

Anisotropic flow and azimuthally sensitive HBT at RHIC

Raimond Snellings

Introduction

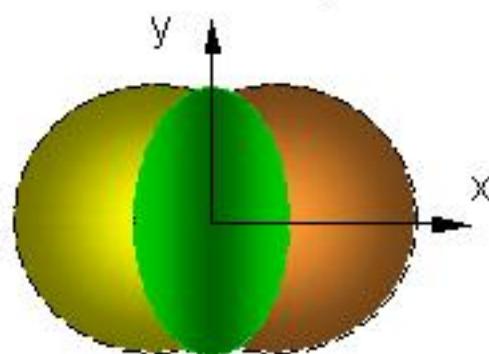
- Heavy-Ion Collisions
 - Study QCD at high temperature and density
 - Establish and characterize properties of deconfined matter
 - Characterize phase transition between nuclear matter and a system of asymptotically free quarks and gluons
- Requirement observables
 - Provide information about the early, possibly deconfined phase
 - Sensitive to bulk properties

Observables and their sensitivity

Parameter	Symbol	Spectra	Elliptic flow $v_2(p_t, m)$	HBT (p_t, ϕ_R)
Temperature	T	yes	yes	yes
Average transverse flow velocity	β_t or ρ_0	yes	yes	yes
Azimuthal modulation in flow velocity	β_a or ρ_a		yes	yes
Coordinate-space anisotropy	S_2		yes	yes
Radius in y-direction	R_y			yes
Duration of particle emission	τ			yes

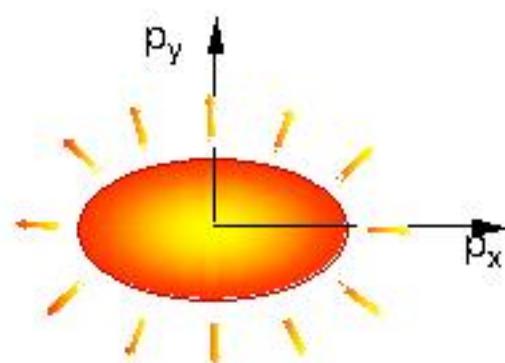
Why is elliptic flow interesting?

coordinate space



- Coordinate space configuration anisotropic (almond shape) however, initial momentum distribution isotropic (spherically symmetric)

Momentum space



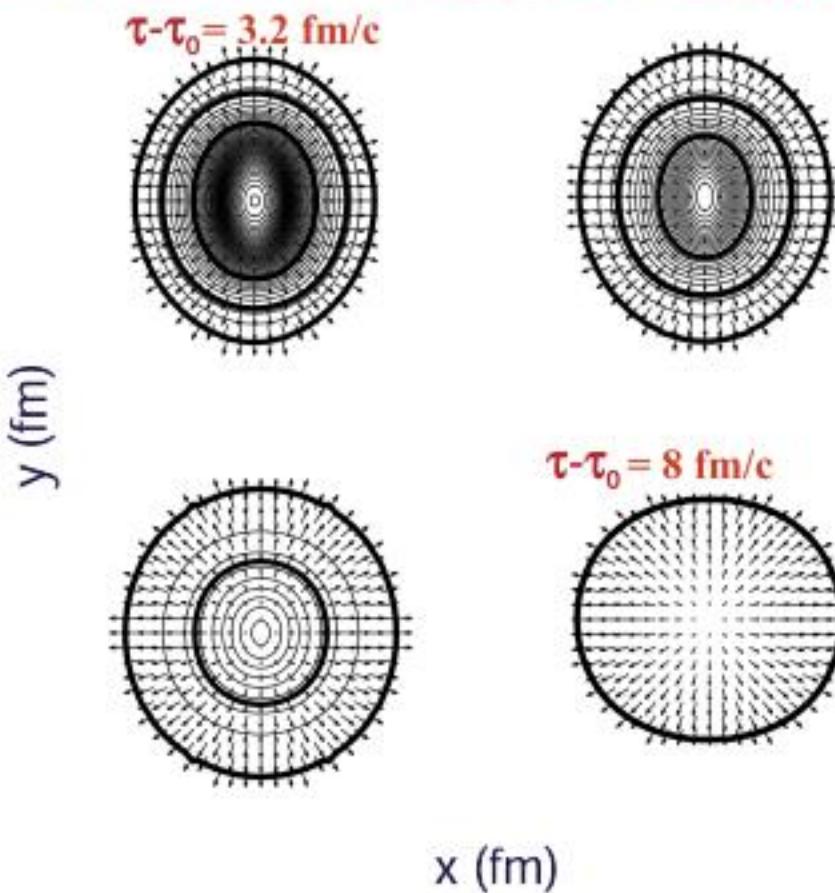
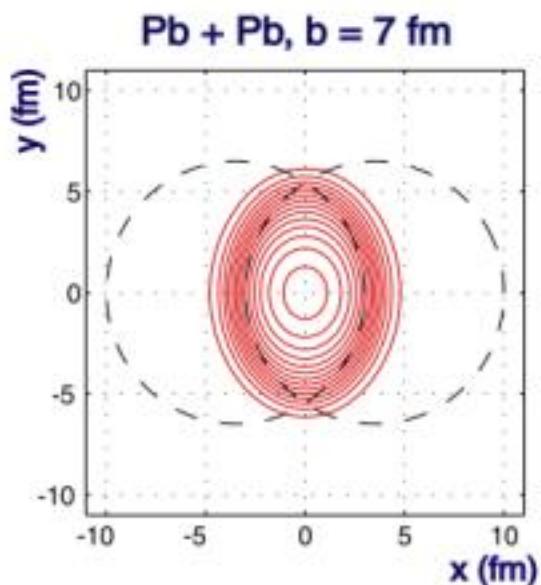
- Only interactions among constituents generate a pressure gradient, which transforms the initial coordinate space anisotropy into a momentum space anisotropy (no analogy in pp)

- Multiple interactions lead to thermalization -> limiting behavior ideal hydrodynamic flow

$$E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi} \frac{d^2 N}{p_t dp_t dy} \left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\varphi - \Psi_r)) \right)$$

$$v_2 = \langle \cos 2(\varphi - \Psi_r) \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

