Flow in nuclear collisions :
a review & selected puzzles

Future of Nuclear Collisions at High Energies
Kielce, Oct. 17, 2004

J.-Y. Ollitrault (Saclay)

- What is anisotropic flow?
- v_2 from SIS to RHIC
- Are we able to measure the flow?
- Illustration: centrality dependence of v_2
- Why is v_2 so large at high p_t?
- Why is the rapidity dependence of v_2 so steep?
- Why is v_4 so large?
- Why is v_1 so large at low p_t?

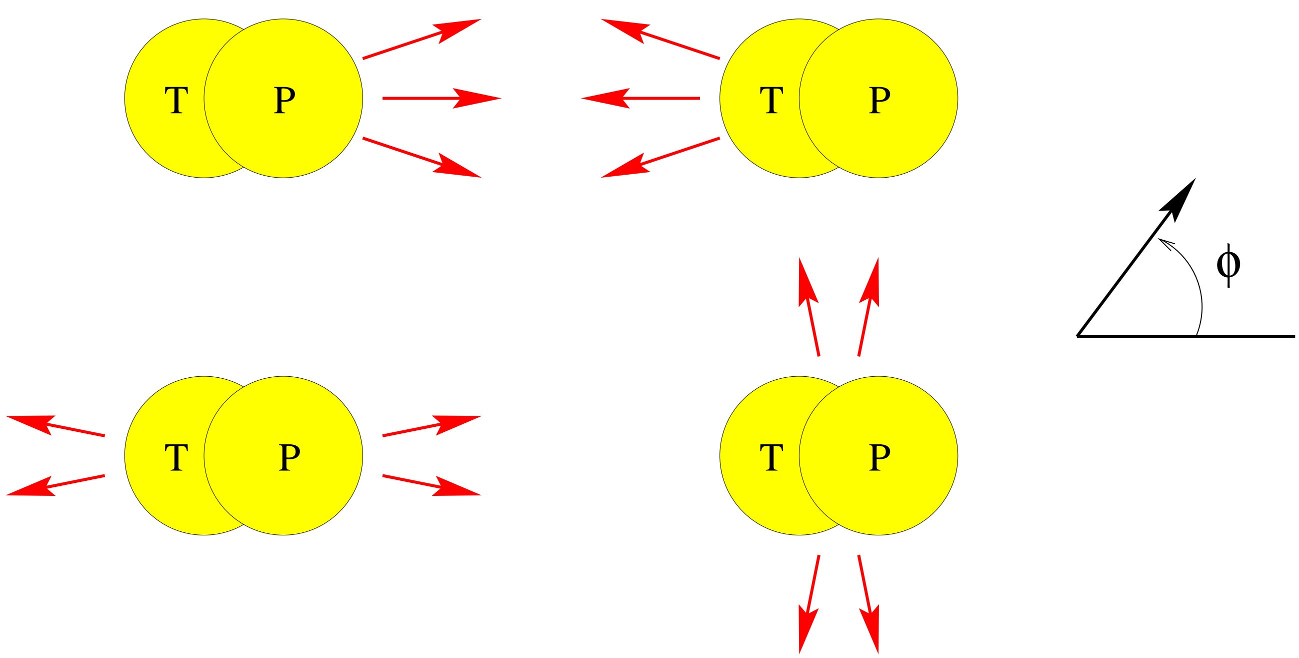
What is anisotropic flow?

Non-central collision

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1 + 2\, v_1 \cos\phi + 2\, v_2 \cos 2\phi + \ldots$$

isotropic   directed   elliptic

$$\begin{aligned} v_n &= \langle \cos n\phi \rangle \\ &= \text{Correlation to the reaction plane} \\ &\equiv \text{“anisotropic flow”} \end{aligned}$$



