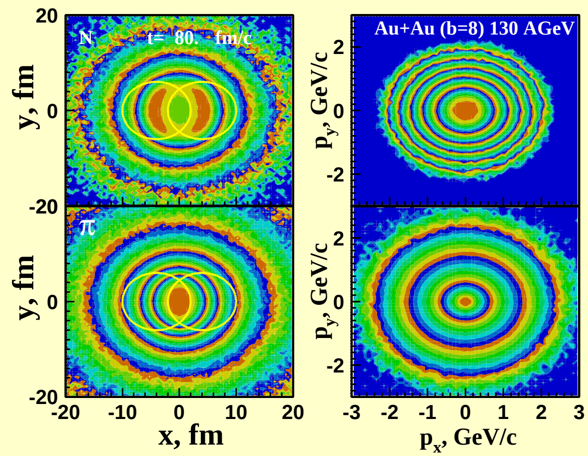
Collective flow and freeze-out in relativistic HICs

E.Z, L. Bravina, K. Tywoniuk, J. Bleibel, G. Burau, C. Fuchs, A. Faessler

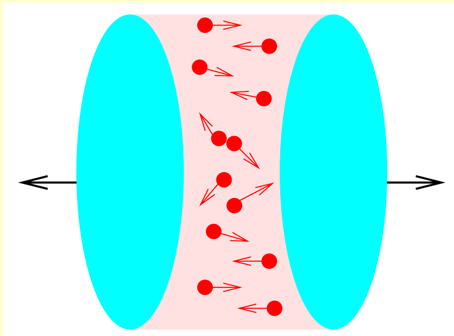
September 30, 2005
QCD at Cosmic Energies -II

- Motivation
- Basic principles of microscopic models
- Directed flow of hadrons at SPS and RHIC
- Elliptic flow
- Influence of particle freeze-out on the development of elliptic flow
- Conclusions



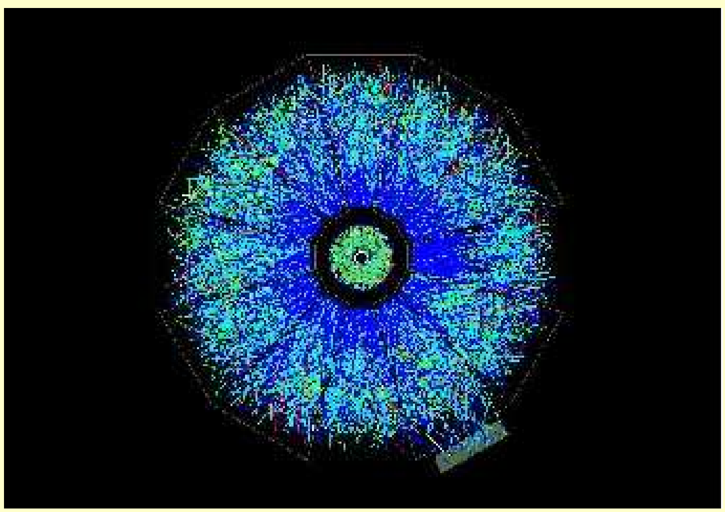
Introduction

K. Werner, hep-ph/0206111



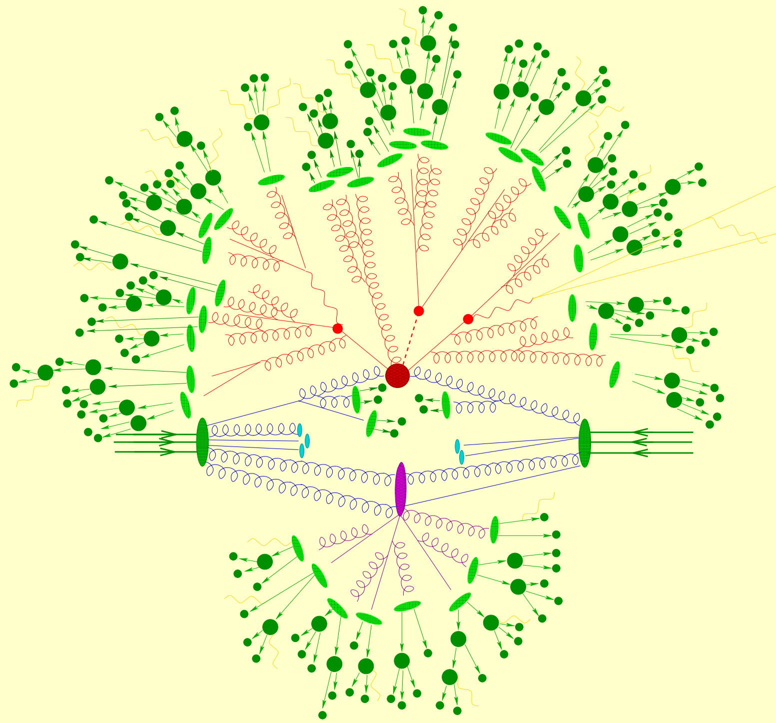
Schematic picture of A + A collision

J.S. Lange, hep-ph/0403104



STAR: Au+Au collision at $\sqrt{s}$=200 GeV

A. Schaelicke et al., hep-ph/0311270



Event generator view of pp interaction at high energy

Basic principles of microscopic models

Transport equation

$$\underbrace{\mathcal{L}_1^{(0)} f_1(x,p,t)}_{\text{streaming term}} = \underbrace{C(x,p)}_{\text{collision term}} + \underbrace{S(x,p)}_{\text{source term}}$$

Model:

- Initialization of projectile and target
- Propagation (with given H)

$$\dot{p}_i = -\frac{\partial H}{\partial r_i}$$
$$\dot{r}_i = \frac{\partial H}{\partial p_i}$$

- Scattering and particle production
- (next time-step)

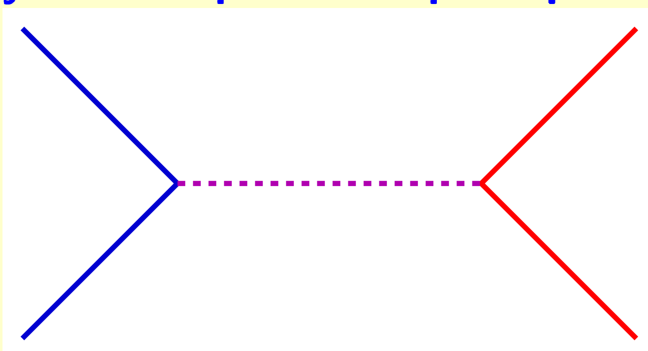
Input:

- Fermi-gas model; liquid drop model
- Potentials: Coulomb, Yukawa, Skyrme, etc.
- Cross sections (tabulated); resonances (widths and branching ratios);
- Partons (distribution and clusterization) or Strings

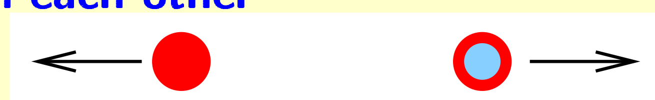
The string picture

K. Werner, hep-ph/0206111

Let us consider e^+e^- annihilation. Electron and positron annihilate and form a virtual photon, then the virtual photon decays into a quark-antiquark pair.

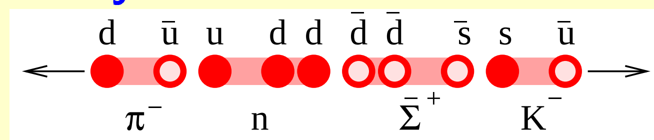


The quark and antiquark move apart from each other

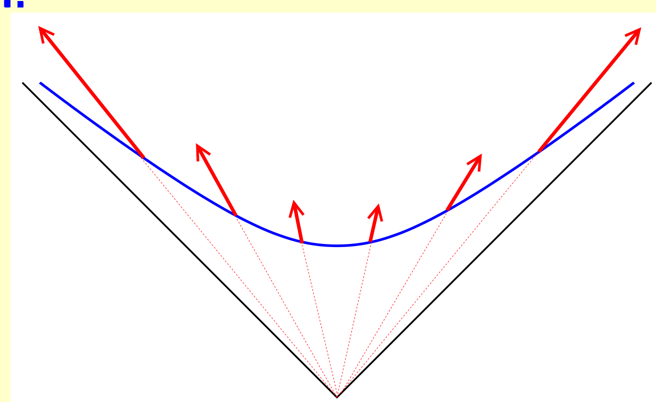


But there is a gluon field acting between the two, whose energy is proportional to the separation distance. This object is called string.

The string breaks via quark-antiquark production, and these new string pieces are finally hadrons or resonances.

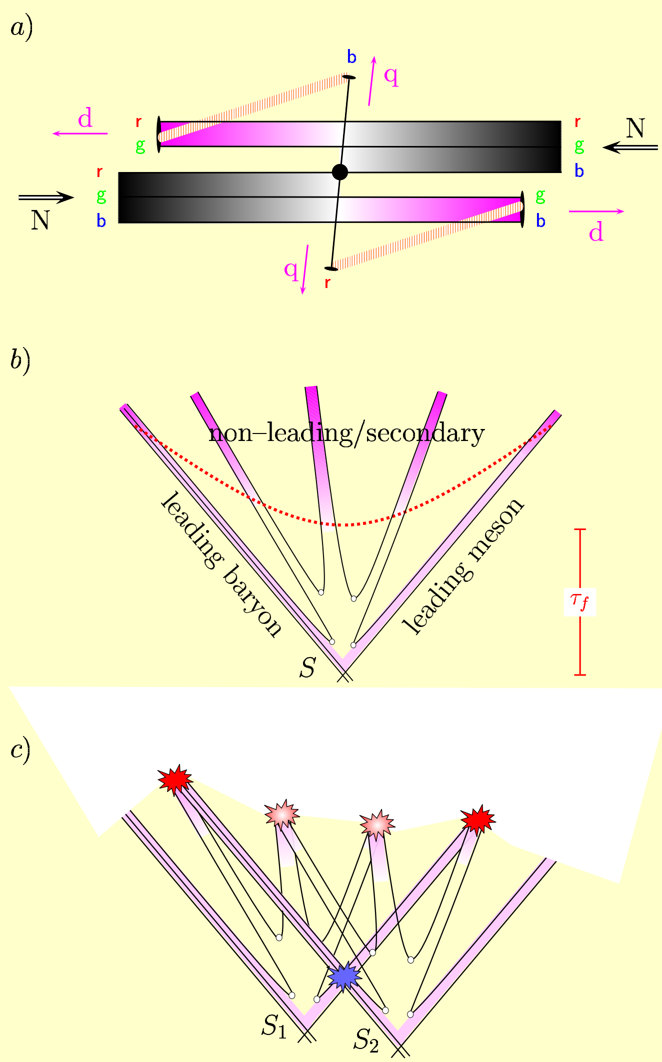


The space-time picture of the string dynamics: at given τ (hyperbola) the velocities of the string pieces (arrows) point all back to the origin and are larger towards the edges. This string decay provides a flat rapidity distribution.



Hadron-String-Dynamics (HSD) approach

W. Cassing, E. Bratkovskaya, Phys. Rep. 308 (1999) 65
W. Cassing et al., hep-ph/0311358



Schematic picture of N + N collision

Model features

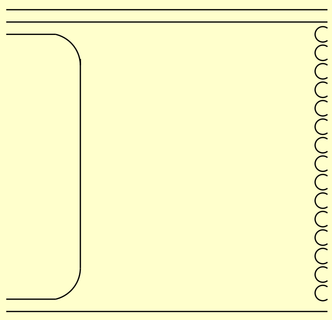
- **baryons:** $\mathbf{N, \Delta, N^*(1440), N^*(1535), \Lambda, \Sigma, \Sigma^*, \Xi, \Xi^*, \Omega}$ + anti-states;
- **mesons:** $0^-, 1^-$ octet states;
- hh @ $\sqrt{s} \geq 2.6\,GeV$: FRITIOF + PYTHIA(5.5) + JETSET(7.3);
- **lower energies** : in line with experimental cross sections;
- **very high momentum tail** : PYTHIA(6.2);
- formation time $\tau_f \approx 0.8\,\mathrm{fm}$;
- o explicit parton cascading

Dual Topological Unitarization Models

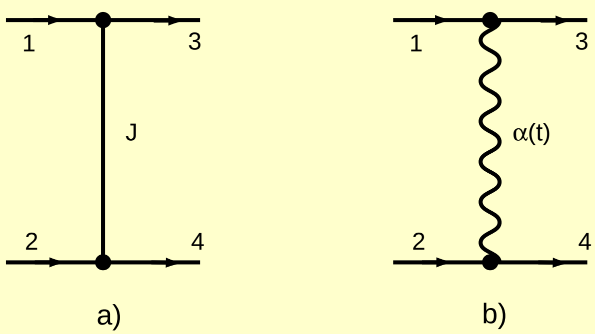
These models are based on Gribov-Regge field theory (color exchange)

Planar digram

In hh interactions a one-string mechanism (with quark-antiquark annihilation) is possible in $p\bar{p}$ collisions but not in pp

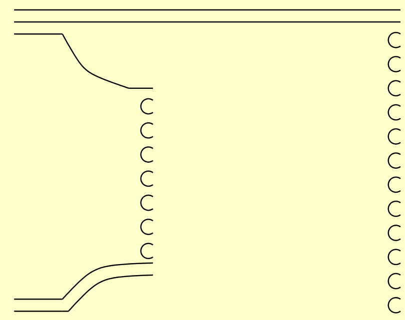


Such a diagram corresponds to the Reggeon exchange in the GRT (weight $\propto \mathbf{1/N}$; contribution $\propto \mathbf{s^{-1/2}}$)

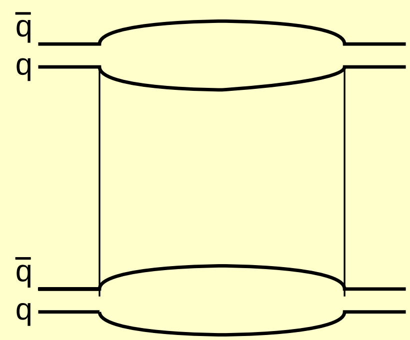


Cylinder digram

The simplest topology which contribution does not vanish at $\mathbf{s} \to \infty$ is a two-string diagram



Such a diagram corresponds to the Pomeron exchange in the GRT (weight $\propto \mathbf{1/N^2}$). Its square has the topology of a cylinder