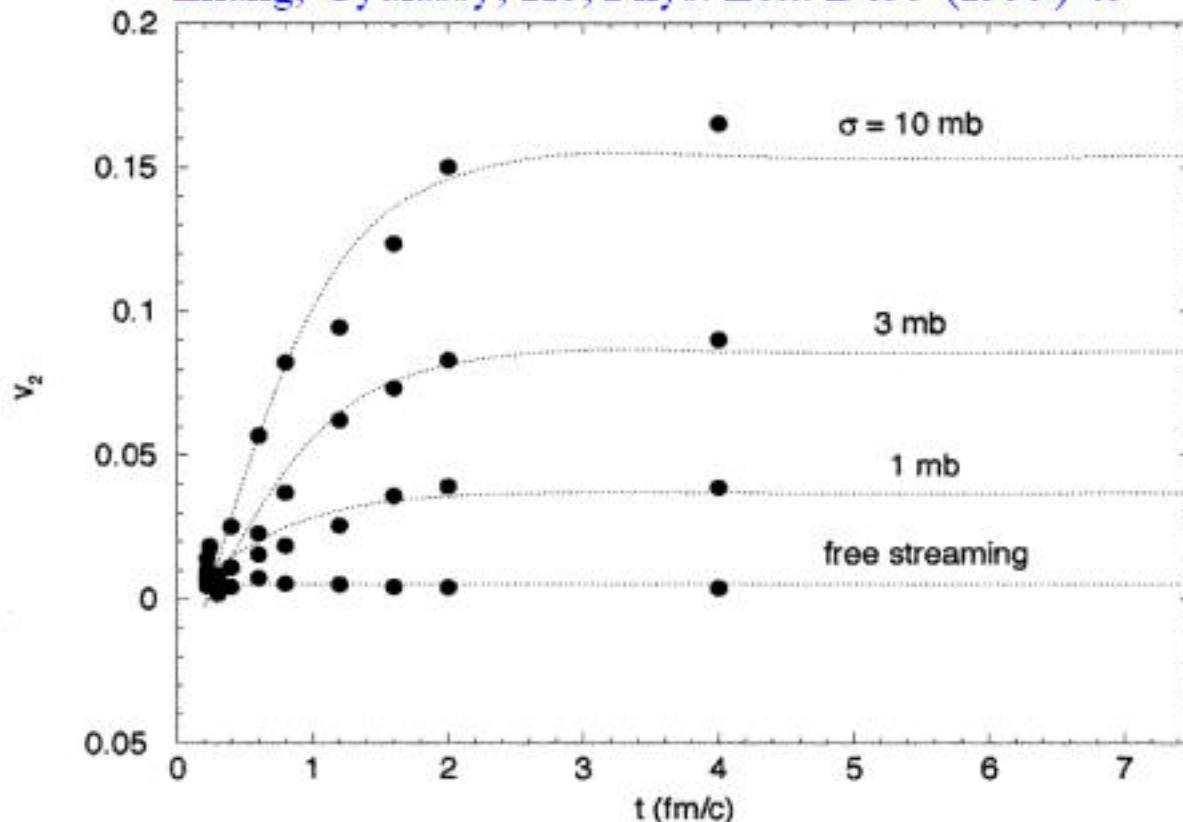
Time evolution in an ideal hydrodynamic model calculation



- Elliptic Flow reduces spatial anisotropy \rightarrow shuts itself off

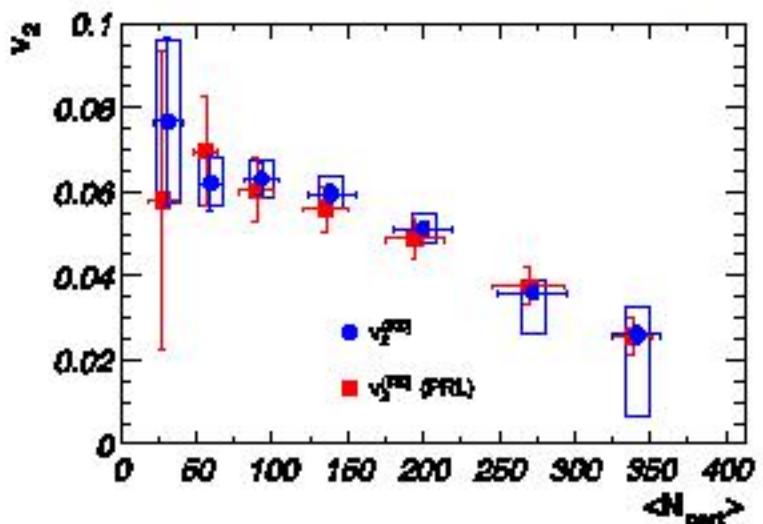
Main contribution to elliptic flow early in the collision

Zhang, Gyulassy, Ko, Phys. Lett. B455 (1999) 45



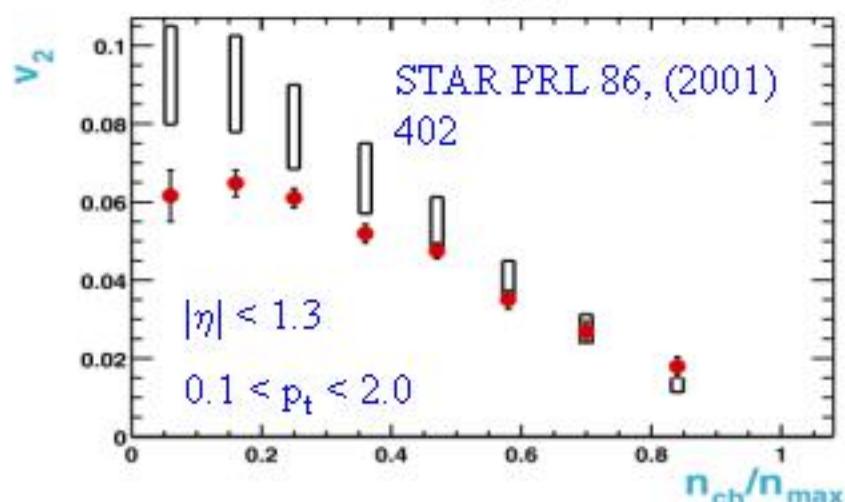
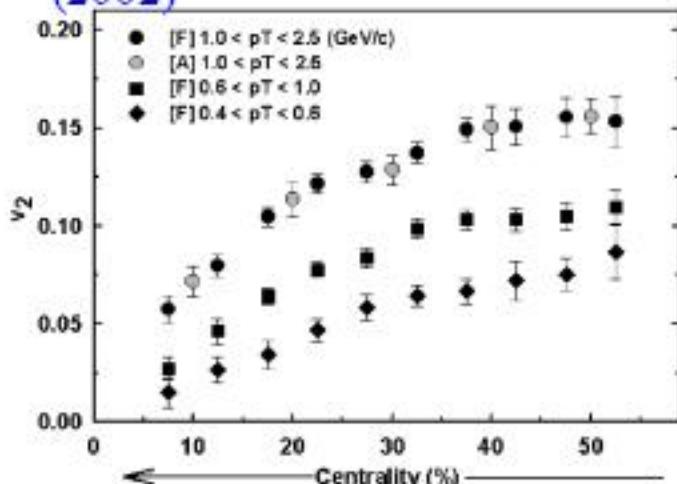
v_2 versus centrality