A wealth of recent data

Since the last review at Quark Matter '2002

S. Voloshin nucl-ex/0210014

- First extensive analysis of v_1 at SIS

FOPI nucl-ex/0301009

- First accurate results on v_1 and v_2 at SPS

NA49 nucl-ex/0303001

CERES nucl-ex/0407019

- Discovery of v_1 and v_4 at RHIC

STAR nucl-ex/0310029

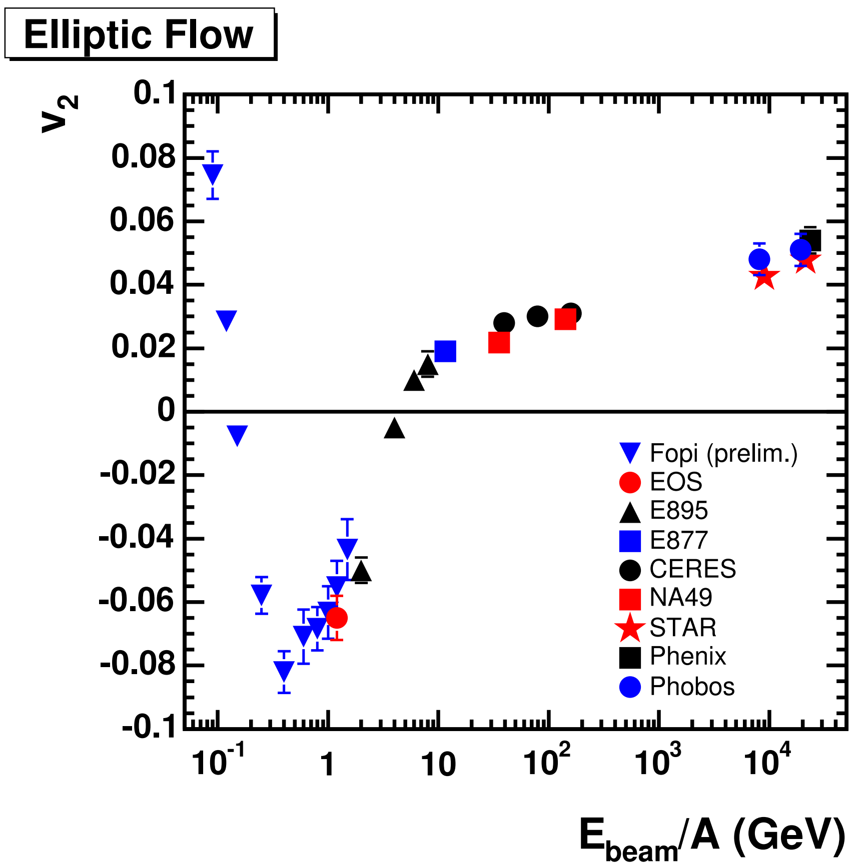
- Extensive analyses of v_2 at RHIC

PHENIX nucl-ex/0305013

PHOBOS nucl-ex/0406021

STAR nucl-ex/0409033

v_2 from SIS to RHIC

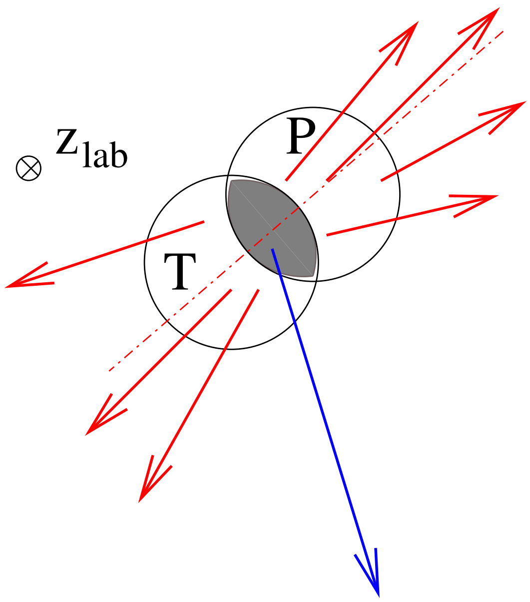


A. Wetzler, cited by R. Stock nucl-ex/0405007

As energy increases:

- Rotation-like effect $v_2 > 0$
- Squeeze-out $v_2 < 0$
- Interactions between secondary particles $v_2 > 0$

Physics of elliptic flow at RHIC



Shaded area : high pressure
+ spatial asymmetry

→ flow along the pressure gradient
→ generates positive elliptic flow

JYO Phys. Rev. **D46** (1992) 229

elliptic flow is due to final state interactions
sensitive to thermalization
equation of state

Are we able to measure the flow?