Hard processes and multipomeron exchanges

The inelastic *hh* cross section $\sigma_{in}(s)$ can be calculated via the real part of the eikonal $u(s, b)$

$$\sigma_{in}(s) = 2\pi \int_0^\infty \left\{1 - \exp\left[-2u^R(s,b)\right]\right\} bdb$$

The eikonal can be presented as a sum of three terms corresponding to soft and hard Pomeron exchange, and triple Pomeron exchange, which is responsible for the single diffraction process,

$$u^R(s,b) = u^R_{soft}(s,b) + u^R_{hard}(s,b) + u^R_{triple}(s,b)$$

Using the Abramovskii-Gribov-Kancheli (AGK) cutting rules we get

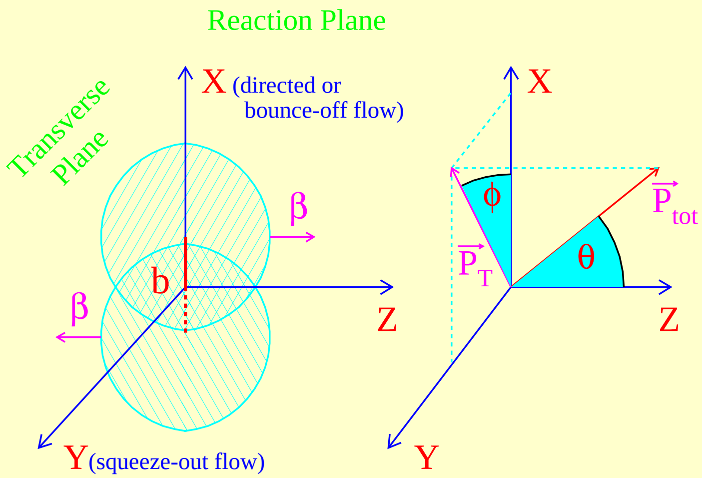
$$\sigma_{in}(s) = \sum_{i,j,k=0;i+j+k\geq 1} \sigma_{ijk}(s) \ ,$$

$$\sigma_{ijk}(s) = 2\pi \int_0^\infty bdb \exp\left[-2u^R(s,b)\right]$$

$$\times \frac{\left[2u^R_{soft}(s,b)\right]^i}{i!} \frac{\left[2u^R_{hard}(s,b)\right]^j}{j!} \frac{\left[2u^R_{triple}(s,b)\right]^k}{k!} \ .$$

The last equation enables one to determine the number of strings and hard jets.

Transverse Collective Flow of Particles



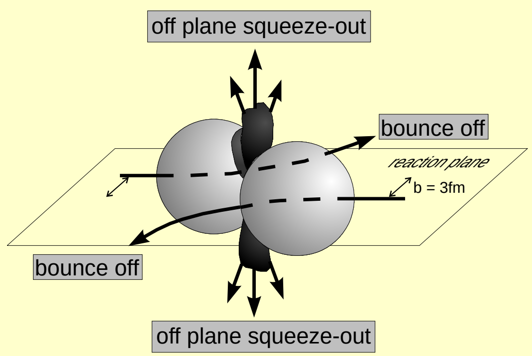
Flow Decomposition:

Transverse flow = Radial + Bounce-off + Squeeze-out

S. Voloshin and Y. Zhang, ZPC 70 (1996) 665

Modern analysis:

Transverse flow =
Radial + Directed + Elliptic + . . .
{isotropic} {anisotropic}



$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n\phi')\right)$$

Directed flow:

$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle \equiv \langle \cos(\phi') \rangle$$

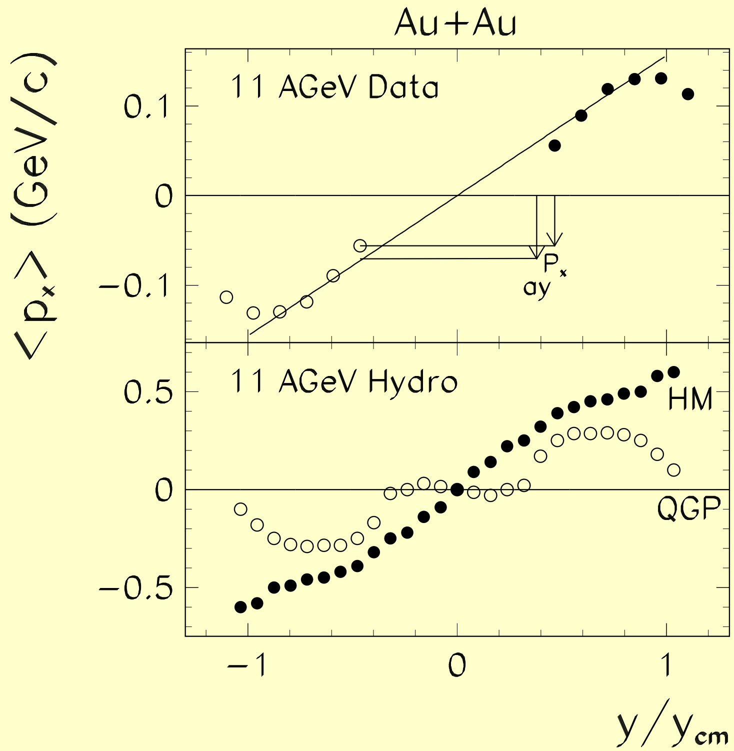
Elliptic flow:

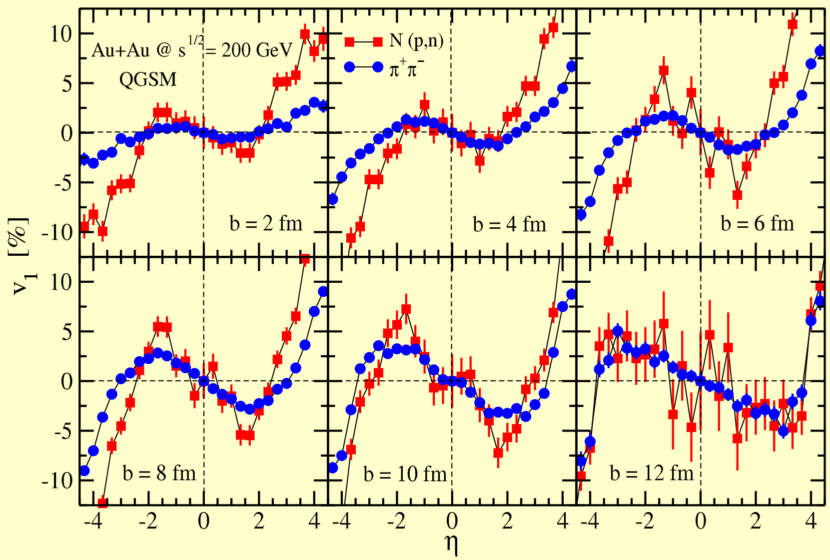
$$v_2 = \left\langle \left(\frac{p_x}{p_T}\right)^2 - \left(\frac{p_y}{p_T}\right)^2 \right\rangle \equiv \langle \cos(2\phi') \rangle$$

Softening of Directed Flow

L.P. Csernai, D. Röhrich, PLB 458 (1999) 454

L. Bravina, PLB 334 (1995) 49
H. Liu, S. Panitkin, N. Xu, PRC 59 (1999) 348
R.J.M. Snellings *et al.*, PRL 84 (2000) 2803
G. Burau *et al.*, PRC 71 (2005) 054905





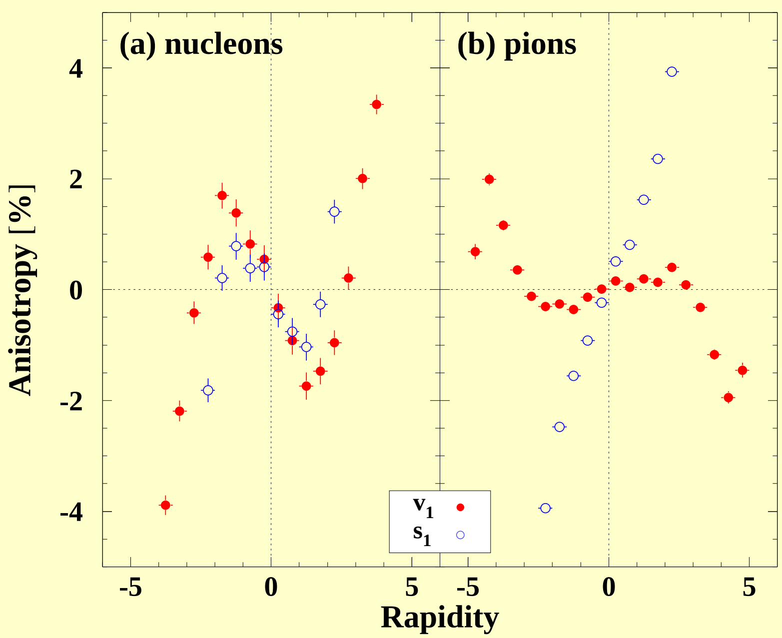
Transition to the Quark-Gluon Plasma $\longrightarrow$ decrease in pressure $\longrightarrow$ softening of the directed flow

Wiggle structure: The effect is more pronounced in peripheral and light-ion collisions, therefore, it cannot be explained by the softening of the EOS because of the formation of strings QGSM calculations for Au+Au at $\sqrt{s} = 200$ AGeV)

Directed Flow at RHIC

R.J.M. Snellings *et al.*, PRL 84 (2000) 2803

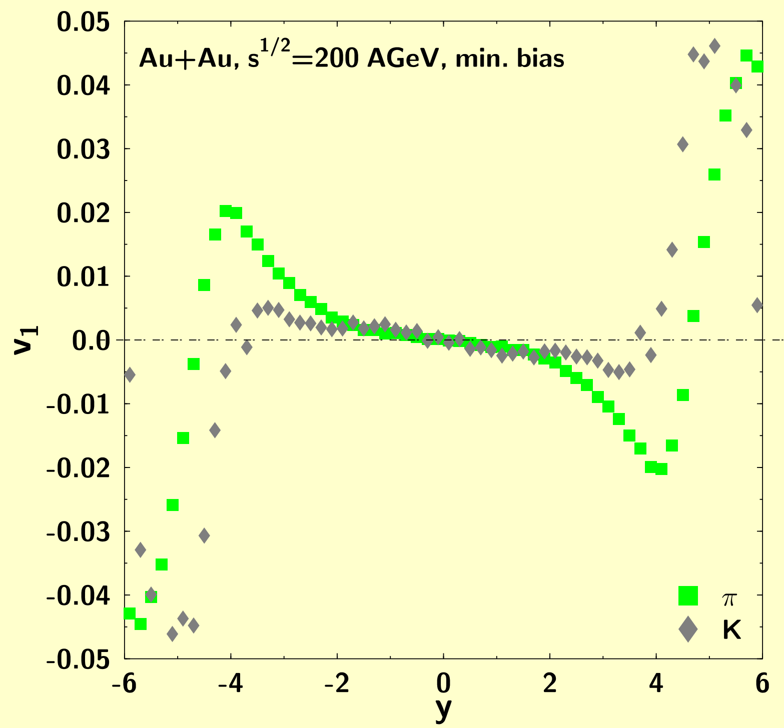
Rapidity dependence of the v_1 of π, N



RQMD calculations for Au+Au at $\sqrt{s} = 200$ AGeV $(5fm \leq b \leq 10fm)$

M. Bleicher and H. Stöcker, PLB 526 (2002) 309

Rapidity dependence of the v_1 of π, K



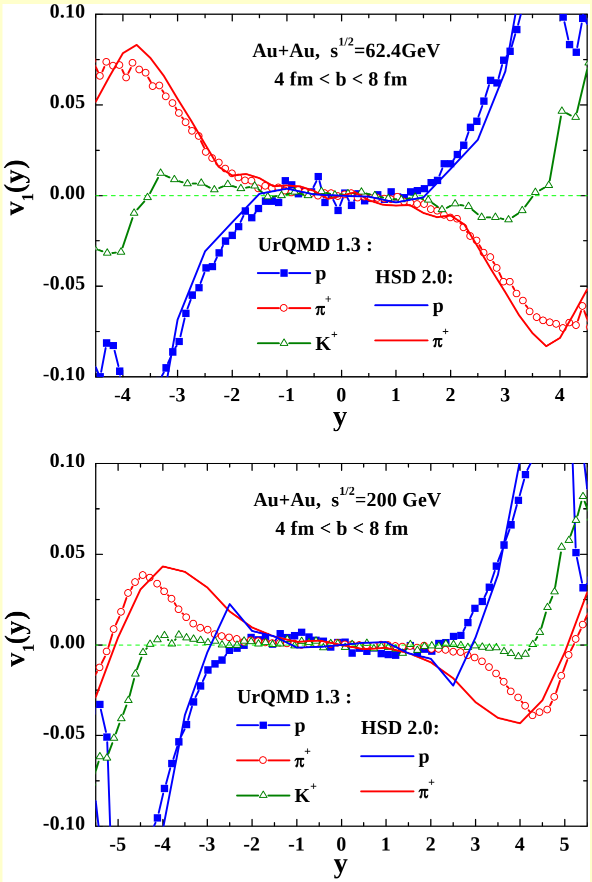
UrQMD calculations for Au+Au at $\sqrt{s} = 200$ AGeV (minimum bias events)

Antiflow / vanishing of flow at midrapidity

Directed Flow at RHIC

H. Stöcker *et al.*, nucl-th/0412022

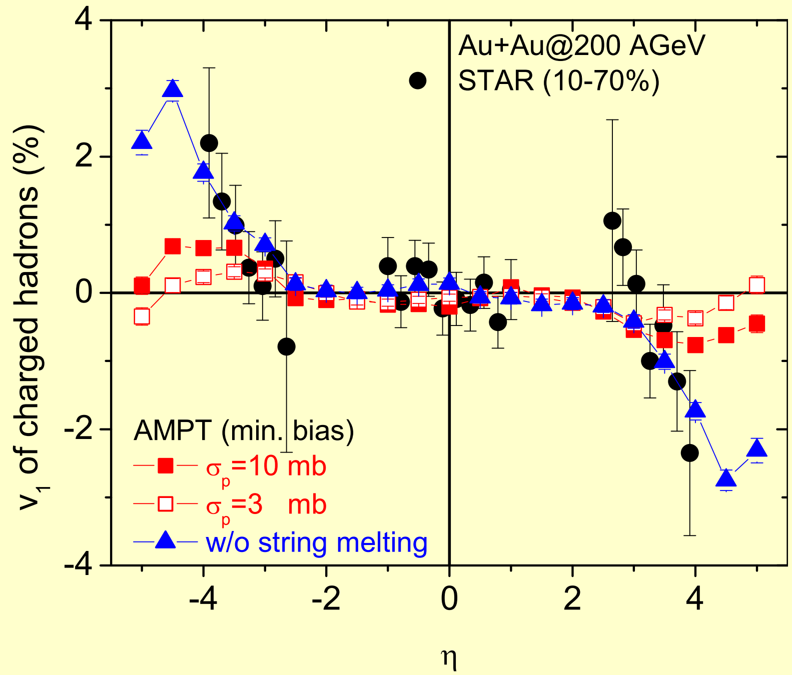
Rapidity dependence of the v_1



UrQMD and HSD calculations for Au+Au at $\sqrt{s} = 200$ AGeV $(4fm \leq b \leq 8fm)$