PHOBOS: Phys. Rev. Lett. 89, 222301 (2002)



First time in Heavy-Ion Collisions a system created which at low p_t is in **quantitative** agreement with hydrodynamic model predictions for v_2 up to mid-central collisions

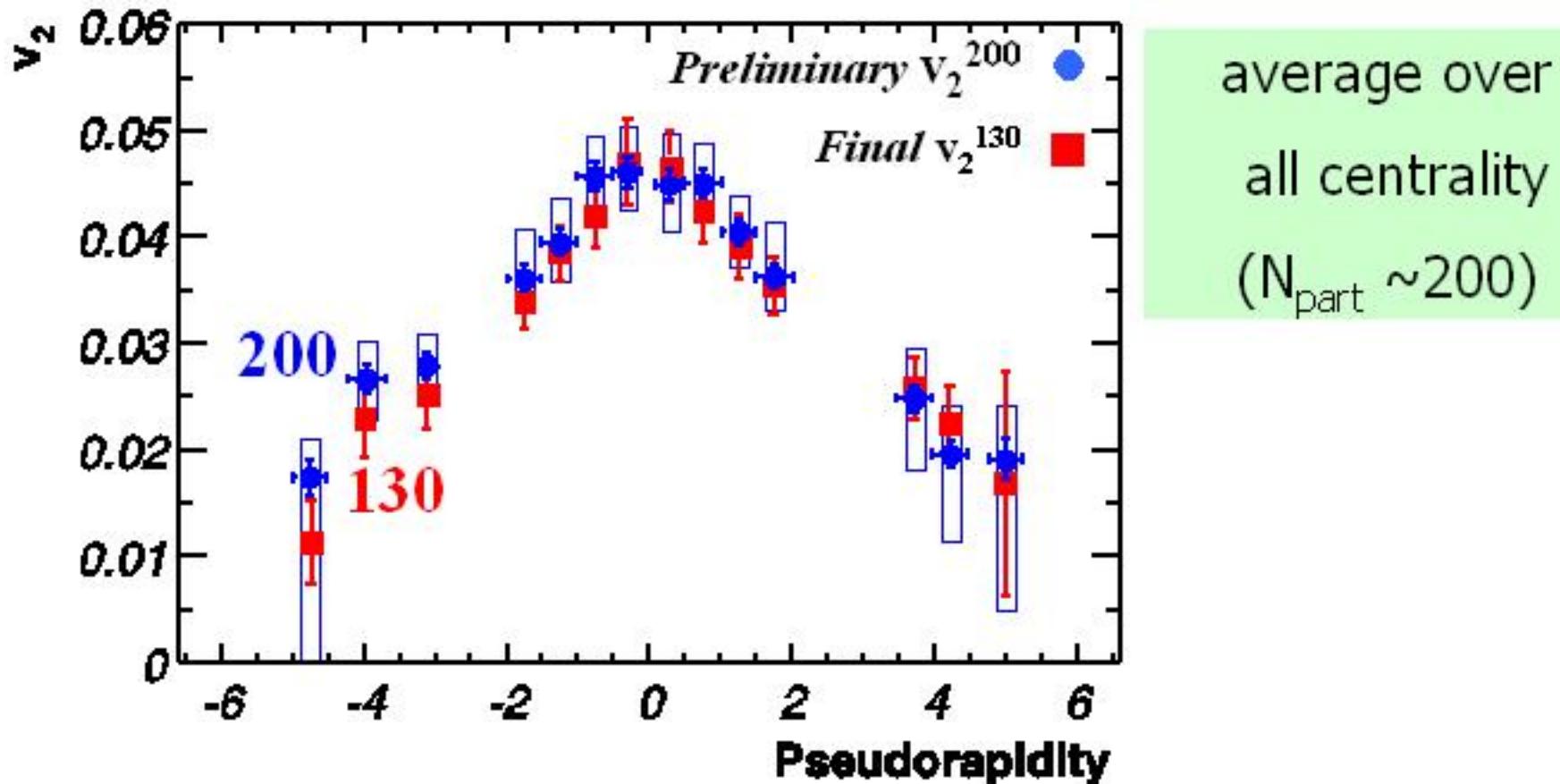
PHENIX: Phys. Rev. Lett. 89, 212301 (2002)



