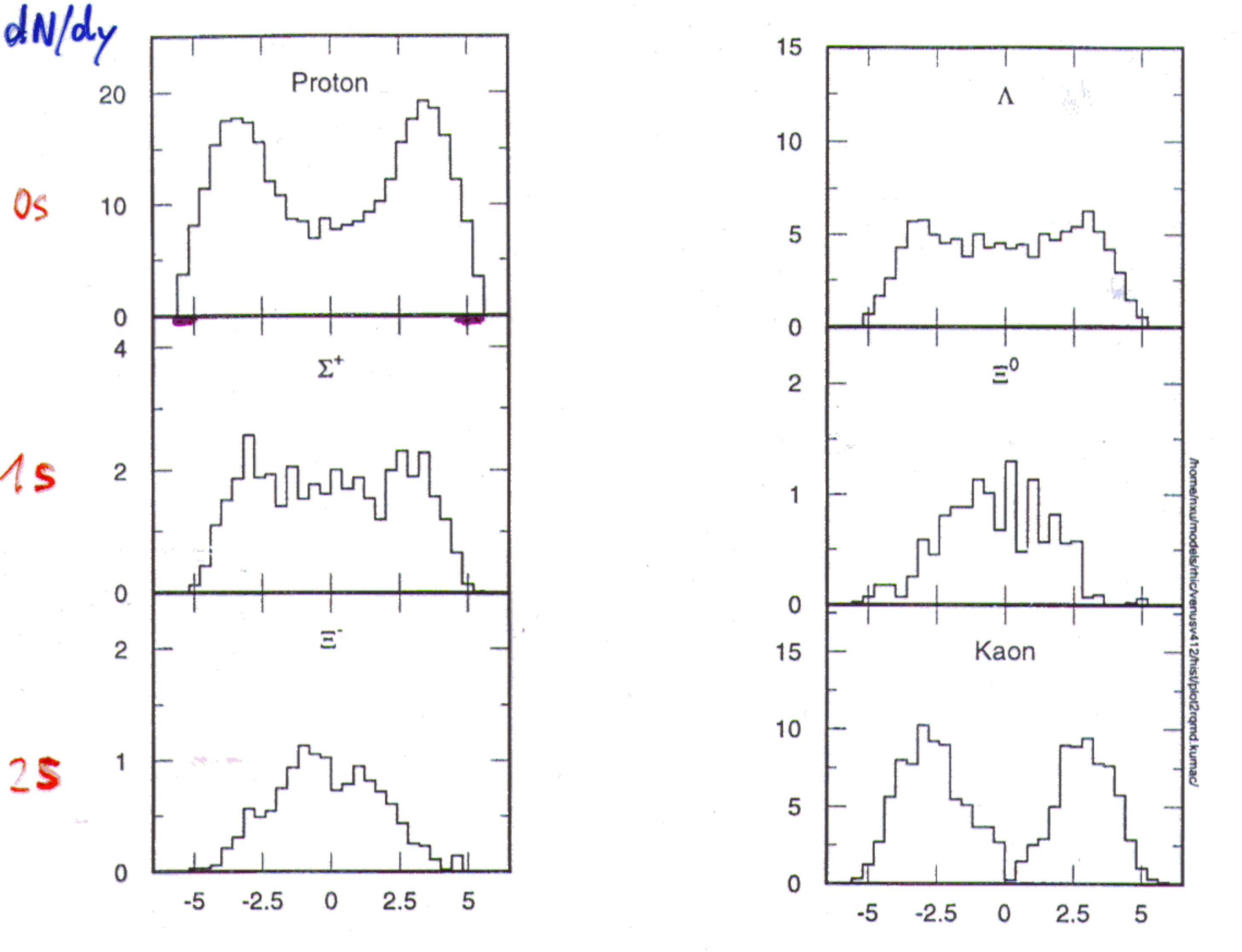
Ex.:

$\Xi + \pi \leftrightarrow \bar{K}\,\Lambda$

BB means $(BB)^n$

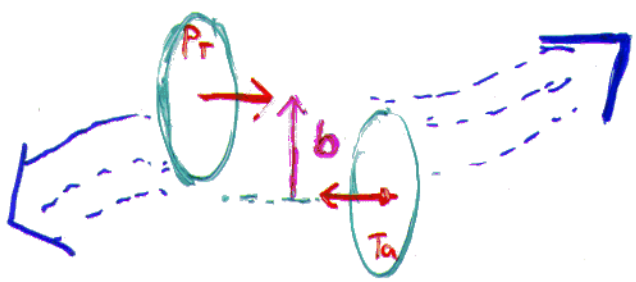
NET distributions (Particles - Anti-Particles)

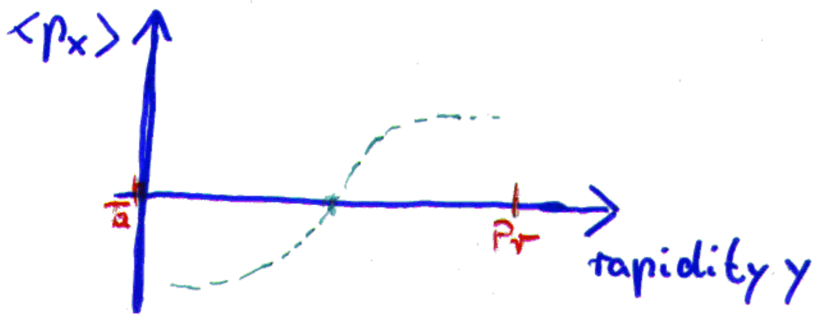
RQMD(v2.4) 100AGeV Au + 100AGeV Au (b<3 fm/230events)



HS, N. Xu

Transverse flows in AA collisions:

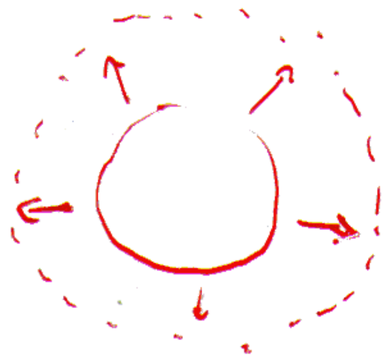




Directed flow

HS et al.: PLB 243 (1990) 7

$t \sim 2R/\gamma$



$t \gtrsim R_t$

Radial flow:

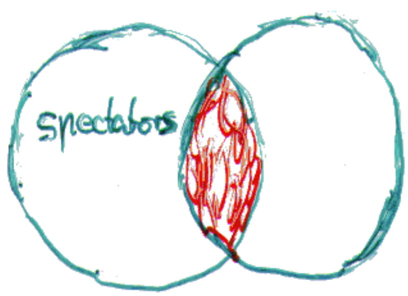
⊗ beam axis

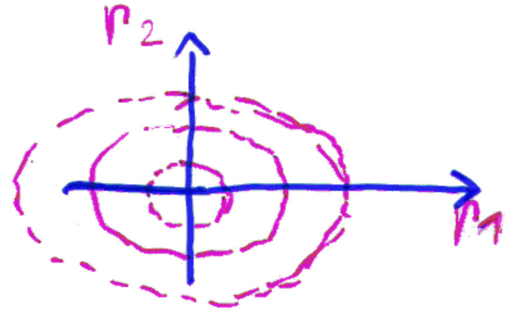
hardening of transverse momentum spectra

Two time scales:

$t_1 \simeq 2R/\gamma$

$t_2 \simeq R_t$



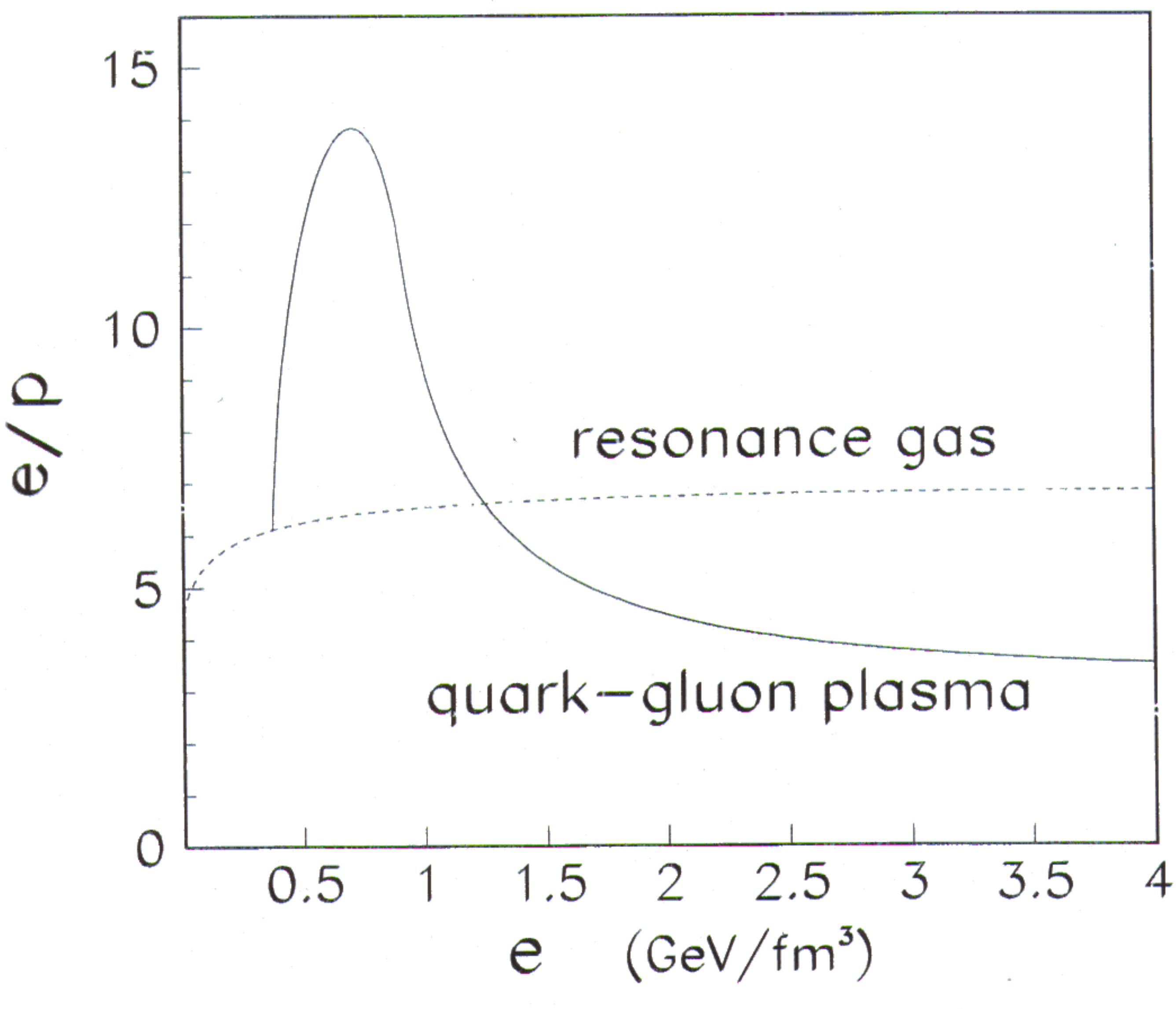


Azimuthal asymmetry

Elliptical flow

Equation of State in QCD at finite T

energy density / pressure



Quasi-particle Model of quark-gluon plasma:

Thermal Masses of quarks and gluons

$$m_g = \sqrt{\frac{1}{6}\left(N_c + \frac{1}{2}n_{\rm f}\right) g^2 T^2}\,,$$

$$m_q = \frac{1}{2}\left(m_{0q} + \sqrt{m_{0q}^2 + \frac{N_c^2 - 1}{2N_c}\, g^2 T^2}\right).$$

Effective coupling constant:

$$g^2(T) = \frac{48\pi^2}{(11\,N_c - 2\,n_{\rm f})\,\ln[\lambda \cdot (T + T_s)/T_c]^2}$$

Pressure

$$p_{\rm qp}(T) = \sum_i p_{\rm id}(T, m_i(T)) - B(T)\,.$$

Entropy

$$s_{\rm qp}(T) = \sum_i s_{\rm id}(T, m_i(T))\,.$$

which fixes **T** dependence of the "bag constant" **B** .