L.-W. Chen, V. Greco, C.M. Ko, P.F. Kolb, PLB 605, 95 (2005)

Rapidity dependence of the v_1 of charged hadrons

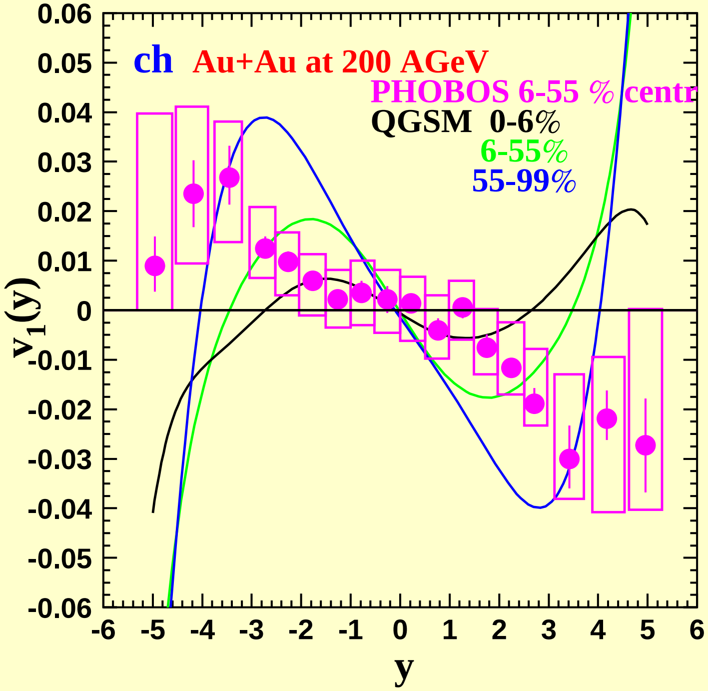


AMPT calculations for Au+Au at $\sqrt{s} = 200$ AGeV (minimum bias events)

Directed Flow at RHIC

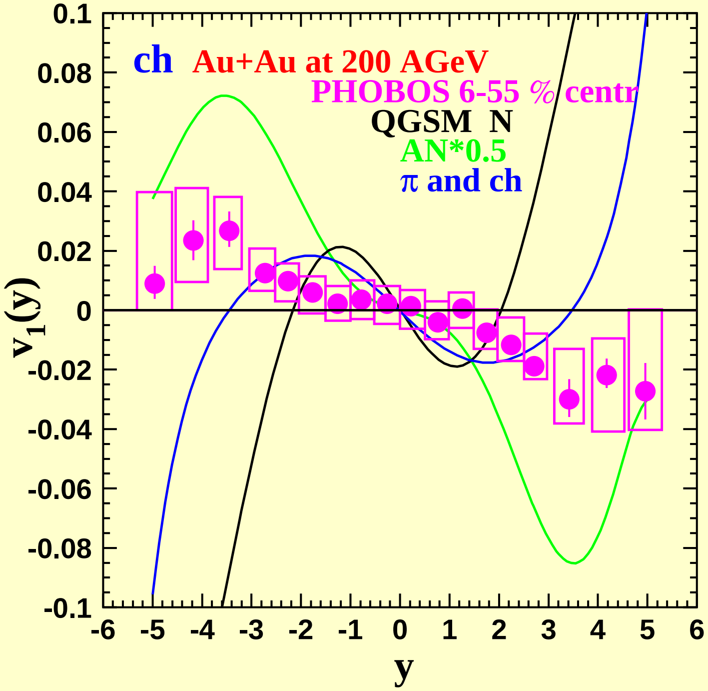
M.B. Tonjes *et al.* (PHOBOS Collab.), JPG 30 (2004) 1243

Centrality dependence of the DF of charged particles in QGSM



(1) DF increases with rising b
(2) Exp.: antiflow increases up to fragmentation regions

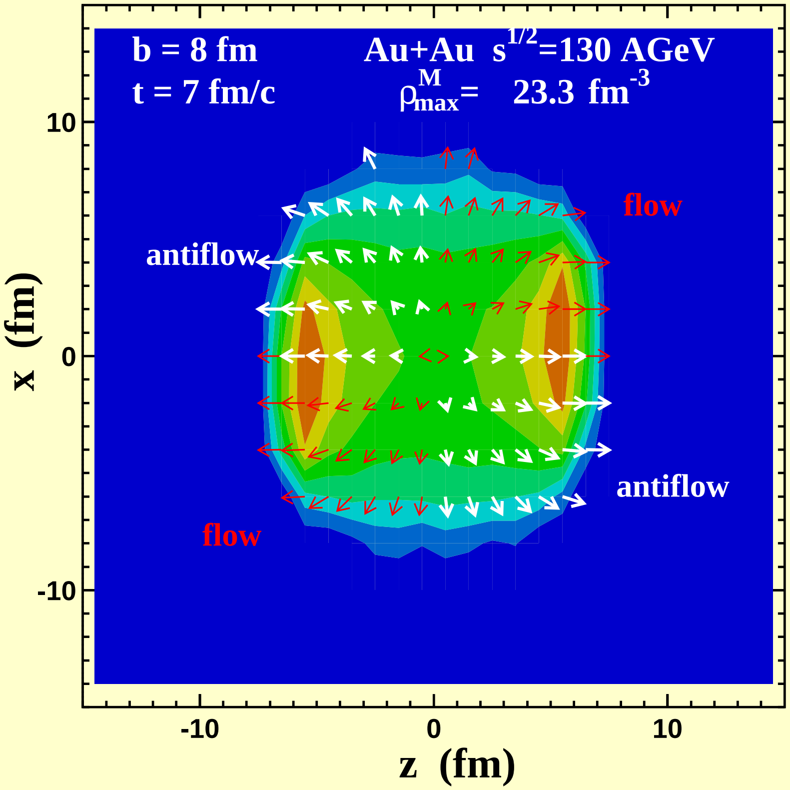
Directed flow of different species



Antibaryons have strongest antiflow because of annihilation

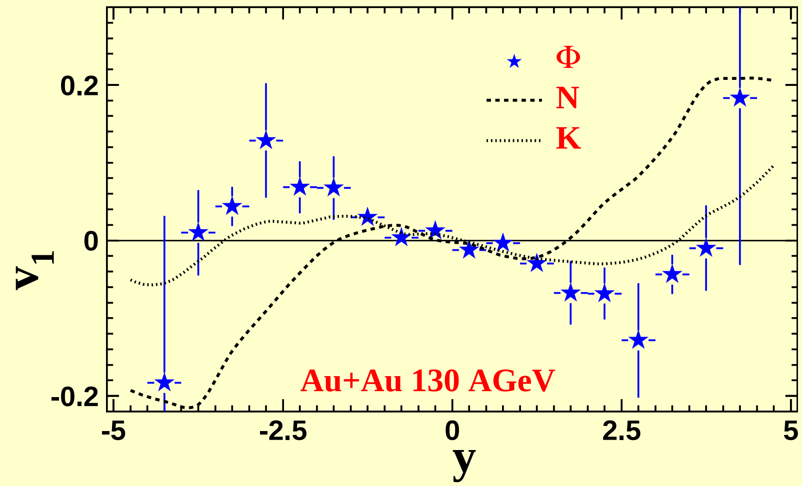
Development of Directed Flow

Resulting flow = normal flow - antiflow



L. Bravina *et al.*, NPA 715 (2003) 665c

Directed flow $v_1(y, all\ p_t)$ of ϕ, N, K in minimum bias Au+Au events at $\sqrt{s} = 130$ AGeV



Although the normal flow component is always slightly larger than the antiflow one, in central rapidity window the anti-flow can overshadow its normal counter-part

Directed flow of ϕ mesons $v_1(y)$ has negative slope (antiflow) at $|y| \leq 2$. This distribution is similar to those of other hadrons at $|y| \leq 2$ in $Au + Au$ at $\sqrt{s} = 130$ AGeV because of similarities of their production and dynamics

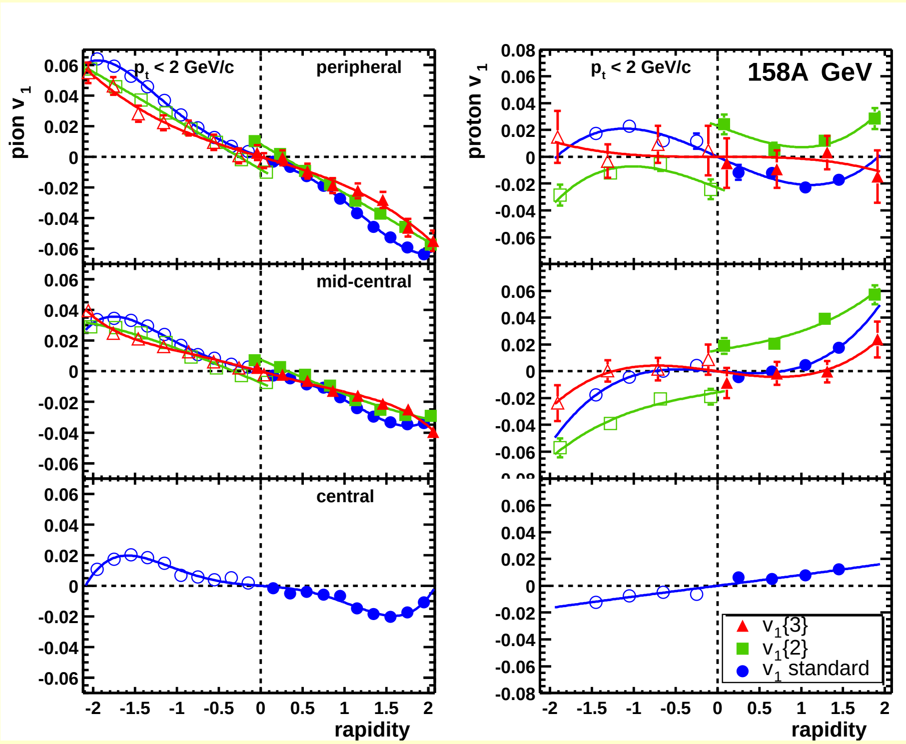
Directed Flow at SPS

C. Alt *et al.* (NA49 Collab.), PRC 68 (2003) 034903

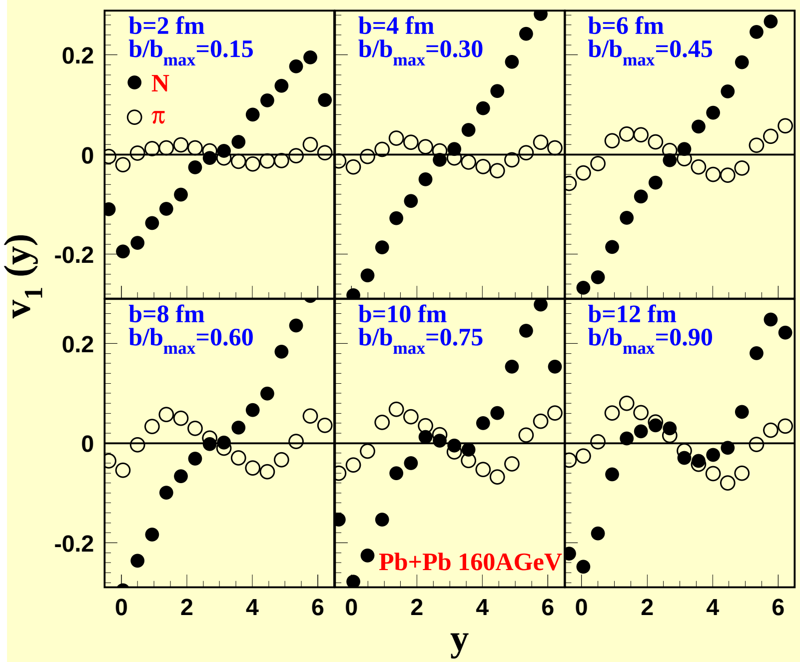
Rapidity dependence of the v_1 of π, p

L. Bravina *et al.*, PRC 61 (2000) 064902

Rapidity dependence of the v_1 of π, N



NA49 Collaboration results for Pb+Pb at 158 AGeV ($p_t \le 2\,GeV$)