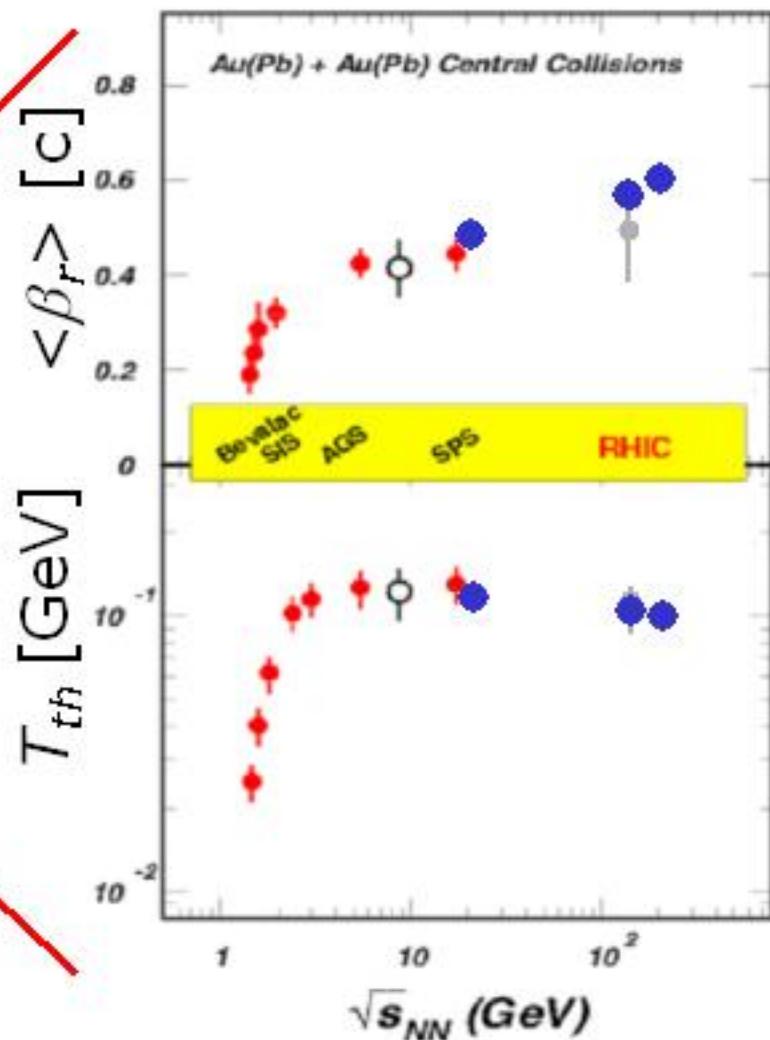
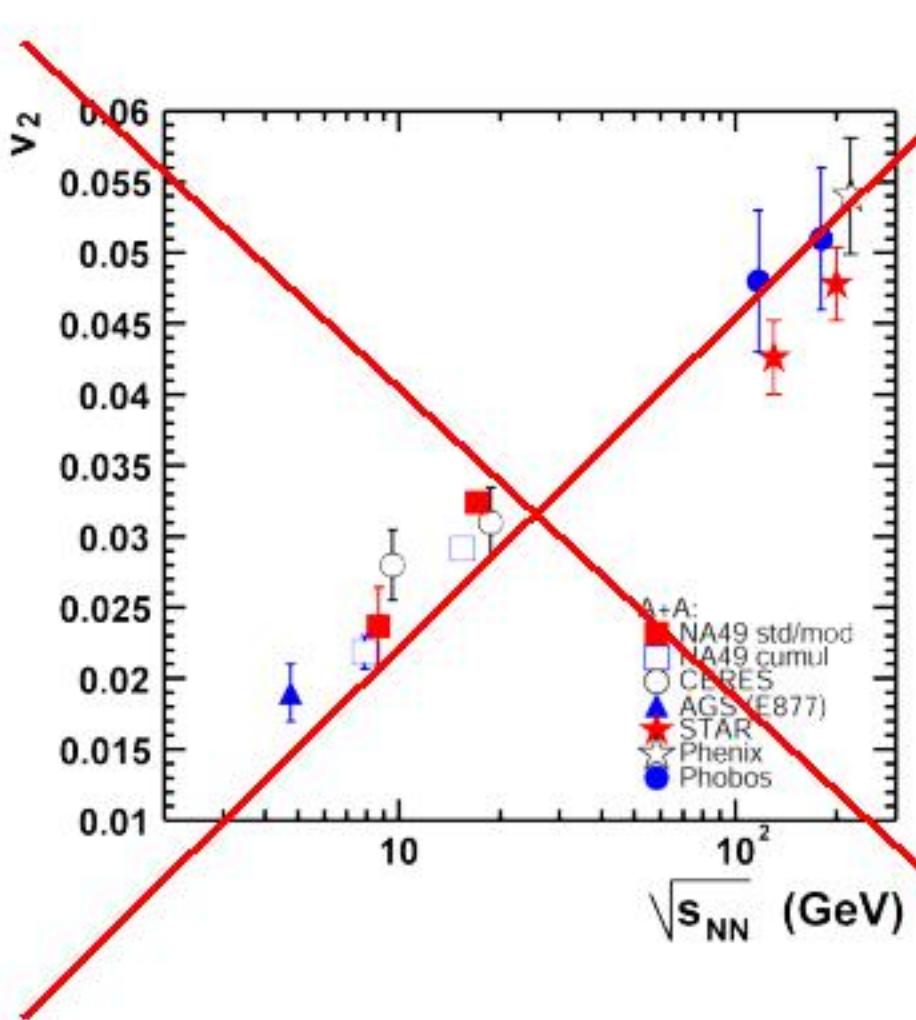
Is there boost invariance?

PHOBOS v2(η)