M. I. Gorenstein, S. N. Yang, Phys. Rev. D52 (1995) 5206

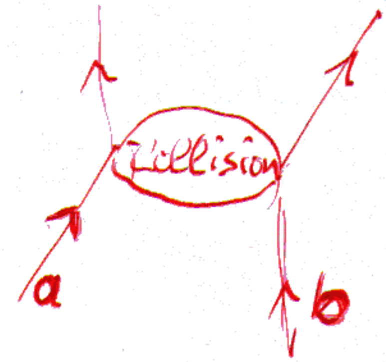
A. Peshier, B. Kämpfer, O. P. Pavlenko, G. Soff, Phys. Rev. D54 (1996) 2399

Parameters: T_c , $B(T_c)$

λ , T_s

How to manipulate the pressure?

VIRIAL THEOREM , special case:



$$P \;=\; P_{id} + \underbrace{\frac{1}{d \cdot V \cdot \Delta T} \sum_{(a,b)} \left(\delta\vec{p}_a \cdot \vec{r}_a + \delta\vec{p}_b \cdot \vec{r}_b\right)}_{\Delta P}$$

Total Pressure	ideal part	add interaction term

$$\langle \delta\vec{p}_a \vec{r}_a \rangle + \langle \delta\vec{p}_b \vec{r}_b \rangle \;\stackrel{!}{=}\; d \cdot \frac{\Delta P}{\rho} \cdot \left(\Delta t_a^{sc} + \Delta t_b^{sc}\right)$$

$$\delta\vec{p}_a(i)\vec{r}_a(i) + \delta\vec{p}_b(i)\vec{r}_b(i) \;\stackrel{!}{=}\; d \cdot \frac{\Delta P}{\rho} \cdot \left(\Delta t_a(i) + \Delta t_b(i)\right)$$

i collision index

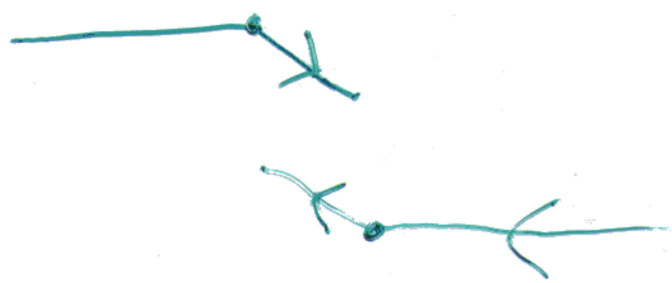
Δt (i) time since last collision

(**Limit N $\rightarrow \infty$, $\Delta t \rightarrow$ 0:**

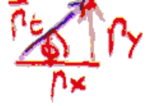
IDEAL HYDRODYNAMICS)

Two basic types of interactions (elastic collisions)

attractive:

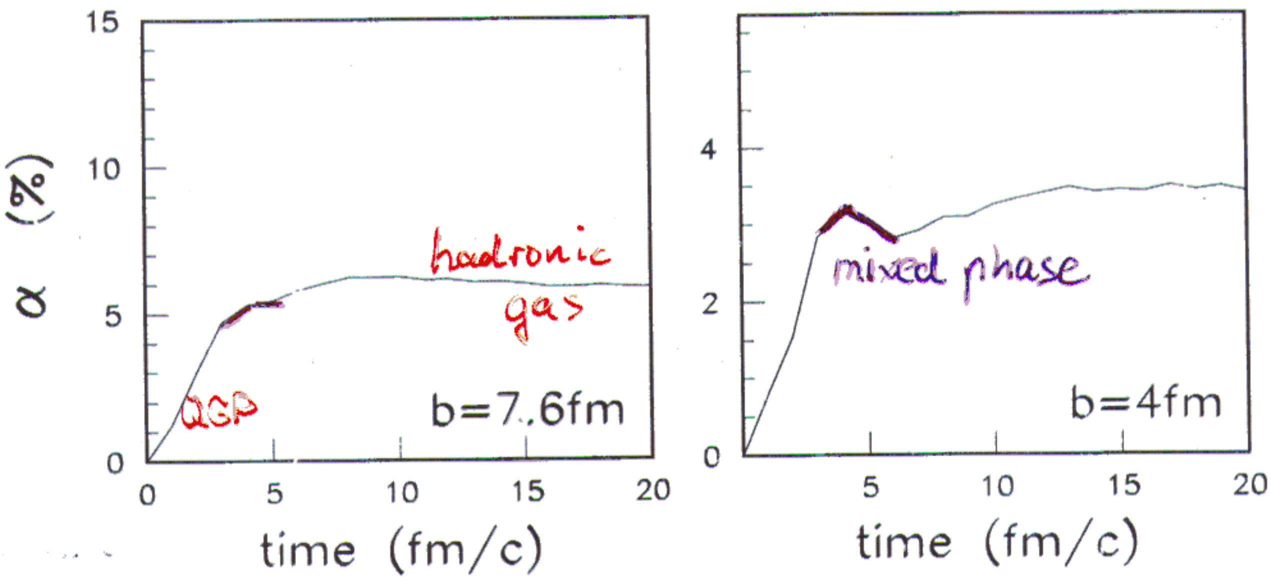


repulsive:



$$\alpha = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle} \quad \text{or} \quad v_2 = \langle \cos(2\phi) \rangle$$

Pb(158AGeV) on Pb



Elliptical flow develops early ($t \simeq R_t/c$), i.e. sensitive to the early pressure.