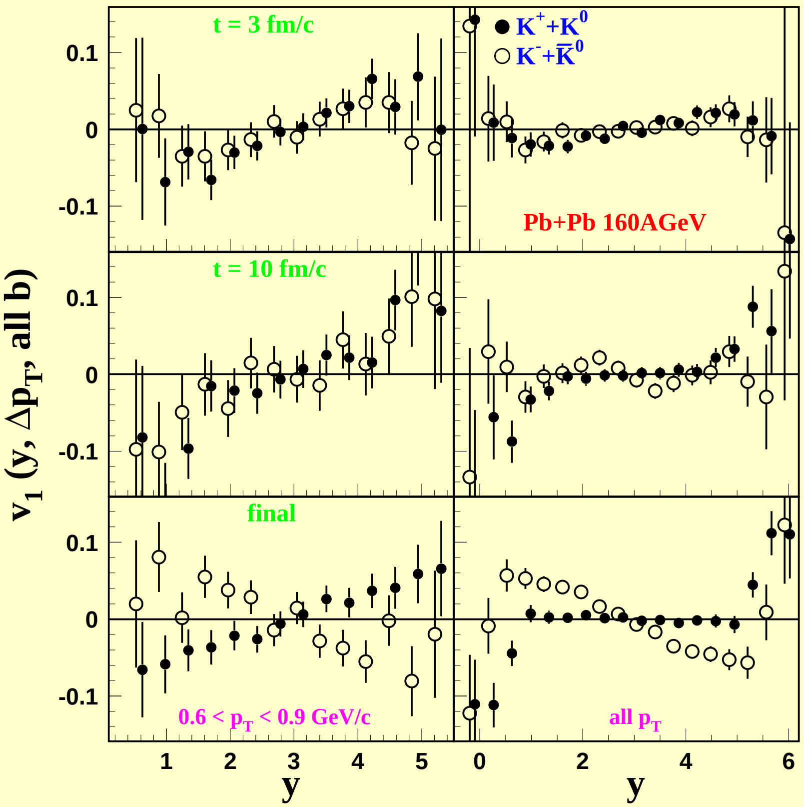


QGSM calculations for Pb+Pb at 158 AGeV

P_T Dependence of Directed Flow

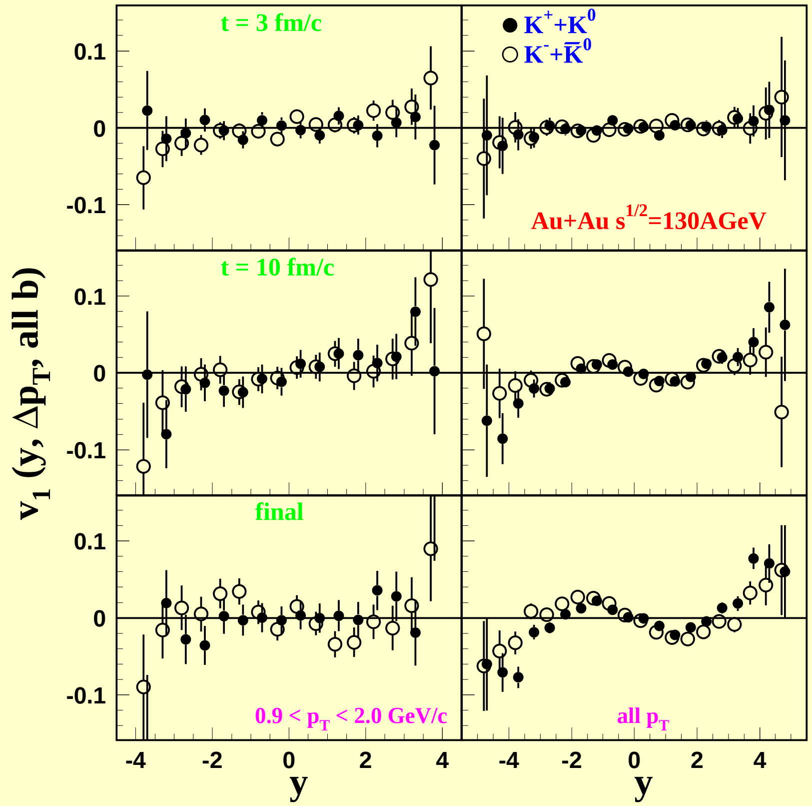
L. Bravina, L. Csernai, A. Faessler, C. Fuchs, E. Z., PLB 543 (2002) 217

Kaon flow at SPS



Strong difference between kaons and antikaons

Kaon flow at RHIC



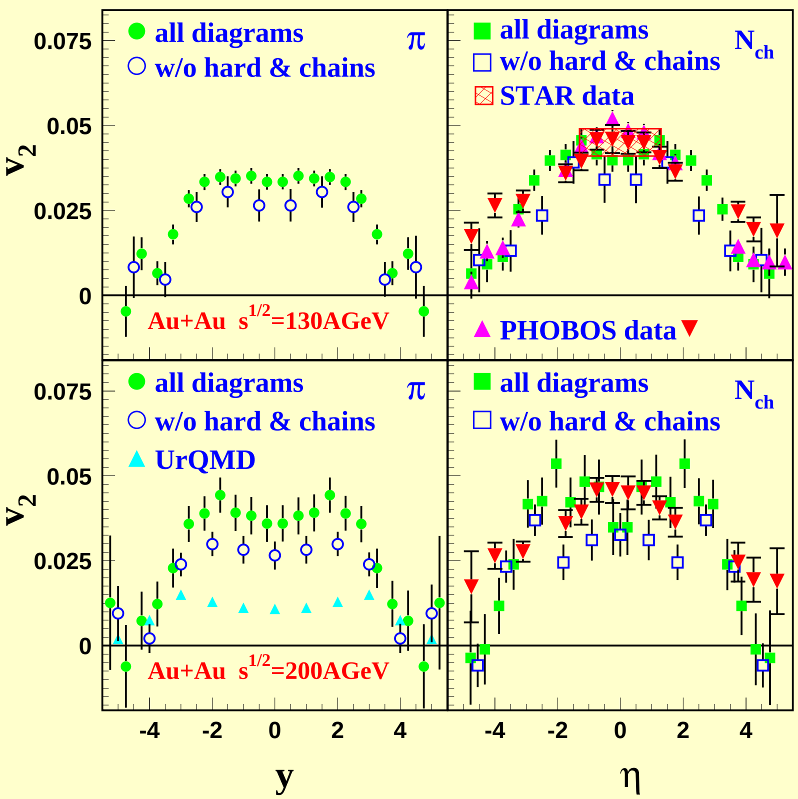
No difference between kaons and antikaons

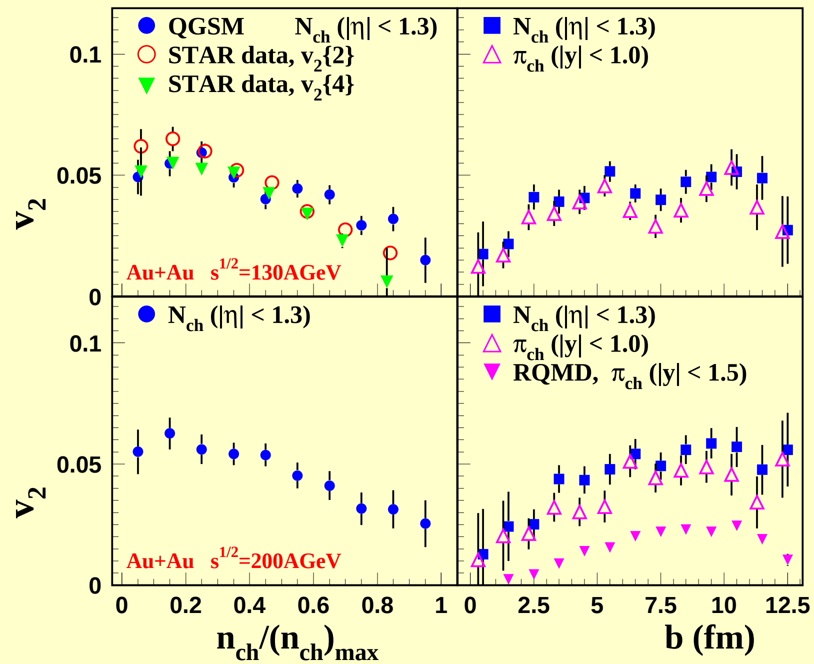
Directed Flow (Conclusions):

- Microscopic models reproduce, at least qualitatively, basic features of the v_1 development
- Directed Flow = Normal Flow − Antiflow
  Normal Flow $\geq$ Antiflow (except of the midrapidity range)
- The softening of the flow may be misinterpreted as the softening of EOS due to formation of the QGP, but:
  QGP $\rightarrow$ the effect is stronger for semi-central collisions
  Cascade $\rightarrow$ the effect is stronger for semi-peripheral and peripheral ones
- At RHIC: The directed flow of both mesons and baryons is zero or antiflow-oriented at $|y| \leq 2$
- The directed flow of high-p_t hadrons is elongated in normal direction

Elliptic Flow at RHIC

E. Z., L. Bravina, A. Faessler, C. Fuchs, PLB 508 (2001) 184
PPNP 53 (2004) 183
M. Bleicher and H. Stöcker, PLB 526 (2002) 309
S. Manly *et al.* (PHOBOS Collab.), NPA 715 (2003) 614c

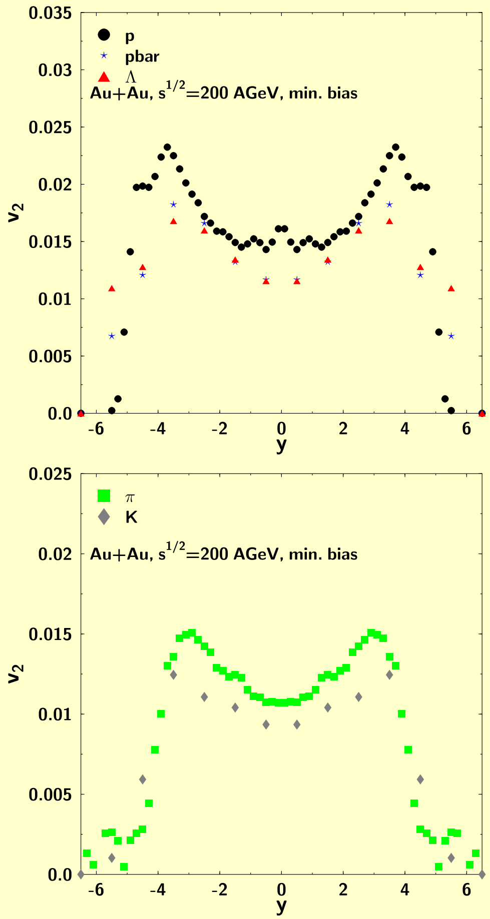




(Pseudo)rapidity dependencies of the elliptic flow of charged particles in the whole η range at both energies were obtained *before* the experimental data became available

Elliptic Flow at RHIC

M. Bleicher and H. Stöcker, PLB 526 (2002) 309

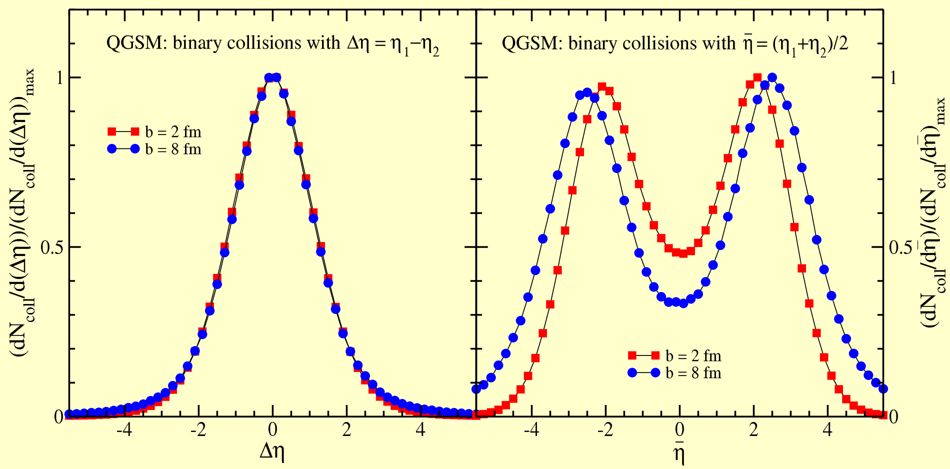


UrQMD calculations for Au+Au at $\sqrt{s} = 200$ AGeV (minimum bias events)

Origin of the two-hump structure

G. Burau *et al.*, PRC 71 (2005) 054905

The number of binary particle collisions per pseudorapidity interval normalized to its maximum as function of the pseudorapidity difference $\Delta\eta = \eta_1 - \eta_2$ (left) and the mean pseudorapidity $\bar{\eta} = (\eta_1 + \eta_2)/2$ (right) of the two colliding particles



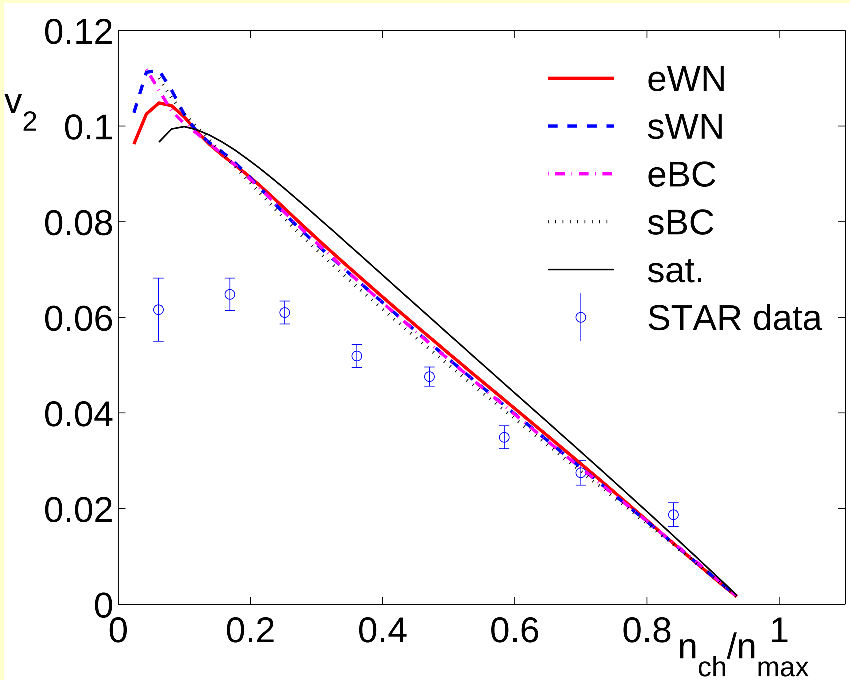
Left: particles with similar rapidities interact most likely

Right: a double peak structure appears in the same rapidity region as seen for the $v_2(\eta)$

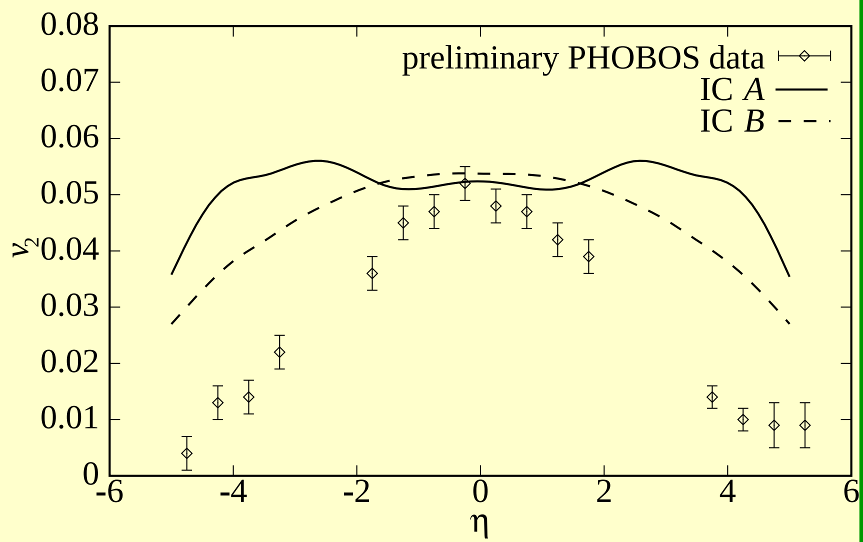
Elliptic Flow at RHIC (Hydro)