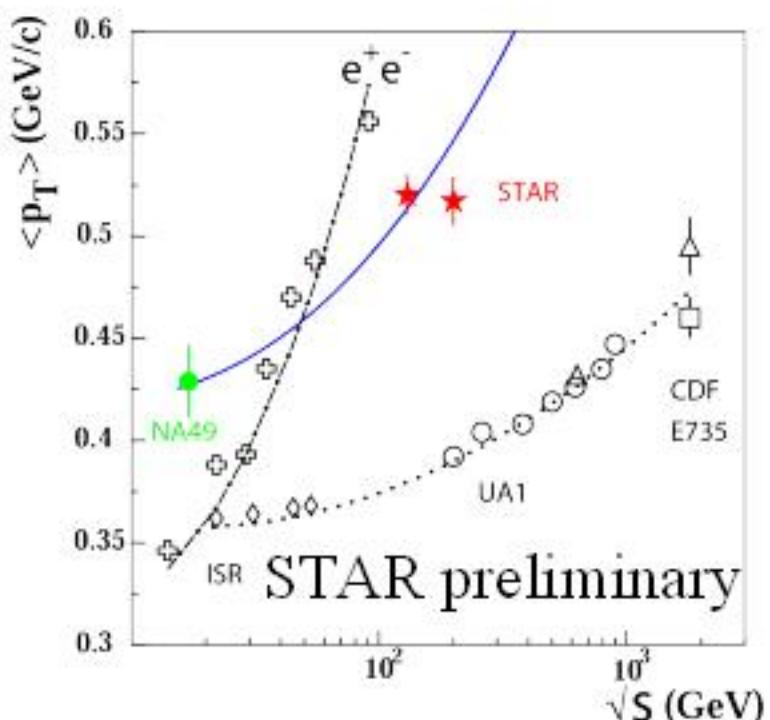
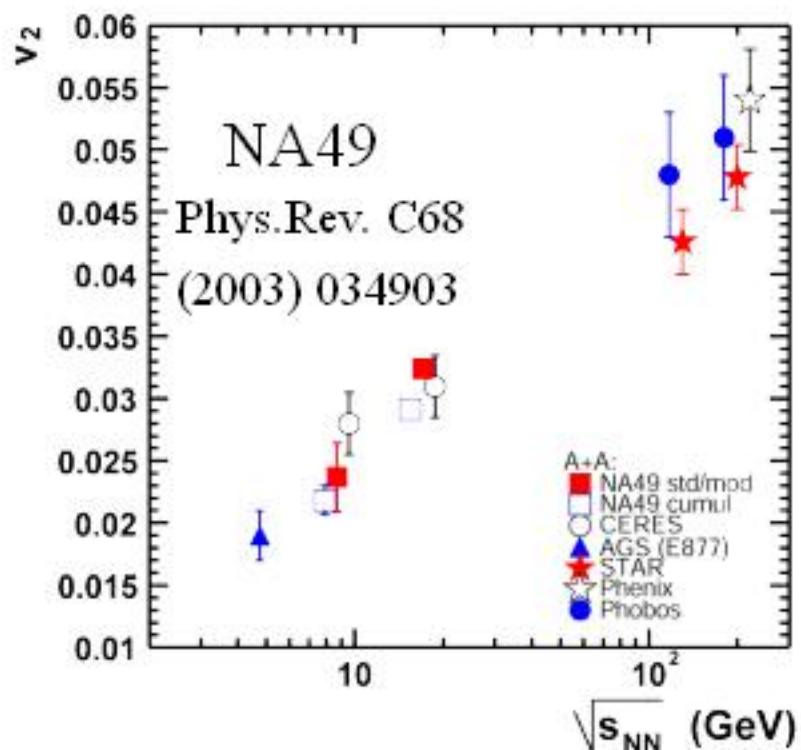
PHOBOS: Phys. Rev. Lett. **89**, 222301 (2002)