Impact parameter not known: ϕ is not measured.

Only relative angles are measured.

Standard methods :

$$\begin{aligned}\langle\cos 2(\phi_1-\phi_2)\rangle &= \langle\cos 2\phi_1\rangle\langle\cos 2\phi_2\rangle \\ &= (v_2)^2\end{aligned}$$

But this assumes uncorrelated particles!
What about jets, HBT, momentum conservation...?

Improved methods of analysis → cumulants

$$\begin{aligned}\langle\cos 2(\phi_1+\phi_2-\phi_3-\phi_4)\rangle &- \langle\cos 2(\phi_1-\phi_3)\rangle\langle\cos 2(\phi_2-\phi_4)\rangle \\ &- \langle\cos 2(\phi_1-\phi_4)\rangle\langle\cos 2(\phi_2-\phi_3)\rangle \\ &= -(v_2)^4\end{aligned}$$

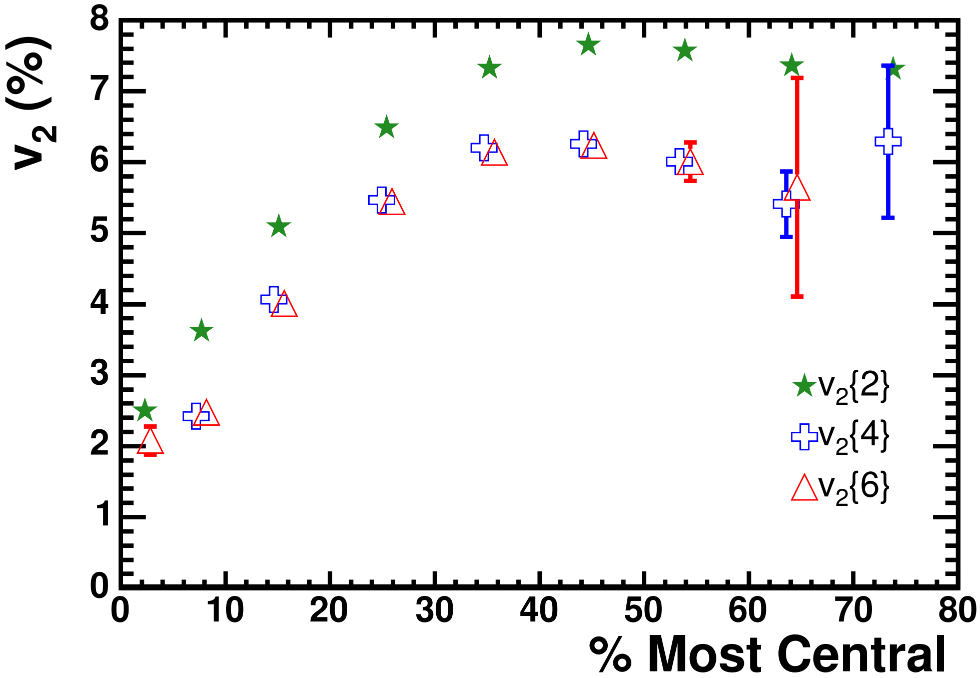
Borghini Dinh Ollitrault nucl-th/0105040

Even better: Lee-Yang zeroes...

Bhalerao Borghini Ollitrault nucl-th/0307018

Apply to experiments with good phase space coverage e.g.
FOPI, E895, STAR, ALICE, CMS, ATLAS...