P. Huovinen *et al.*, PLB 503 (2001) 58
T. Hirano and K. Tsuda, NPA 715 (2003) 821c

Centrality Dependence



Pseudorapidity Distribution

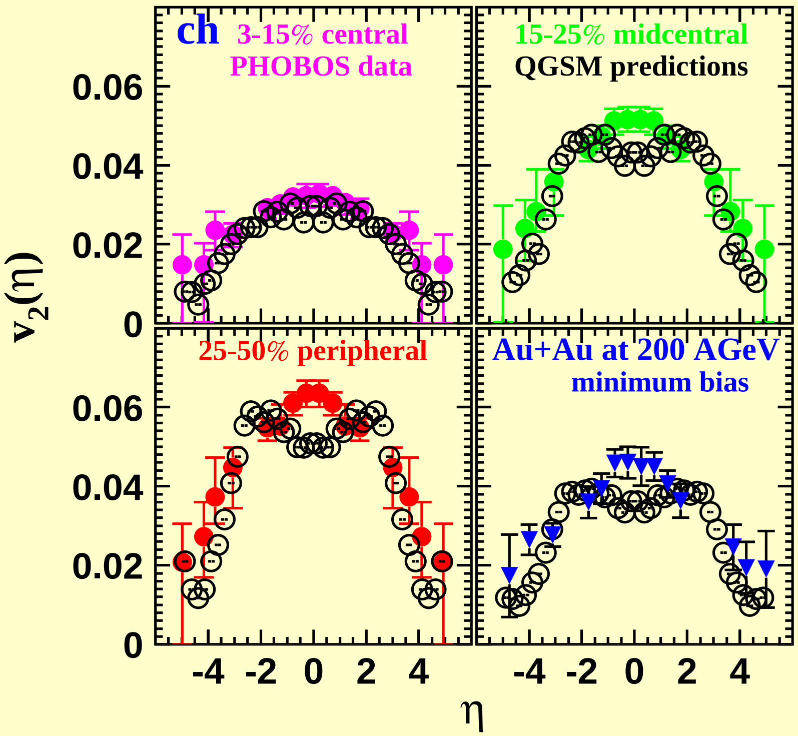


The agreement between the experimental distributions and model simulations is not good.

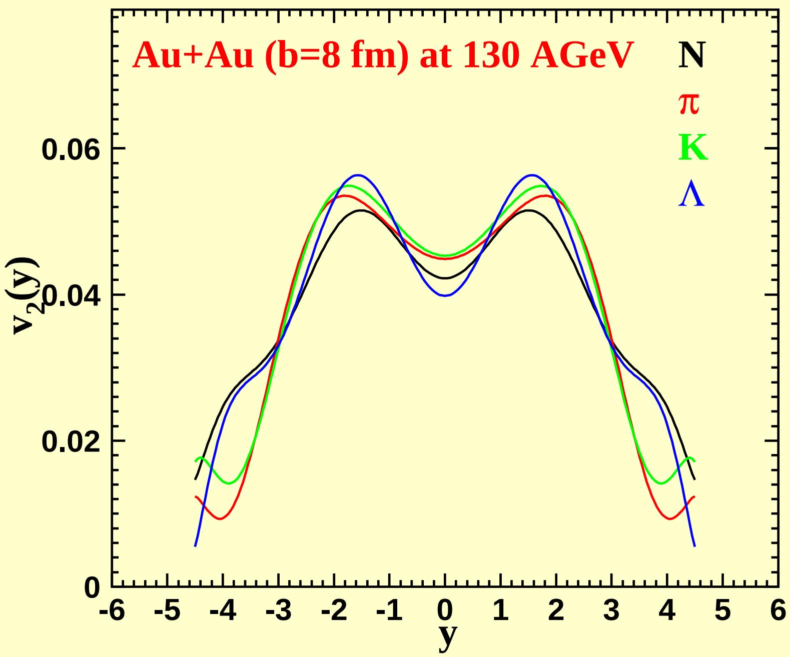
Elliptic Flow at RHIC

B. Back *et al.* (PHOBOS Collab.), nucl-ex/0407012

L. Bravina *et al.*, hep-ph/0412343



Rapidity dependence of the v_2



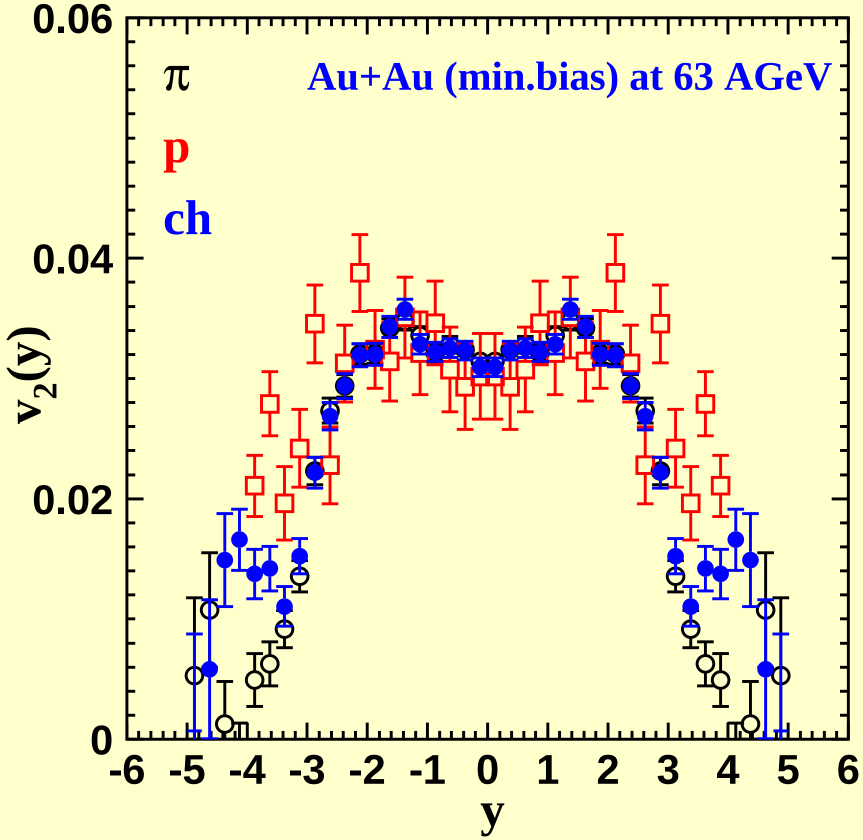
$v_2(\eta)$ of charged hadrons in Au+Au at $\sqrt{s} = 200$ AGeV for (a) $\sigma/\sigma_{geo} = 0 - 15\%$, (b) $\sigma/\sigma_{geo} = 15 - 25\%$, (c) $\sigma/\sigma_{geo} = 25 - 50\%$, and (d) minimum bias events.

$v_2(\eta)$ distribution of π, N, K, Λ in Au+Au at $\sqrt{s} = 200$ AGeV

No difference for different species

Elliptic Flow at RHIC

Rapidity dependence of v_2 in Au+Au at $\sqrt{s} = 63$ AGeV

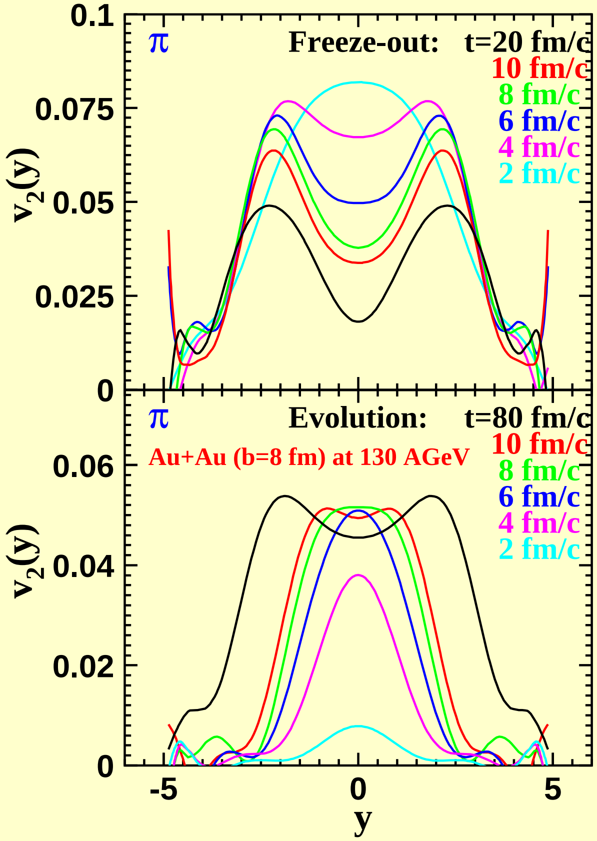


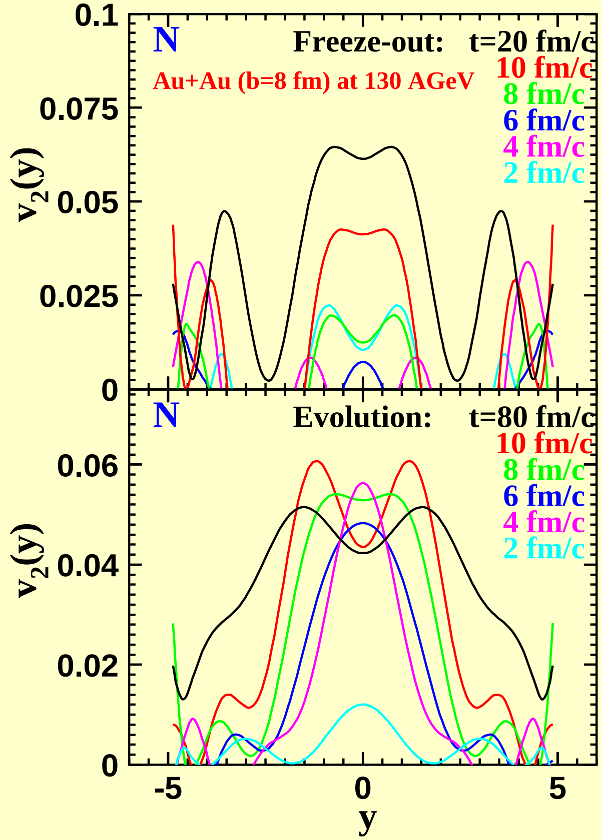
(1) No difference for different species

(2) The flow is only slightly weaker than that at 200 AGeV

Time Evolution of the Elliptic Flow

PIONS (Au+Au, 130 AGeV, b=8 fm) **NUCLEONS**

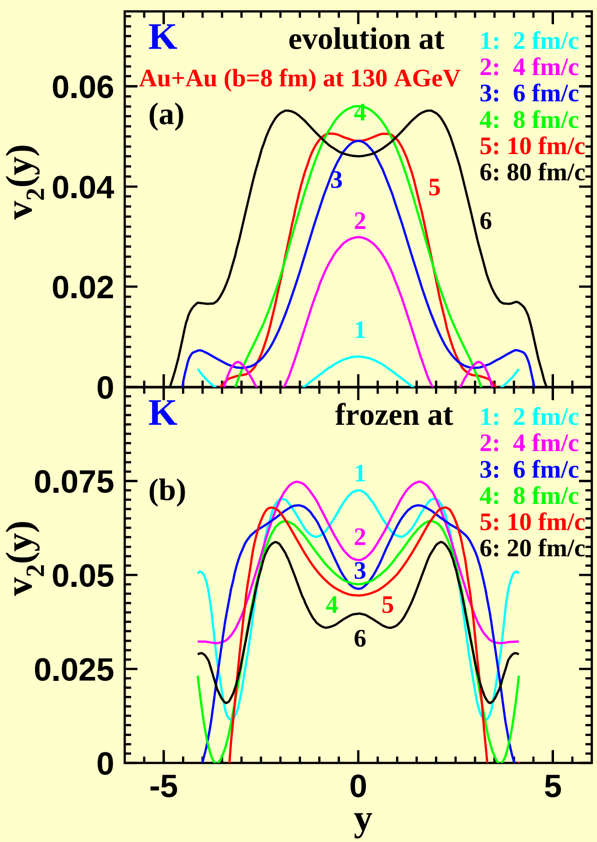


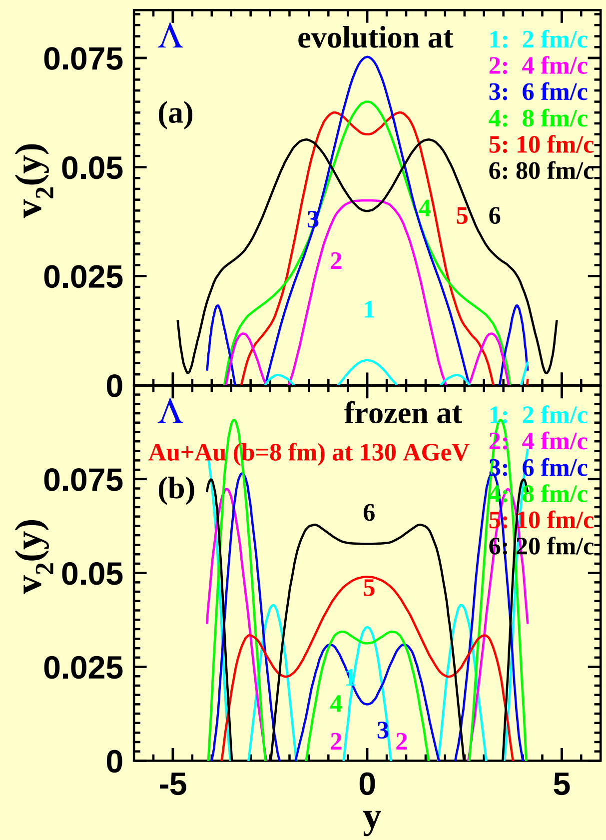


(1) The earlier the freeze-out of pions, the stronger their elliptic flow
(2) The later the freeze-out of nucleons, the stronger their elliptic flow
(3) The flow formation is not over e.g. at $t = 6$ fm/c due to continuous freeze-out of particles