Excitation Functions

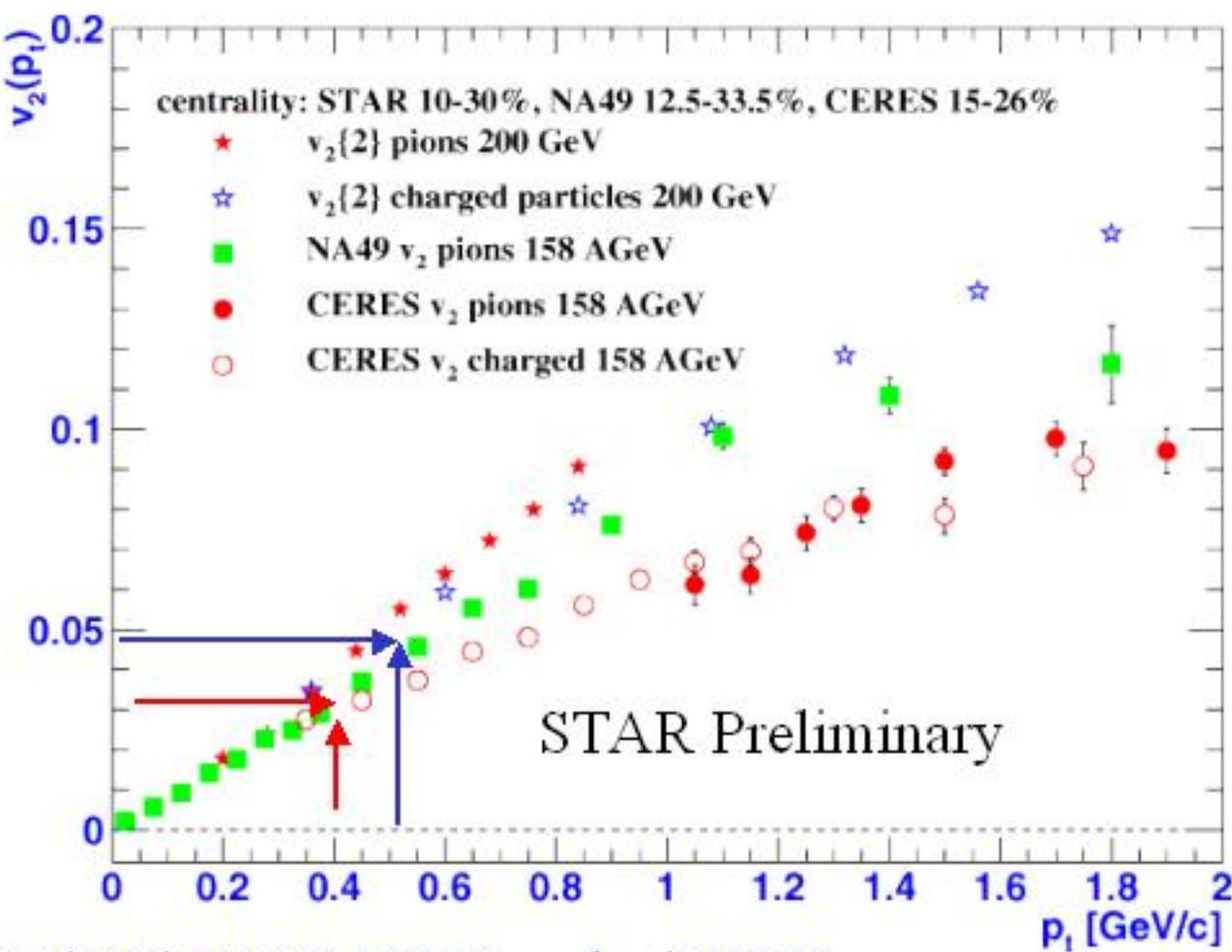


Elliptic flow; excitation function



$v_2(p_t)$ SPS-RHIC

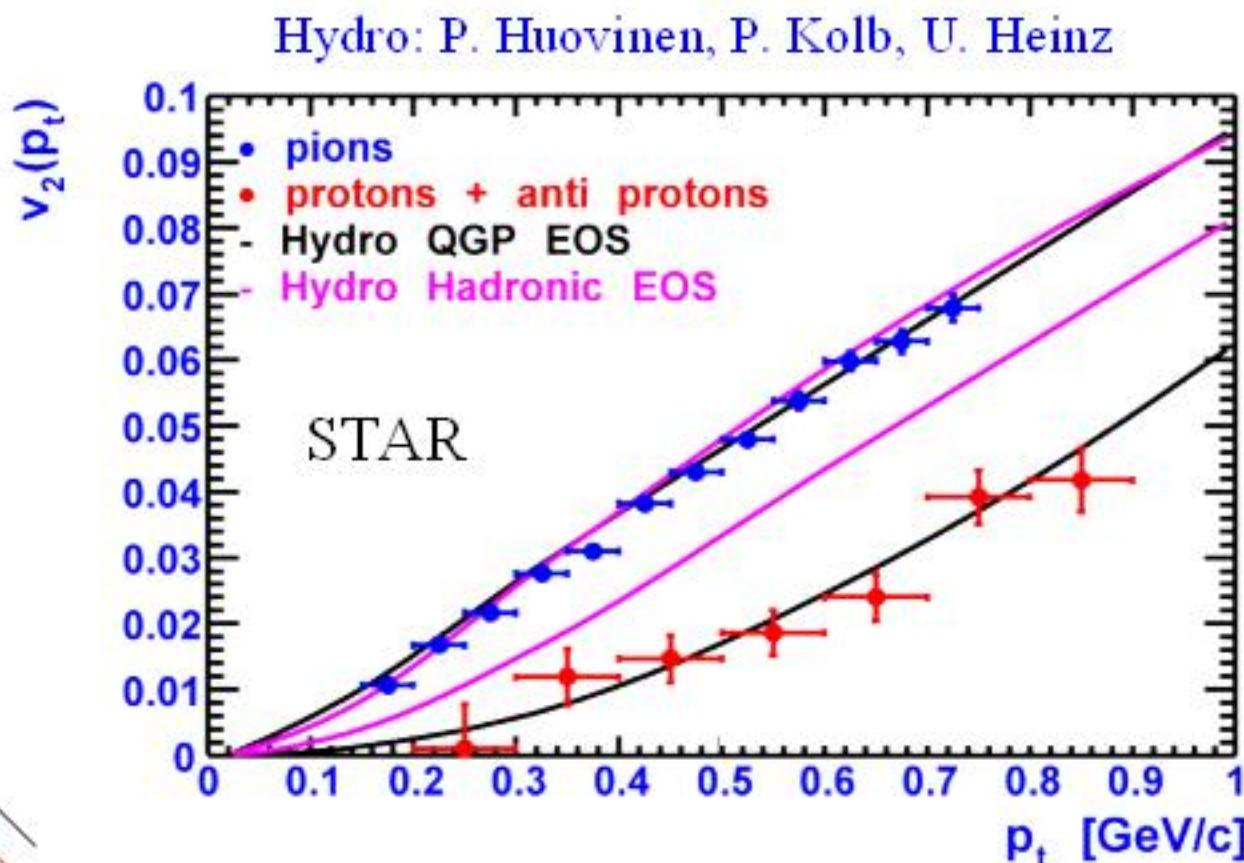
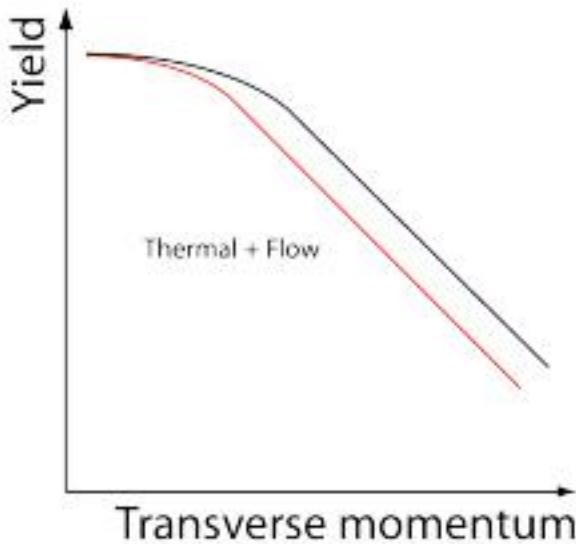
- Surprisingly close!
- $\langle p_t \rangle$ pions 158 A GeV ≈ 400 MeV/c
- $\langle p_t \rangle$ charged particles 200 GeV ≈ 500 MeV/c
- Integrated v_2 mainly driven by $\langle p_t \rangle$
- Note: In comparison SPS data the slight difference in centrality and systematic uncertainties, about 1.5% are not plotted



NA49: Phys.Rev. C68 (2003) 034903; CERES: nucl-ex/0303014

Identified particle v_2

- Typical p_t dependence
- Heavy particles more sensitive to velocity distribution (less effected by thermal smearing) therefore put better constrained on EOS



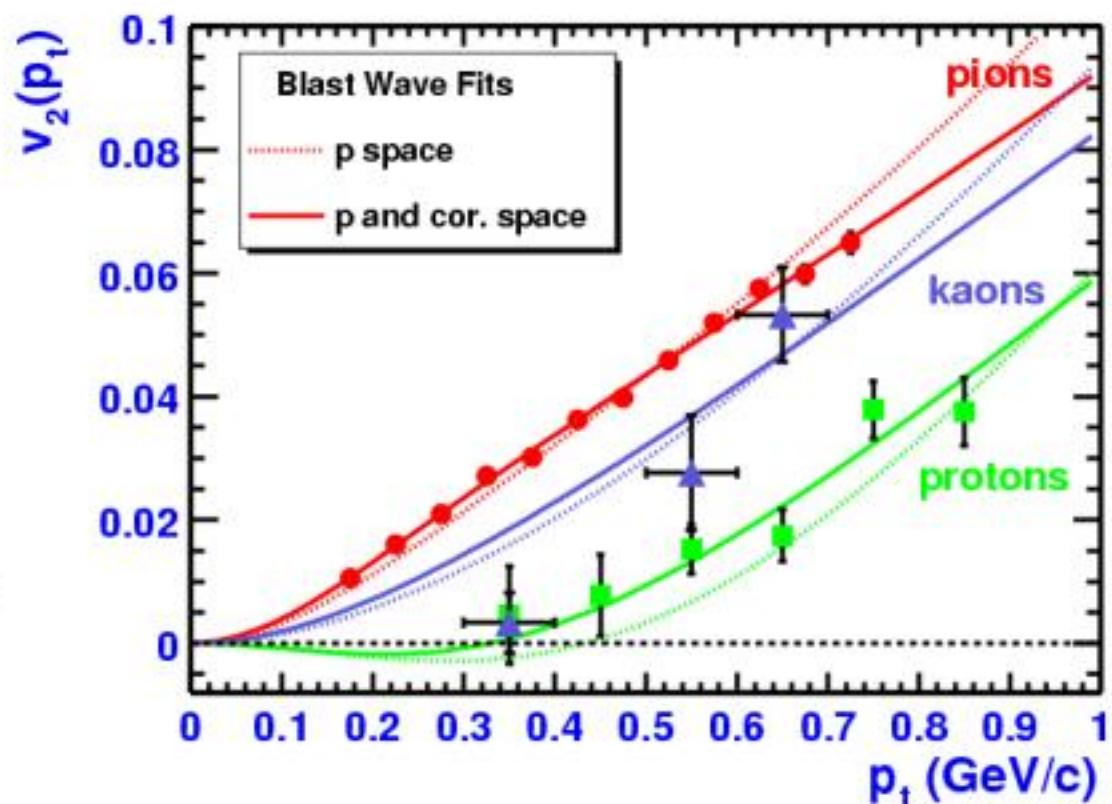
Fluid cells expand with collective velocity v , different mass particles get different Δp