The centrality dependence of v_2



STAR collaboration, nucl-ex/0409033

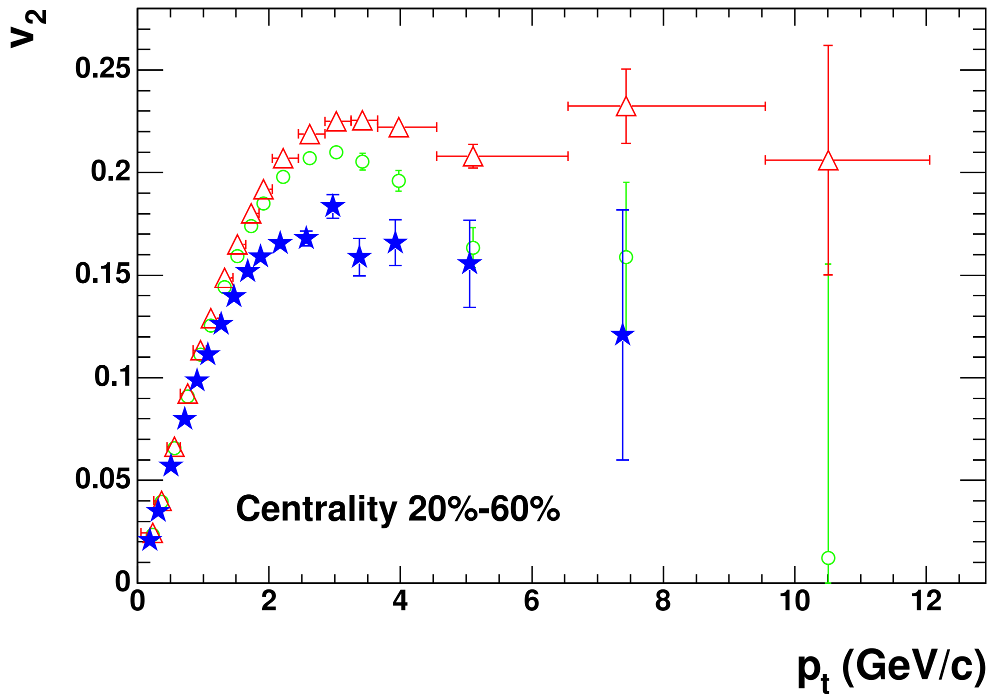
Comparison between 2, 4 and 6 cumulant results:
Results depend on the method of analysis.
Is this due to

- "nonflow" jet-like correlations ?
- Or to event-by-event fluctuations of v_2?

Miller Snellings nucl-ex/0312008

$$2-\text{particle } v_2 \simeq \langle v_2\rangle + \frac{(\delta v_2)^2}{2\langle v_2\rangle}$$
$$4-\text{particle } v_2 \simeq \langle v_2\rangle - \frac{(\delta v_2)^2}{\langle v_2\rangle}.$$

Why is v_2 so large at high p_t?



STAR nucl-ex/0407007

If v_2 builds up through elastic collisions
$\rightarrow$ requires a very small mean free path

Molnar Gyulassy nucl-th/0104073
Teaney nucl-th/0301099

Or equivalently, a very low viscosity; and Yang-Mills theories may have low viscosities...

Policastro Son Starinets hep-th/0104066

Is v_2 at very high p_T due to jet quenching ?

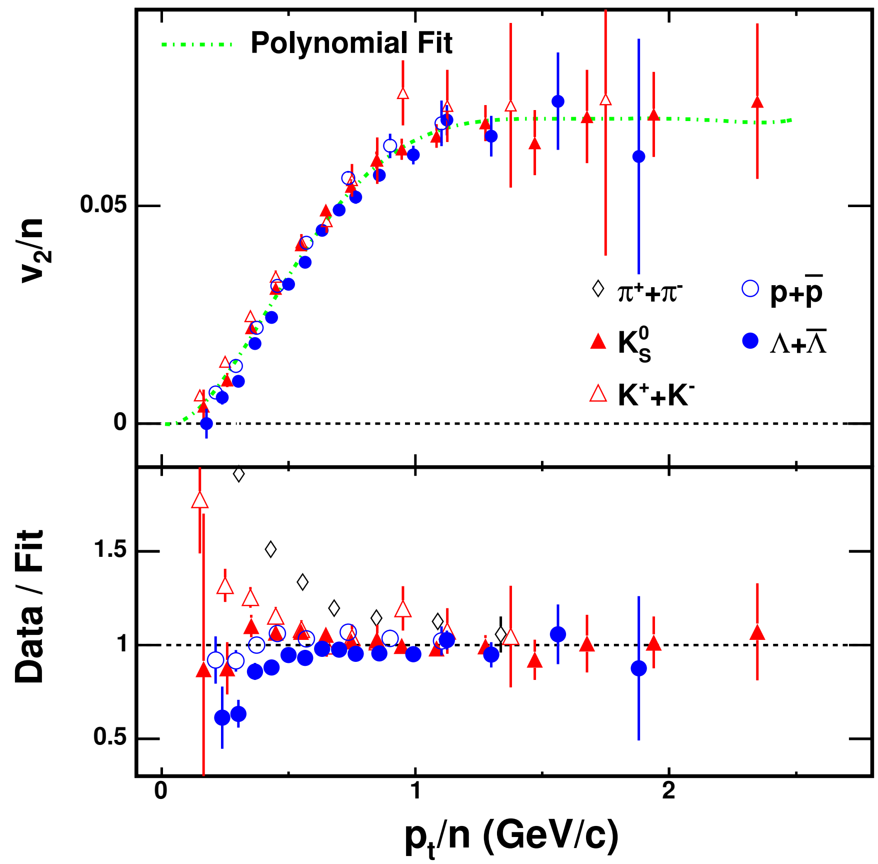
Gyulassy Vitev Wang Huovinen nucl-th/0109063