Time Evolution of the Elliptic Flow

KAONS (Au+Au, 130 AGeV, b=8 fm) **LAMBDAS**





(1) The earlier the freeze-out of kaons, the stronger their elliptic flow

(2) The later the freeze-out of lambdas, the stronger their elliptic flow

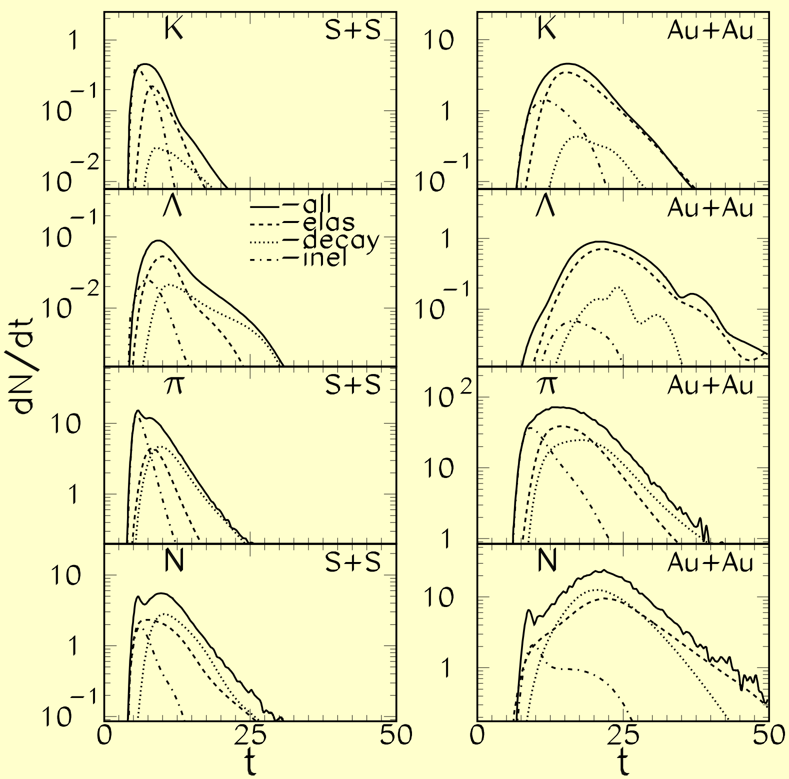
This is the main difference in the formation of the elliptic flow of mesons and baryons

Sequential Freeze-Out

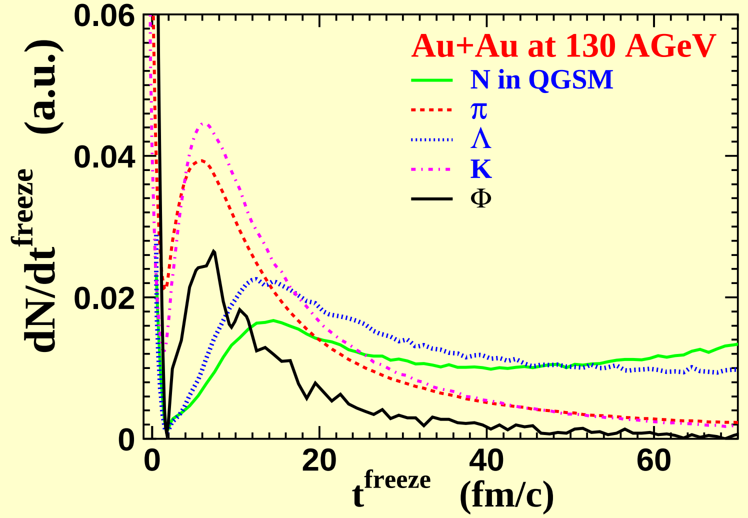
L. Bravina, L. Csernai, *et al.*, PLB 354 (1995) 196

L. Bravina *et al.*, NPA 715 (2003) 665

AGS



RHIC



Freeze-out order: 1 - pions; 2 - kaons; 3 - lambdas; 4 - nucleons

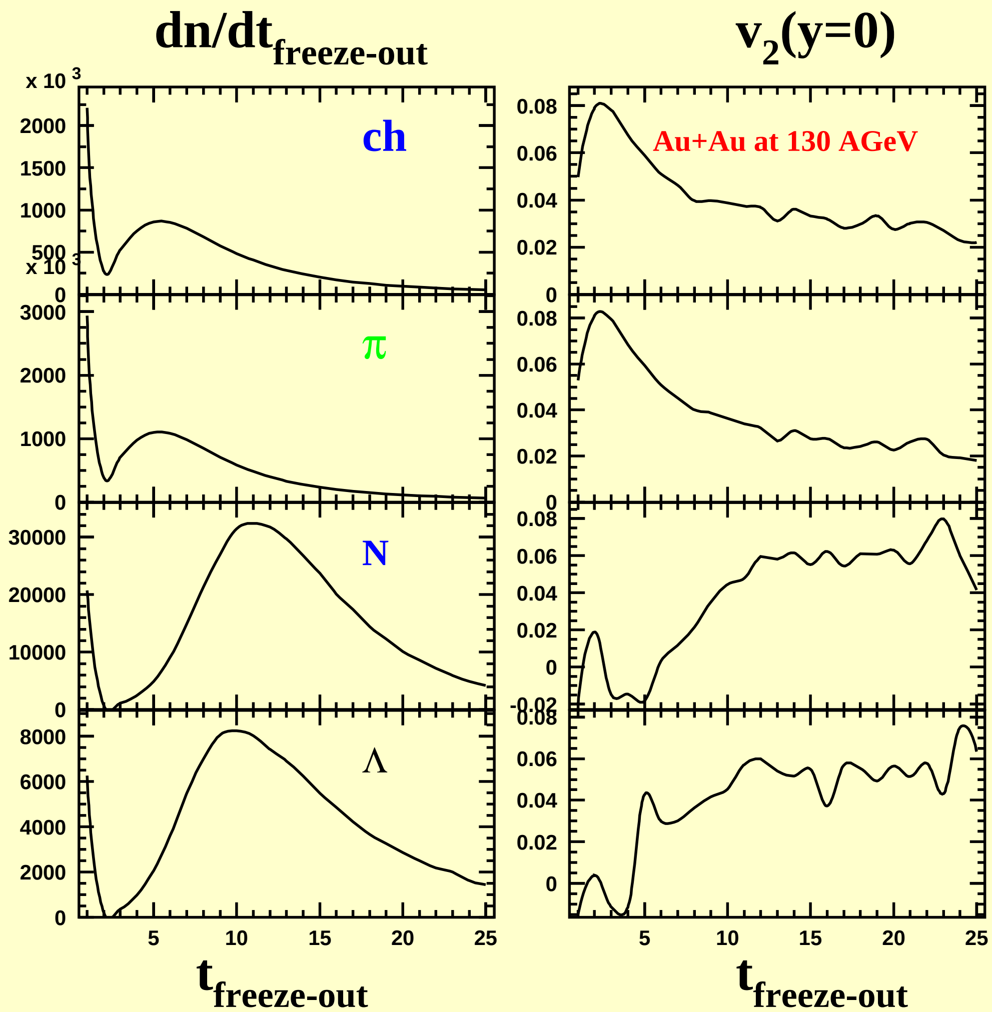
(1) compared to lower energies, many hadrons leave the system immediately after their production

(2) mesonic distributions are peaked at $t = 8 - 10\,\mathbf{fm}/c$

(3) distributions of baryons are wider due to the large number of rescatterings

Freeze-Out and Elliptic Flow

Au+Au (b=8 fm) at $\sqrt{s} = 130$ AGeV

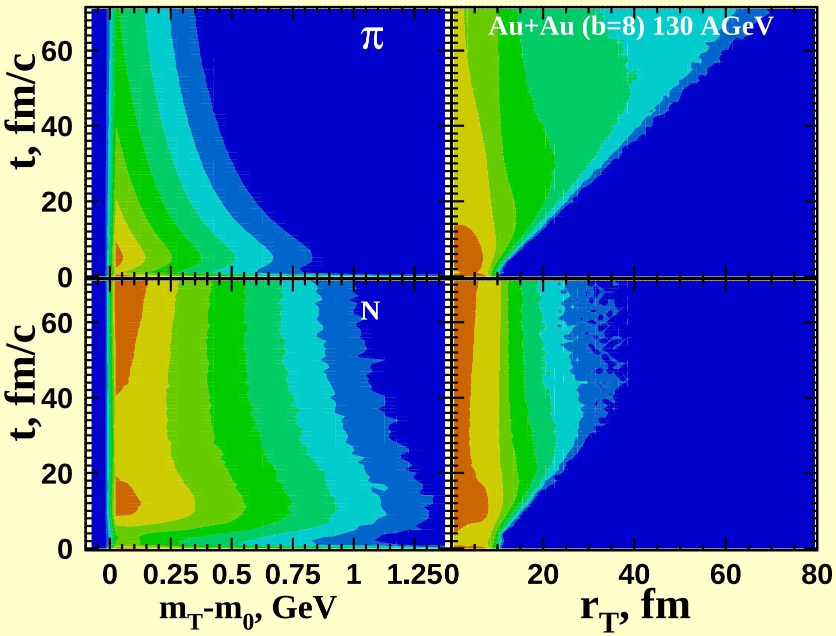


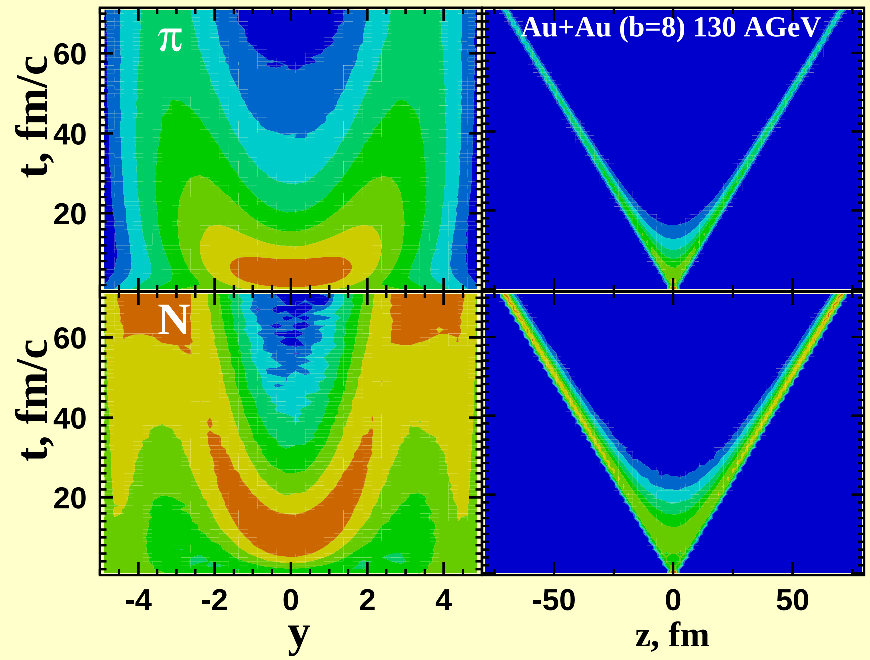
(1) Substantial part of hadrons leaves the system immediately after their production within the first two fm/c.
(2) Baryons and mesons are completely different: pions emitted within the first few fm/c carry the strongest flow. In contrast to pions, the baryon fraction acquires stronger elliptic flow during the subsequent rescatterings, developing the hydro-like flow.

Freeze-Out of Hadrons at RHIC

L. Bravina *et al.*, hep-ph/0412343

Time evolution of m_T and r_T spectra **Rapidity and $z-$ distributions**



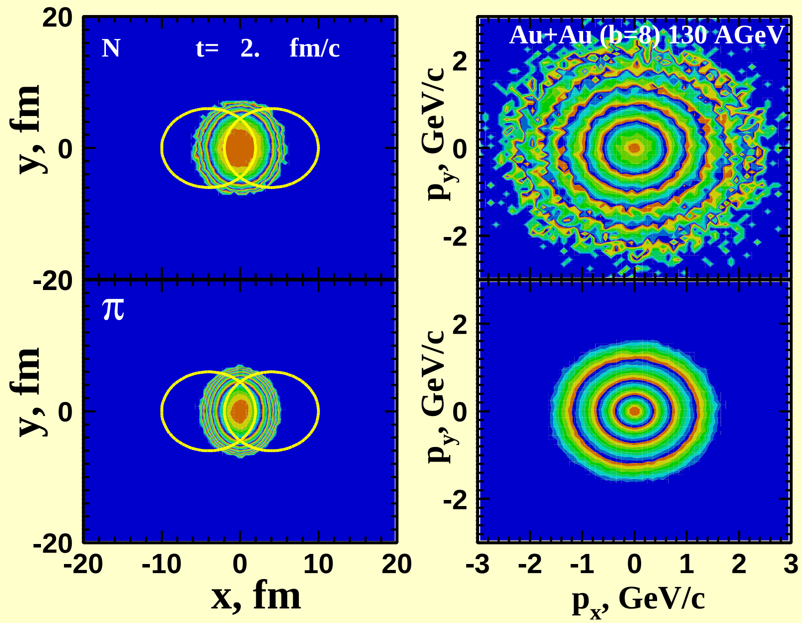


Pions are emitted mainly from the overlapping almond-shaped zone in (x, y)-plane of nuclear collision. As the radial symmetry of this region is restored, the elliptic flow of pions becomes weaker. **Nucleons** are coming both from the overlapping zone and from the spectator regions. This circumstance explains why the v_2^N maintains its strength after $t \approx 12$ fm/c.