Identified particle v_2 (130 GeV)

	<u>dashed</u>	<u>solid</u>
T (MeV)	135 ± 20	100 ± 24
$\beta_0(c)$	0.52 ± 0.02	0.54 ± 0.03
$\beta_a(c)$	0.09 ± 0.02	0.04 ± 0.01
s_2	0.0	0.04 ± 0.01

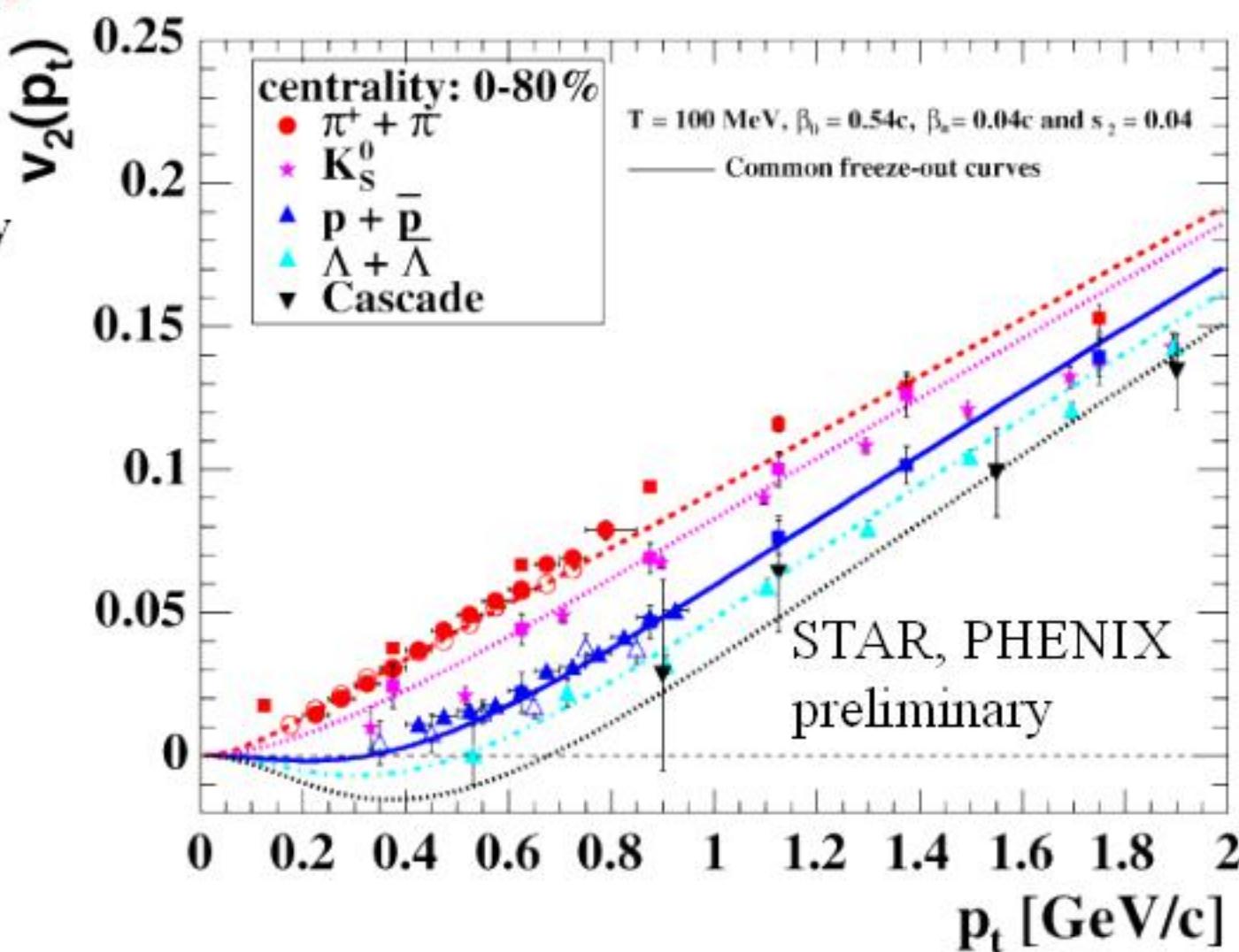
The STAR Collaboration, Phys.
Rev. Lett. 87 (2001) 182301

Source not spherical
in coordinate space at
freeze-out! (see
 $HBT(\phi_R)$ part)



$v_2(p_t, \text{mass})$ 130 vs. 200 GeV

- STAR identified particle v_2 at 130 (open symbols) and 200 GeV very close
- PHENIX (squares) extend for pions and protons the p_t -range and STAR and PHENIX agree nicely
- All particles reasonably described at low- p_t with common set of parameters



Summary: Elliptic flow at low- p_t

- Large v_2 values observed, consistent with Hydro predictions
 - Indicative of early pressure and thermalization
 - Indicative of strong partonic interaction at an early stage
- $v_2(p_t)$ at the SPS close to RHIC, main difference in integrated v_2 due to increase in $\langle p_t \rangle$. Note that this is not trivial
- Mass dependence of $v_2(p_t)$ in accordance with hydro dynamics
 - QGP equation of state best description of data
 - All particles seem to reflect similar values for flow and temperature at freeze-out
- Nice theory overviews: Peter F. Kolb and Ulrich Heinz, review for 'Quark Gluon Plasma 3', nucl-th/0305084. Pasi Huovinen, review for 'Quark Gluon Plasma 3', nucl-th/0305064. D. Teaney, J. Lauret and E. V. Shuryak, nucl-th/0110037; Phys. Rev. Lett. 86, 4783 (2001).