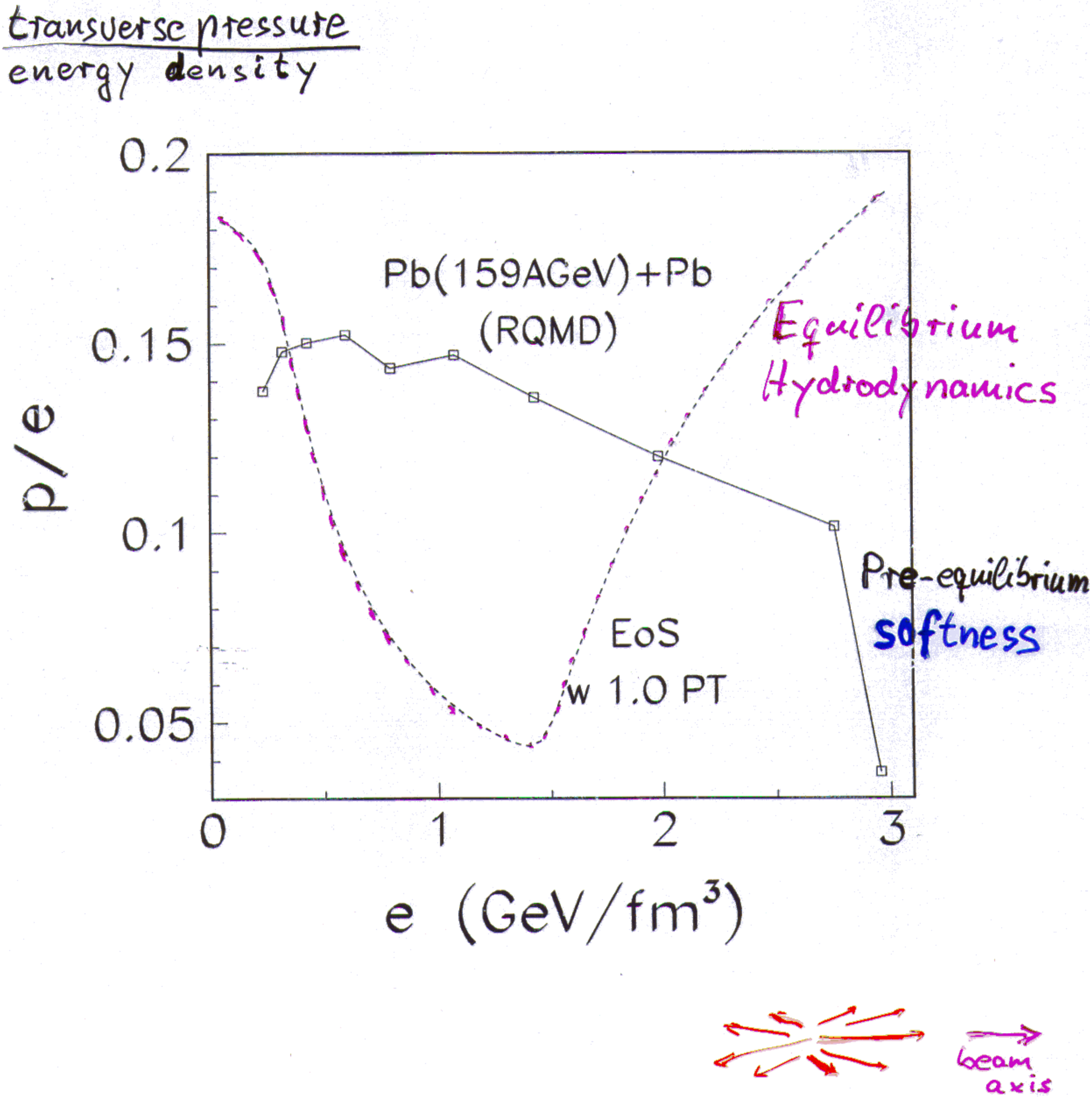
HS, PLB 402 ('97) 251

Better quantity A_2:

$$v_2 = f(\alpha_x, e_0, \cdots) \simeq A_2(\bar{\alpha}_x, e_0, \cdots) \cdot \alpha_x + \mathcal{O}((\alpha_x - \bar{\alpha}_x)^2)$$

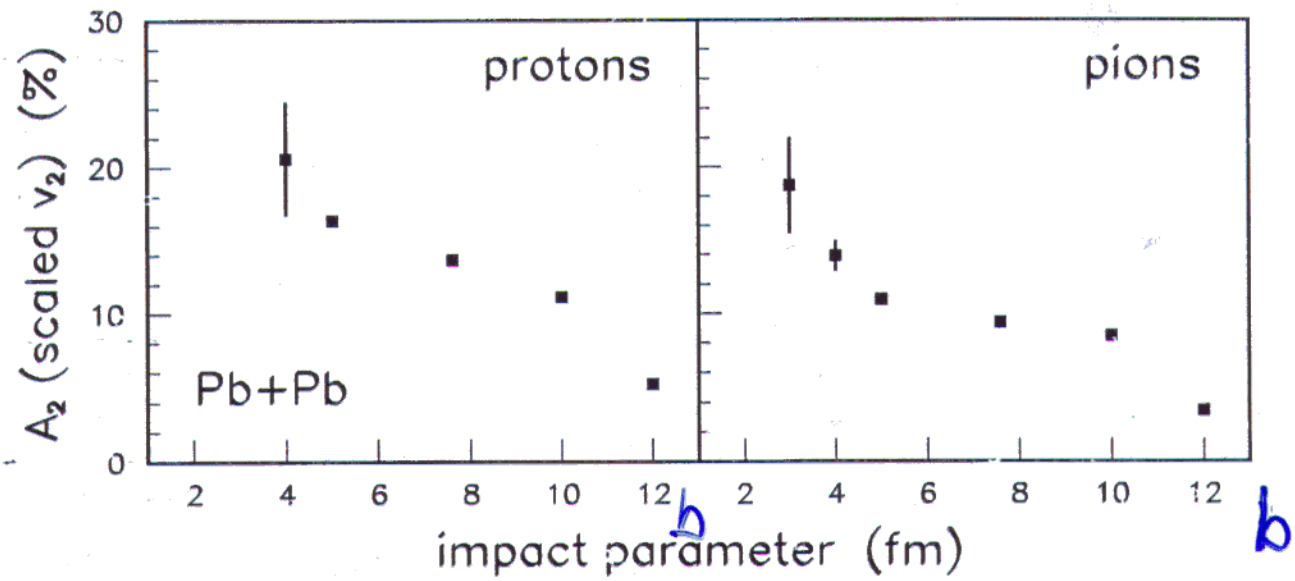
w. $$\alpha_x := \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle x^2 \rangle + \langle y^2 \rangle}$$