Are hadrons formed through quark coalescence?

- A meson is made of two quarks
- A baryon is made of three quarks

Inelastic $2 \to 1$ or $3 \to 1$ processes may be more efficient than elastic $2 \to 2$ to thermalize

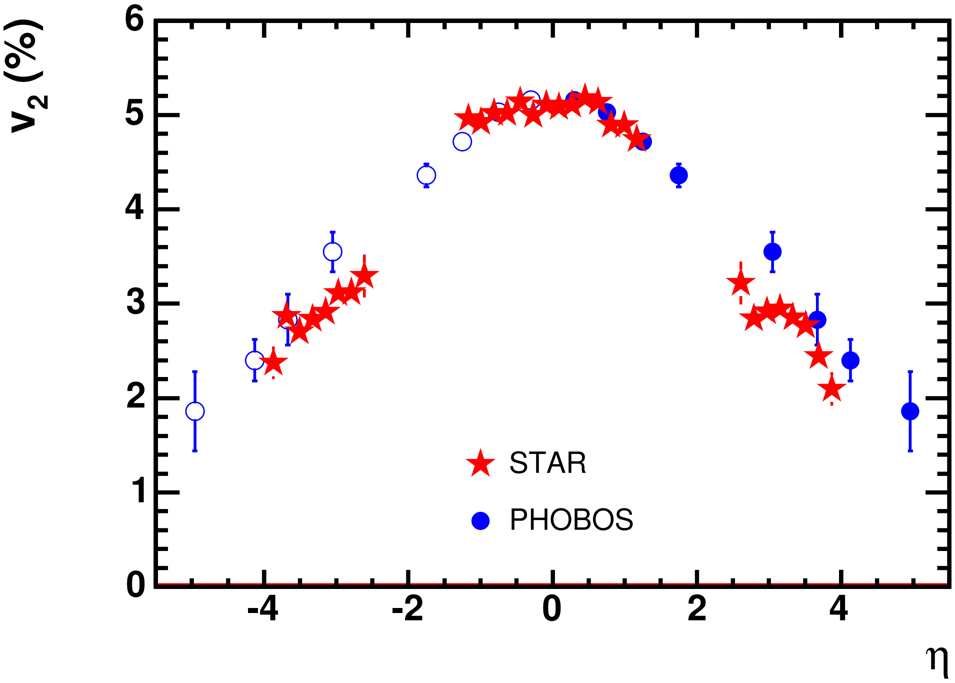
Molnar Voloshin nucl-th/0302014



A phenomenological Ansatz that reproduces several other features of high-p_t particle yields!

But does perturbative QCD like coalescence?

Why is the rapidity dependence of v_2 so steep?