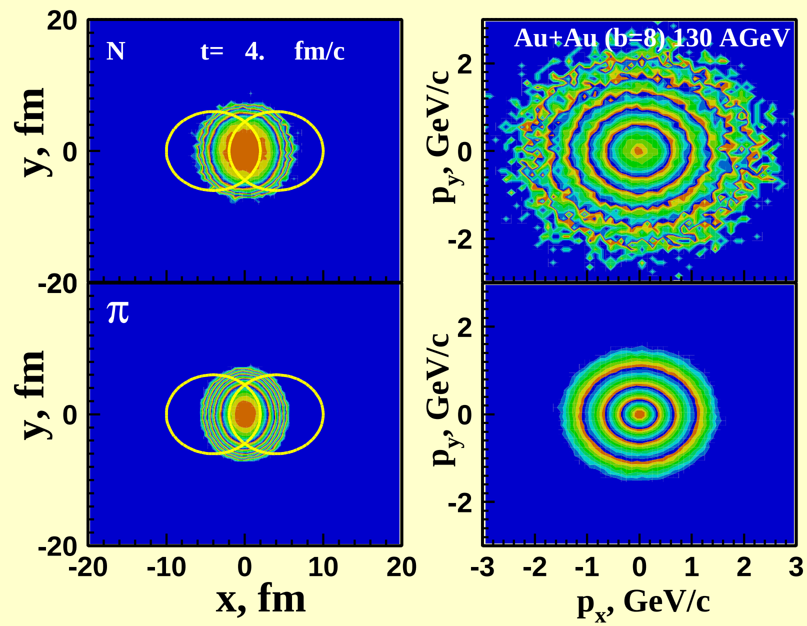
Freeze-out and Elliptic Flow of π, N at RHIC

Anisotropy in coordinate space and elliptic flow of nucleons and pions in Au+Au collisions at $\sqrt{s} = 130$ AGeV with the impact parameter $b = 8$ fm.

$t = 2$ fm/c



$t = 4$ fm/c



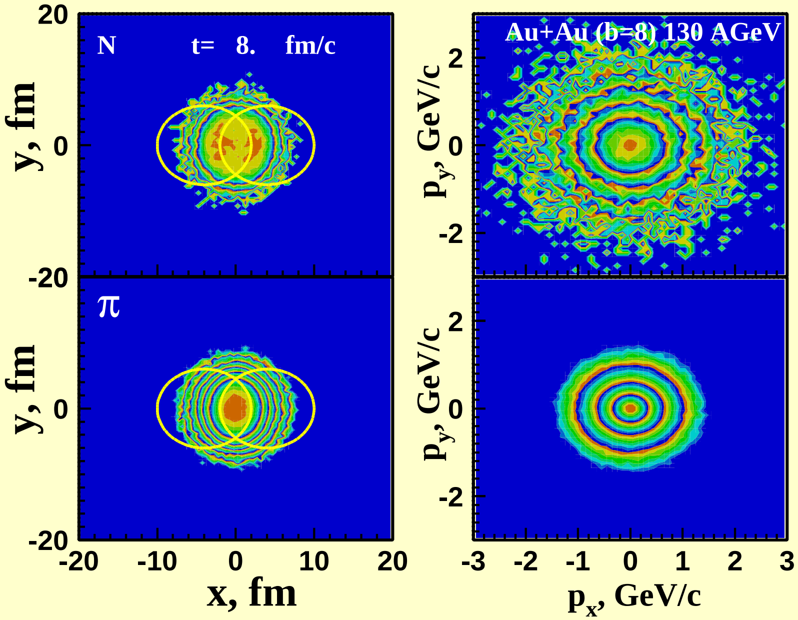
Strong anisotropy in coordinate space, but weak anisotropy in the momentum space

Anisotropy starts to develop in the momentum space for low momenta

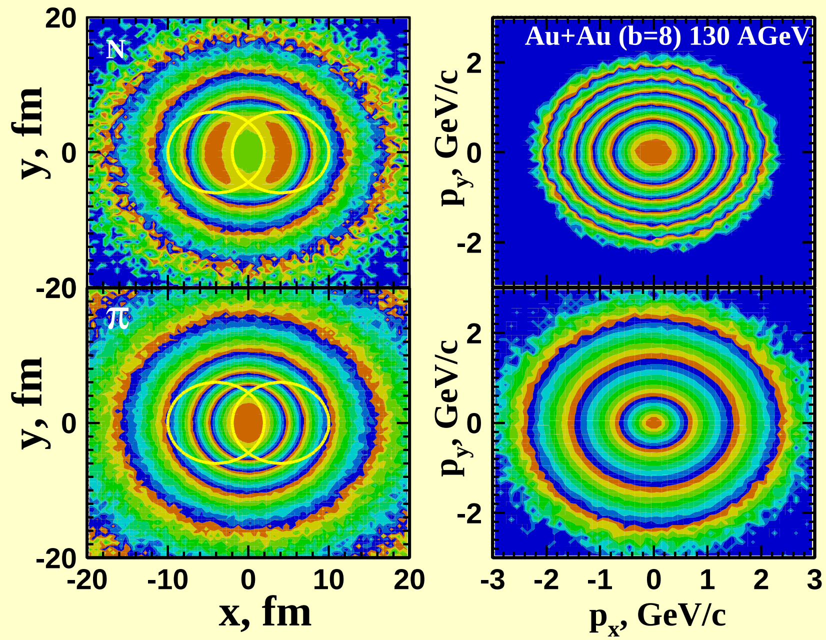
Freeze-out and Elliptic Flow of π, N at RHIC

Anisotropy in coordinate space and elliptic flow of nucleons and pions in Au+Au collisions at $\sqrt{s} = 130$ AGeV with the impact parameter $b = 8$ fm.

$\mathbf{t = 8}$ **fm/**c



final



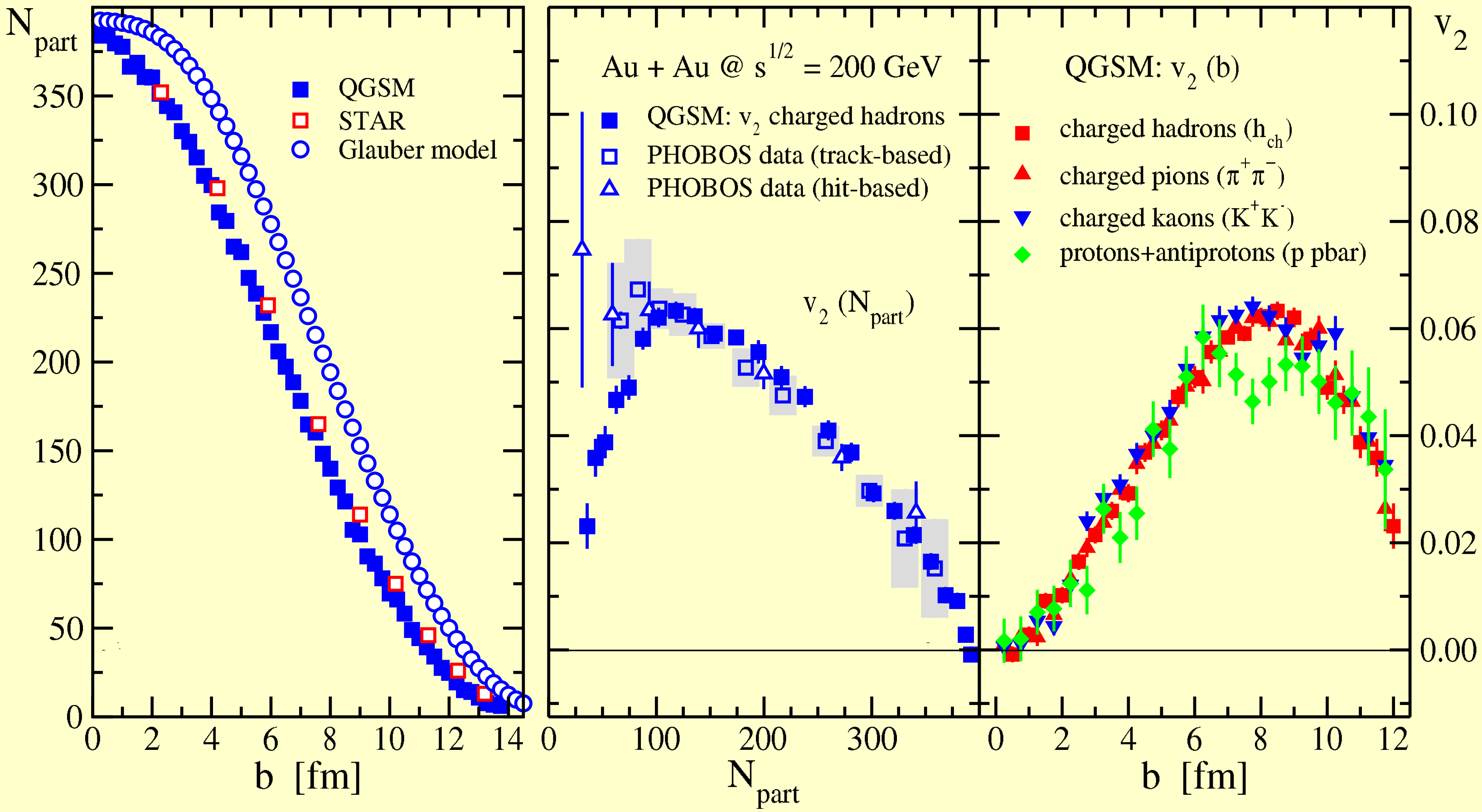
Nucleons leave the overlapping region; at the end of the reaction we see the pronounced maxima at centers of nuclei. Most of the pions is staying within the overlapping area till the end of reaction

The anisotropy in coordinate space (almond-shaped region) is transformed into the anisotropy in the momentum space.

Elliptic Flow at RHIC

G. Burau *et al.*, PRC 71 (2005) 054905
B.B. Back *et al.* (PHOBOS Collab.), nucl-ex/0407012
J. Adams *et al.* (STAR Collab.), nucl-ex/0409033