spatial asymmetry of nucleon participants

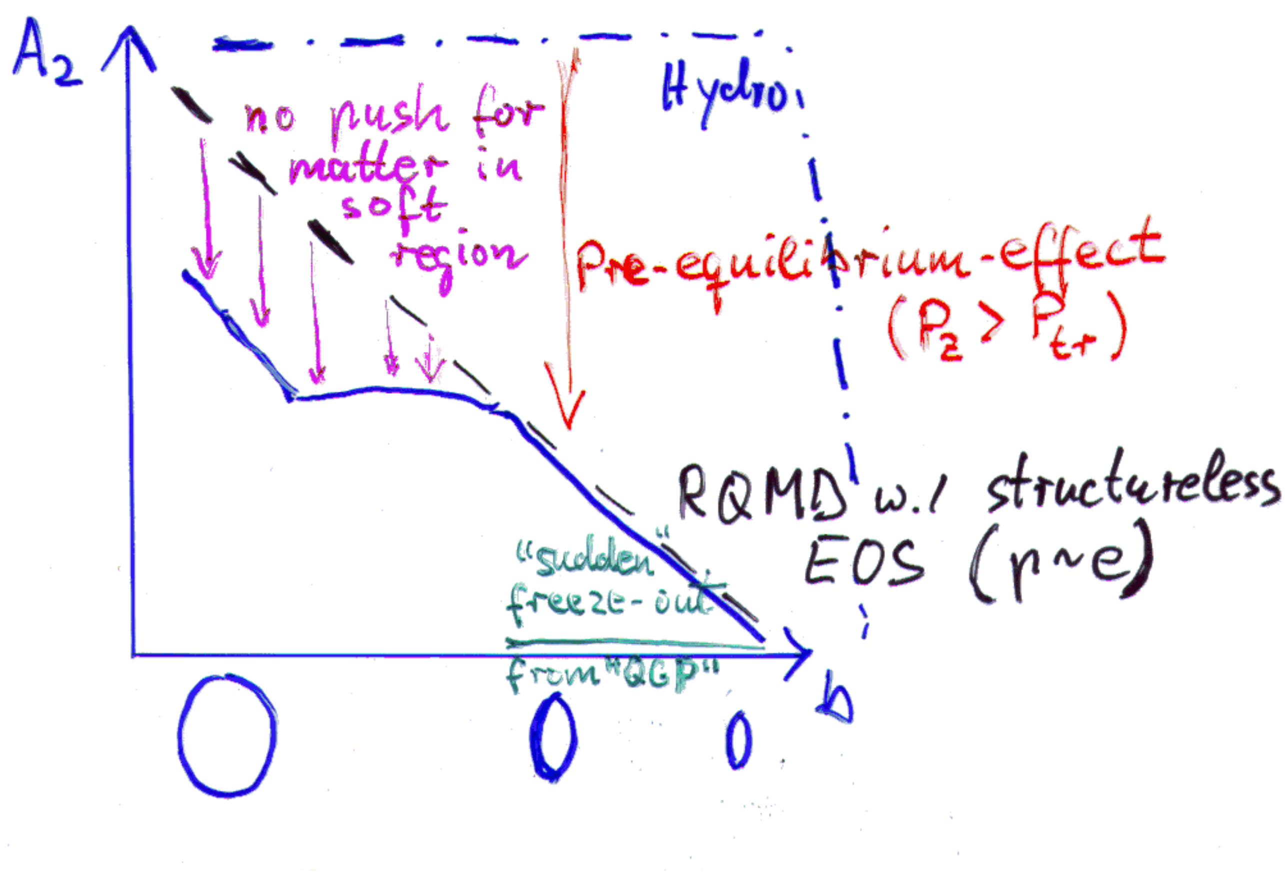

transverse pressure
energy density
p/e
0.2
0.15
0.1
0.05
Pb(159AGeV)+Pb
(RQMD)
Equilibrium
Hydrodynamics
Pre-equilibrium
softness
EoS
w 1.0 PT
0
1
2
3
e (GeV/fm³)
beam
axis

Elliptical flow shows "kinky" b dependence:

HS: nucl-th/9812057



schematic interpretation:



Conclusions:

- Rapidity distributions of different hadron species reveal information on the "initial" (pass-through) stage of the two nuclei: In-homogeneity of charges, baryon number, energy in the produced matter.

- Flows are time integrals of the forces and store information on the EOS in phase transition region ("softest point"). It does not require understanding of QCD around T_c (which is a virtue). Most promising: ELLIPTICAL FLOW w.r. large weight on early stage. "Kinky" centrality dependence is a novel signature of the QCD phase transition.