If thermalization is achieved, v_2 should be insensitive to the multiplicity density:

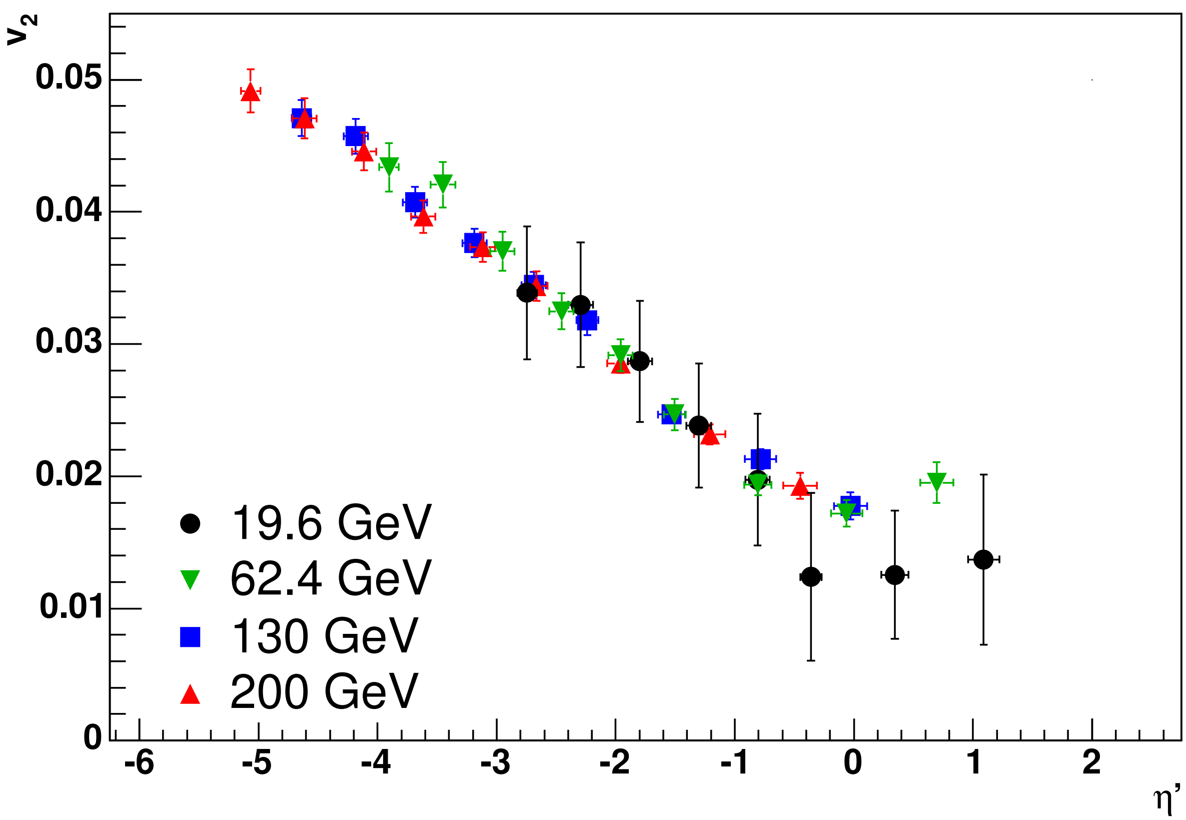
hydrodynamics is scale invariant !

Data are a challenge to hydro calculations.

Hirano nucl-th/0410017

The rapidity dependence of v_2 (continued)

v_2 in the projectile frame, compare different energies:

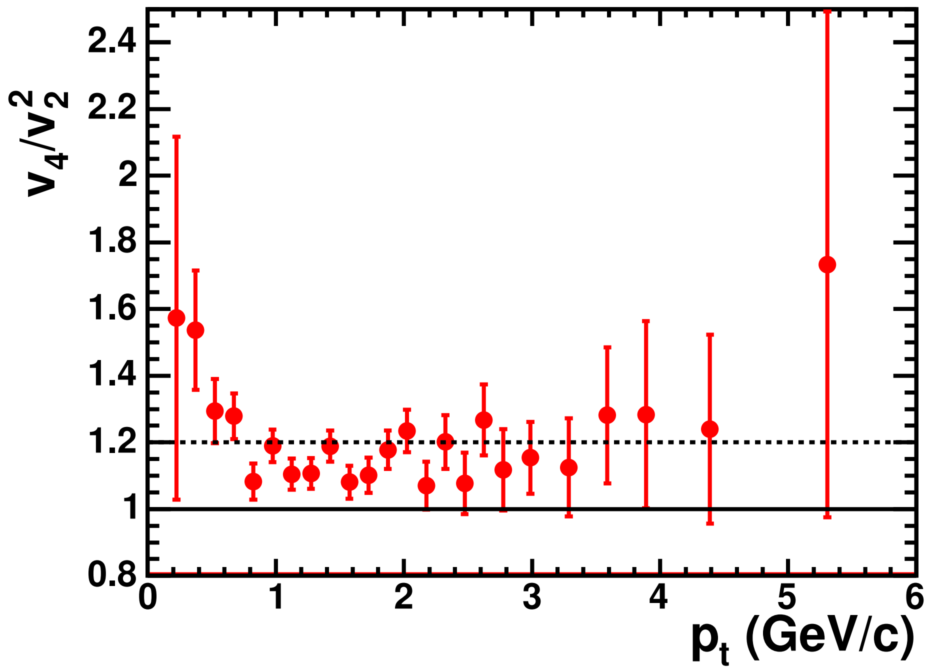


PHOBOS nucl-ex/0406021

Why does v_2 follow the rule of "limiting fragmentation"?

Why is v_4 so large?

$(v_2)^2 \equiv$ "natural" scale for v_4:
$\frac{v_4}{(v_2)^2}$ has less structure than v_4 (versus p_t, centrality...) and is typically of order unity.



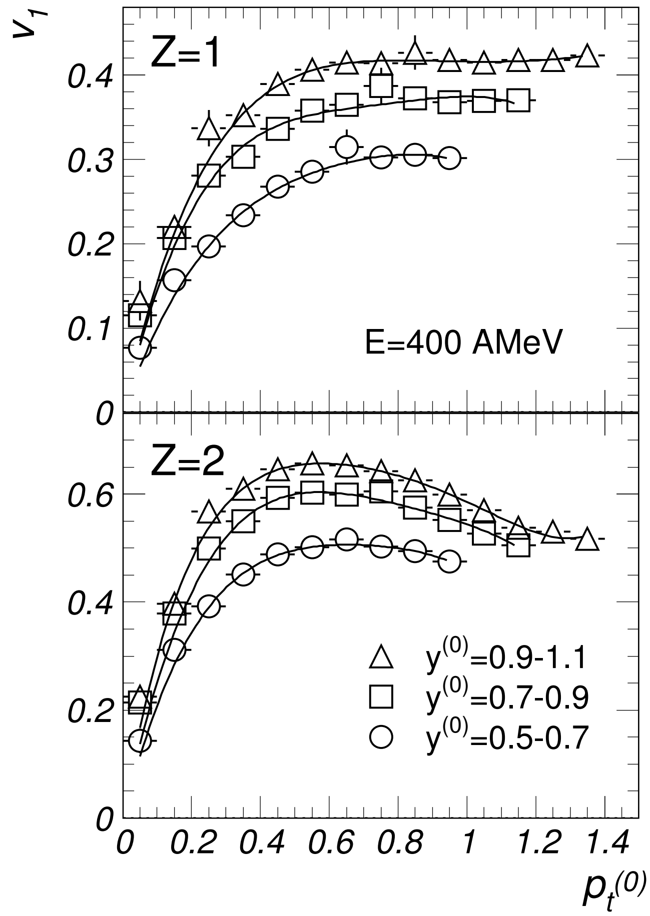
Poskanzer nucl-ex/0403019

Hydro predictions lead to smaller values

Kolb nucl-th/0306081

v_4, v_2: same physics!!
How can hydro work for v_2, not for v_4 ?

Why is v_1 so large at low p_t?



FOPI nucl-ex/0108014

Power-series expansion of the momentum distribution:

$$\frac{dN}{dp_x dp_y} = a + b\, p_x + \cdots$$
$$= a + b\, p_t \cos\phi + \cdots$$

So one generally expects, at low p_t,

$$v_1 = \langle \cos\phi \rangle \propto p_t$$

For large y, v_1 does not seem to go to 0 at low p_t: why?

Conclusions

- We now have for the first time quantitative data at all energies.
- Several simple features are still to be understood
- The standard statement that v_2 implies thermalization at RHIC may be oversimplified