Centrality dependence of v_2 in Au+Au at $\sqrt{s} = 200$ AGeV

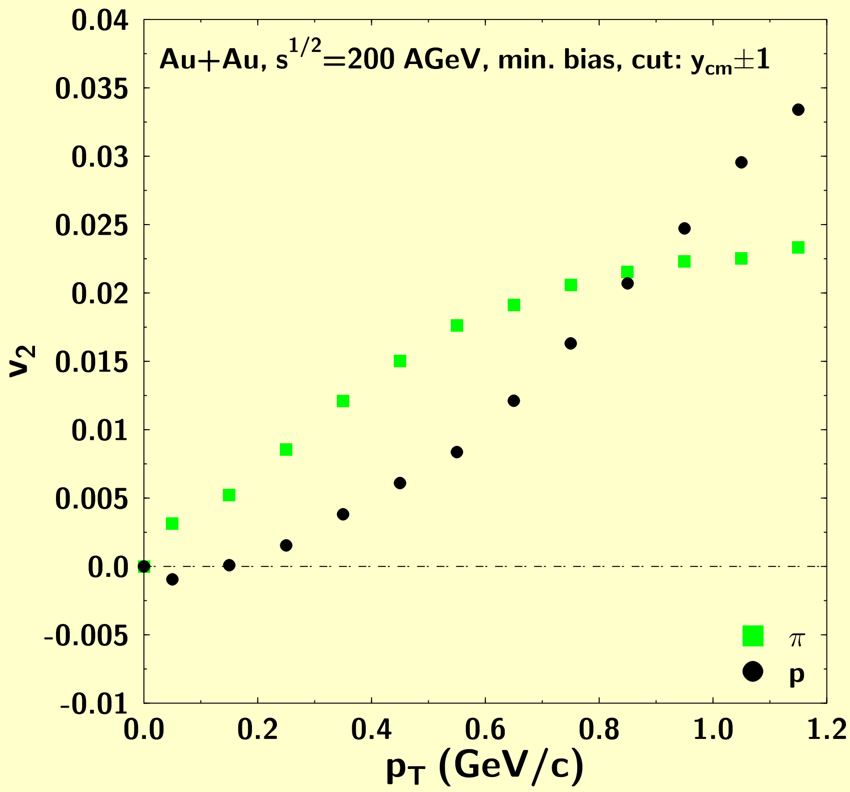


Good agreement between model simulations and experimental data

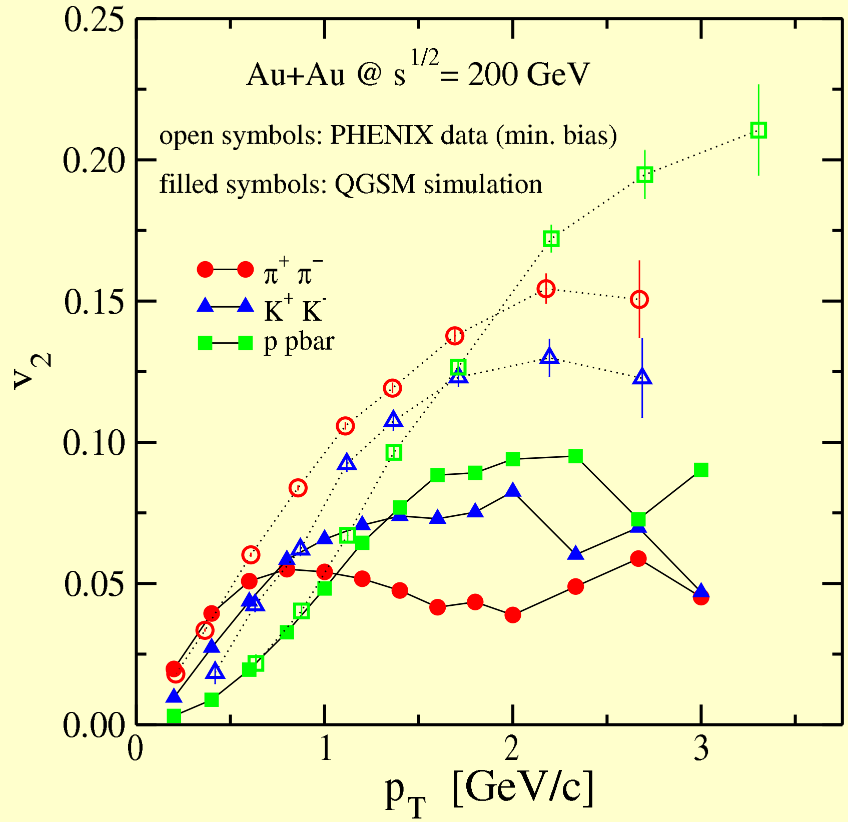
Elliptic Flow at RHIC

Transverse momentum dependence of v_2

M. Bleicher and H. Stöcker, PLB 526 (2002) 309



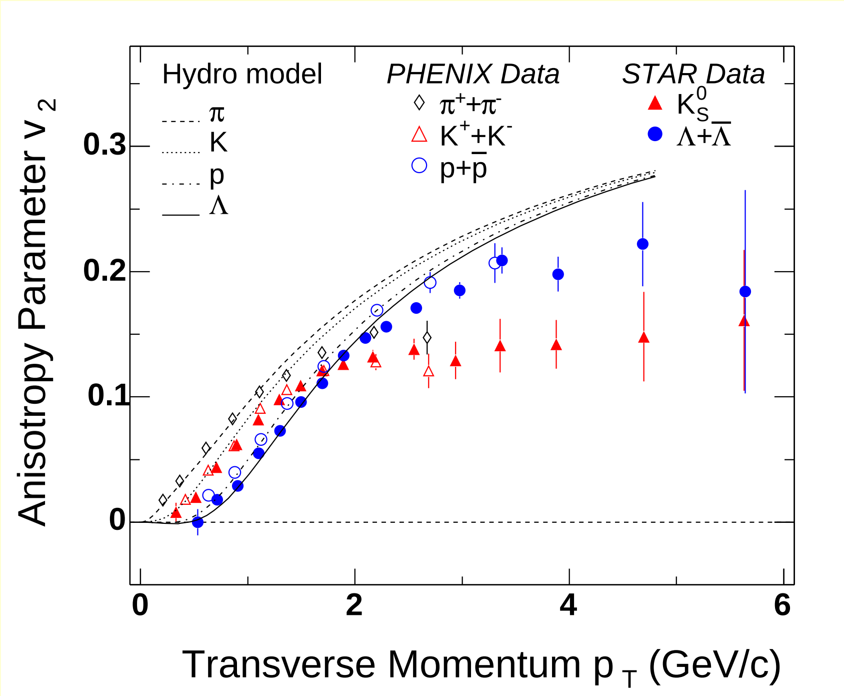
G. Burau *et al.*, PRC 71 (2005) 054905



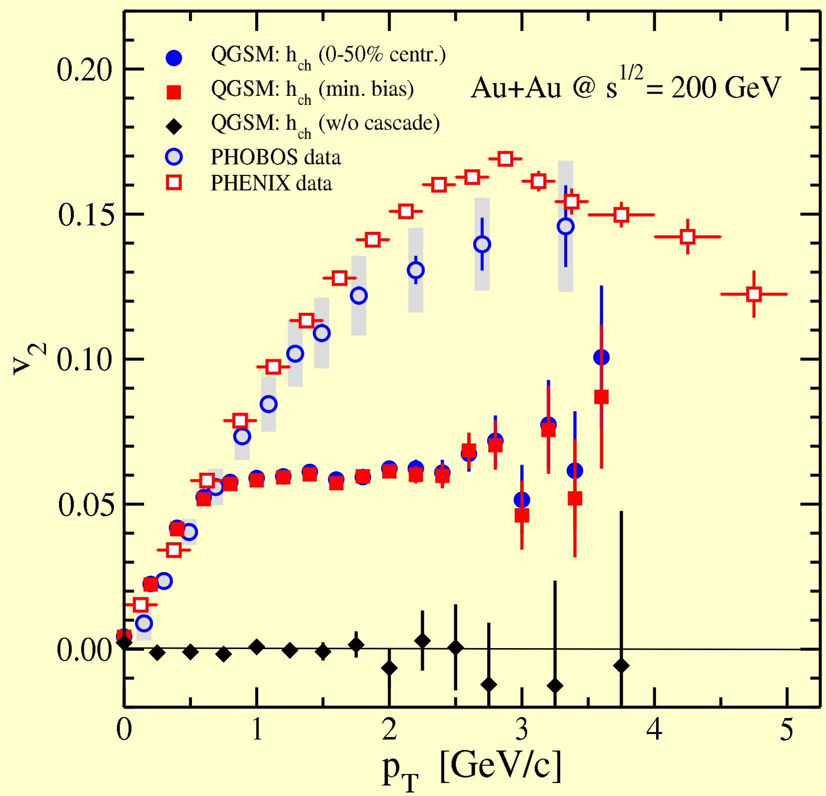
Both UrQMD and QGSM show crossing of the elliptic flow for mesons and baryons. This agrees with the experimental data

Elliptic Flow at RHIC

Hydrodynamics:



QGSM:

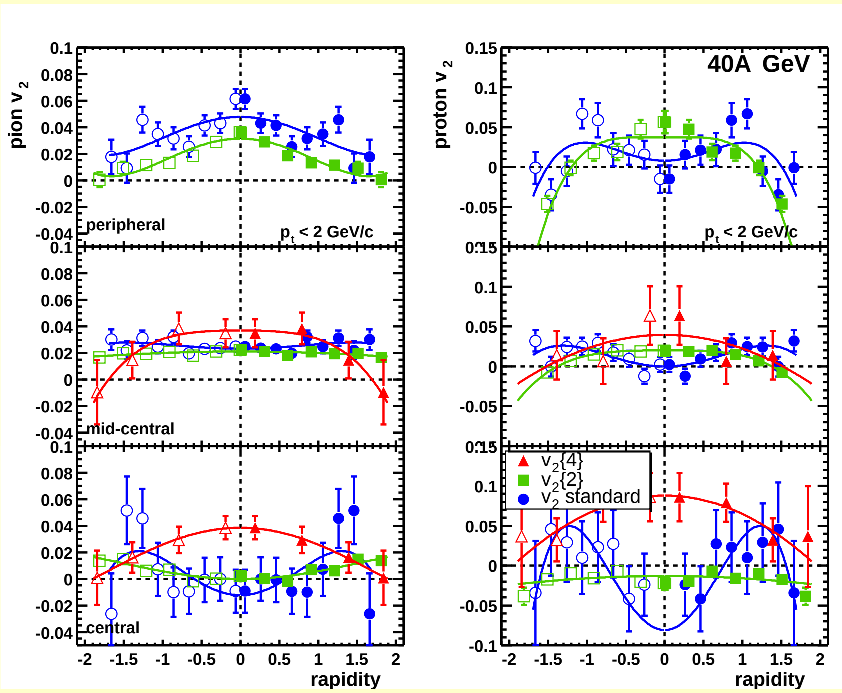


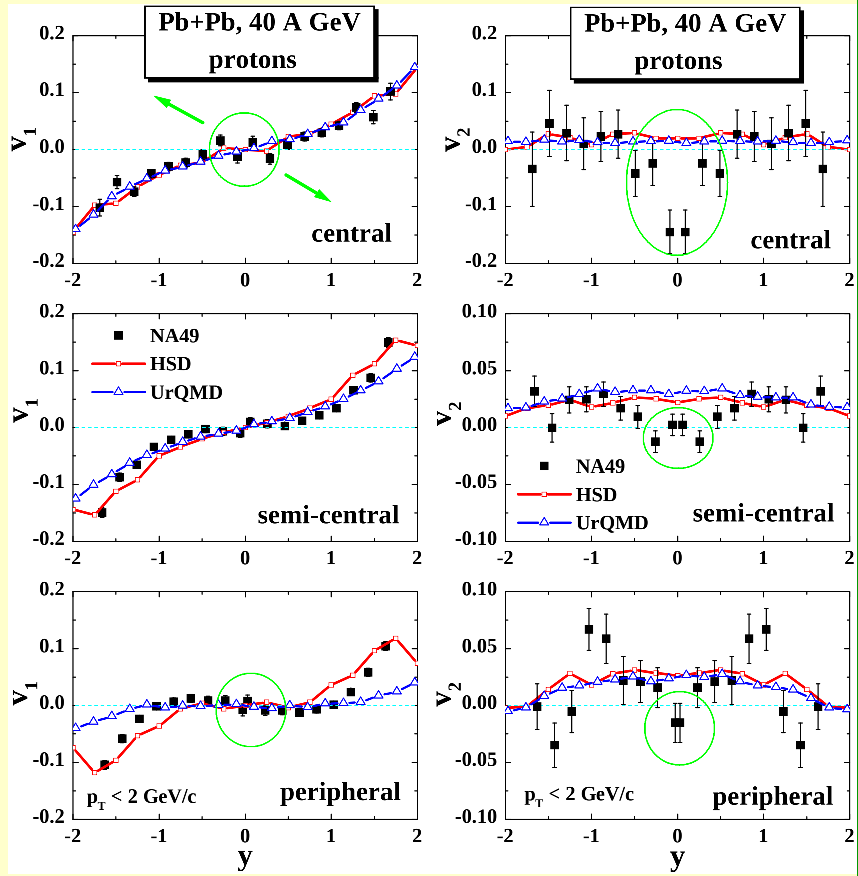
The magnitude of the $v_2(p_t)$ distribution is underestimated
Possible explanation: jets

Elliptic Flow at 40 AGeV

H. Stöcker *et al.*, nucl-th/0412022

C. Alt *et al.* (NA49 Collab.), PRC 68 (2003) 034903





Collapse of proton elliptic flow:

evidence for a first order phase transition

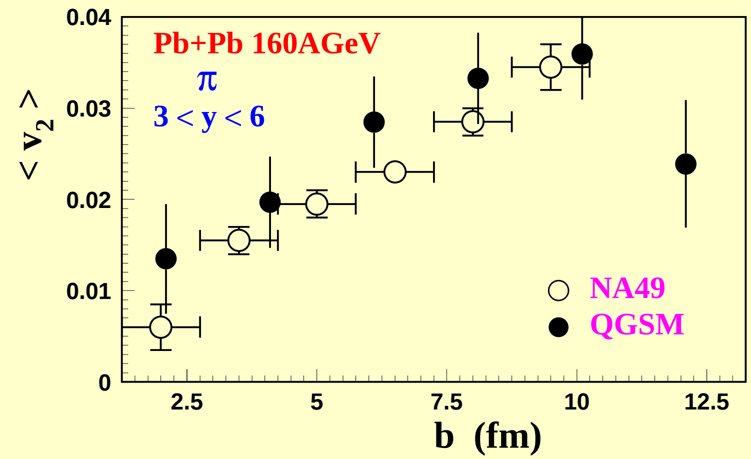
or for non-flow two-particle correlations?

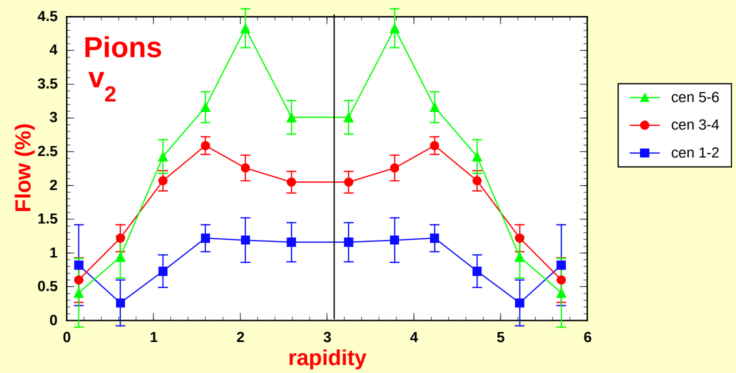
Elliptic Flow and Freeze-Out (Conclusions):

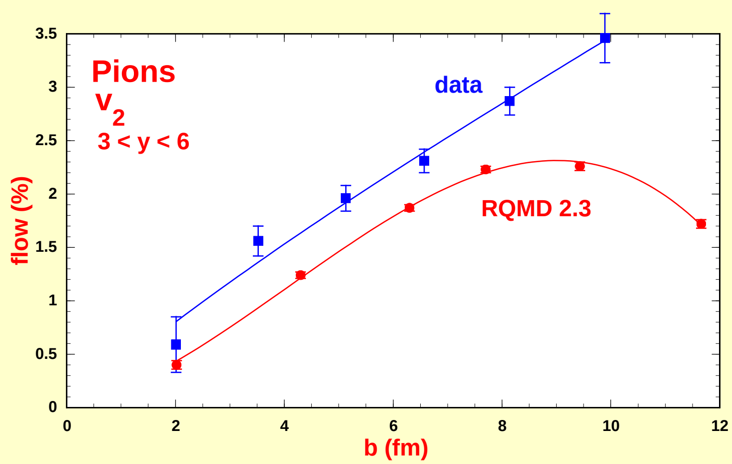
- Microscopic models reproduce, at least qualitatively, basic features of the v_2 development, i.e. centrality, rapidity, and p_t- dependences
- EF of hadrons increases with rising P_T
- EF at $y = 0$ reaches maximum at $t \approx 8$ **fm** at RHIC
- The magnitude of the $\mathbf{v_2(p_t)}$ distribution is underestimated at $p_t \geq 1GeV$
- Pions are emitted mainly from the overlapping almond-shaped zone of the reaction. As the symmetry of the almond is restored, their elliptic flow decreases. Nucleons are coming both from the overlapping area and from the spectator domains
- Freeze-out dynamics for baryons and mesons is different and, therefore, development of particle collective flow should be studied together with the freeze-out picture
- **General trend:** The earlier the freeze-out of mesons, the stronger the $v_2^M(y = 0)$, while the v_2 of baryons frozen earlier is weaker than the v_2 of baryons frozen later on

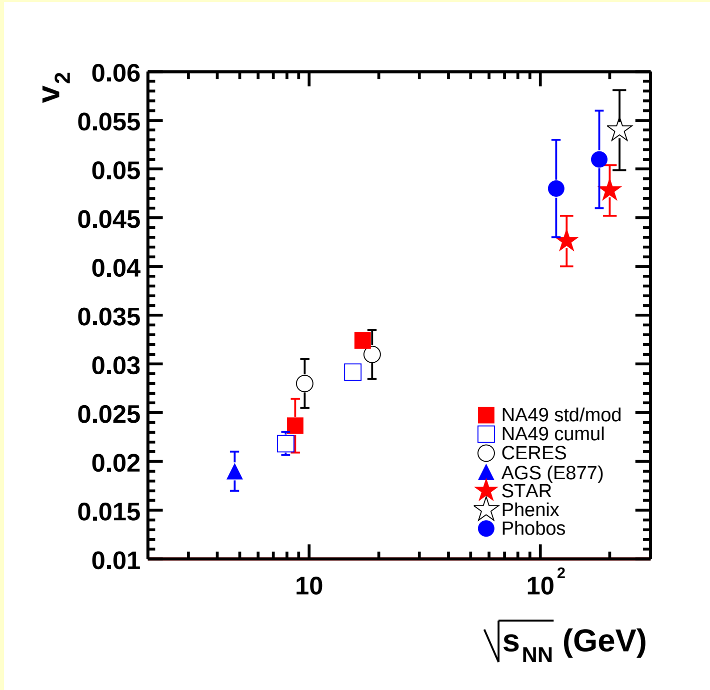
more distributions...

SPS









more distributions...

RHIC