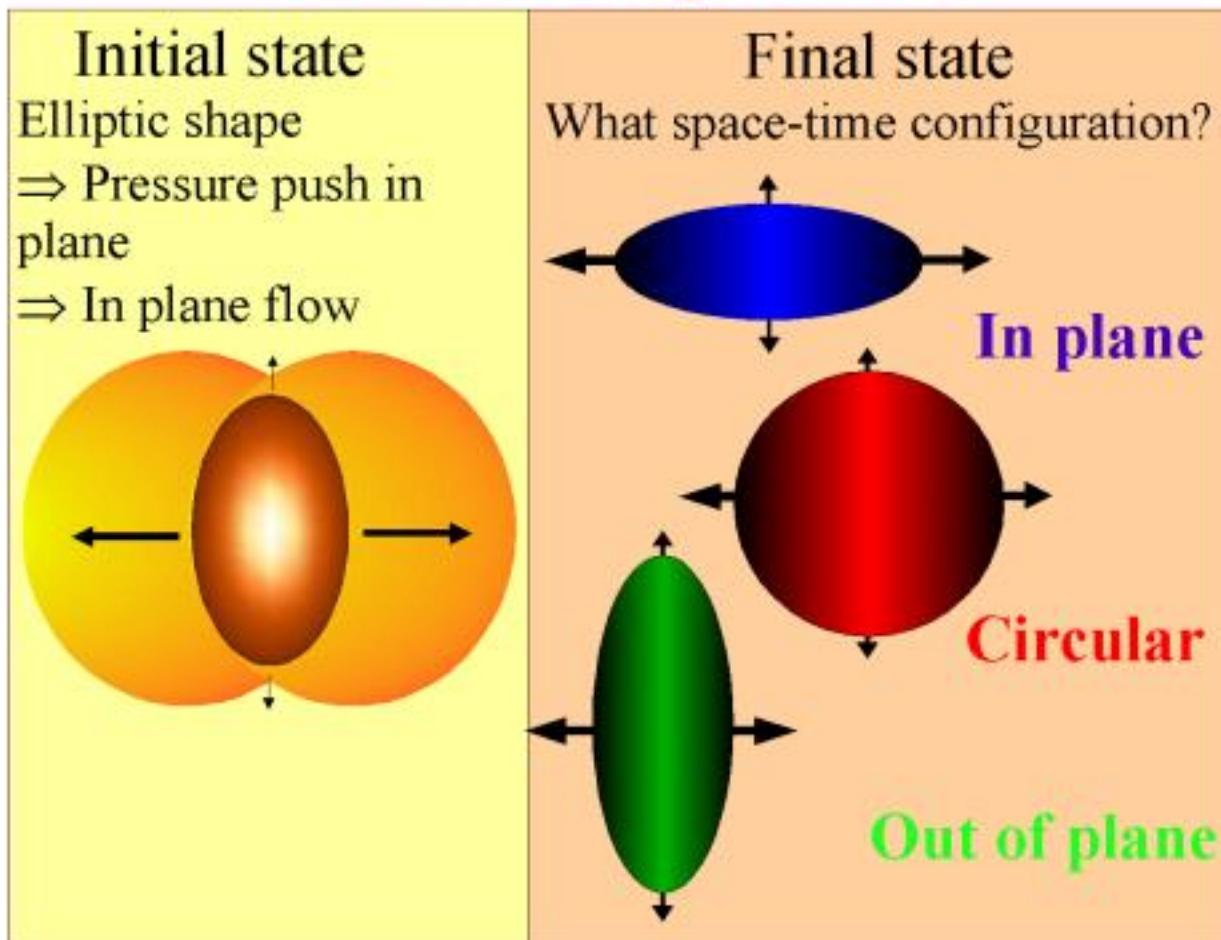
HBT interferometry

- Goal: understand quantitatively space-time evolution (**STE**) of system
 - Lifetime and duration of particle emission
 - Spatial extent of system at thermal freeze-out
 - Collective flow contribution to evolution
- Single-particle p_T spectra & flow signals also determined by STE, but...
- Bose-Einstein \vec{p} correlations → **disentangle STE**
 - Pairs of pions experience B-E correlations
 - Hanbury-Brown Twiss interferometry (HBT): characterize correlations, **in 3 spatial dimensions**
 - Width of correlation peak as $q \rightarrow 0$ reflects "length of homogeneity", related to source size, *i.e.* HBT "radii"

The big
caveat:

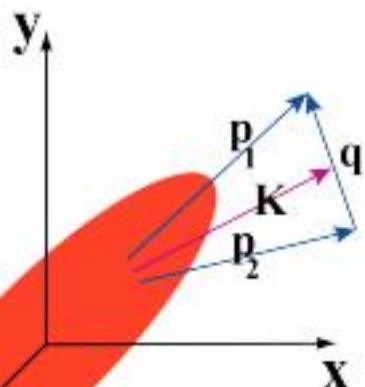
static source: HBT radii \leftrightarrow true geometrical size of system
dynamic source: HBT radii \leftrightarrow flow reduces observed radii
 $\therefore p_T$ dependence of HBT related to collective expansion

Why measure HBT versus the reaction plane?



HBT(ϕ_R)

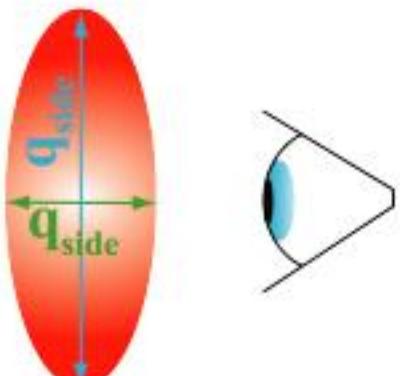
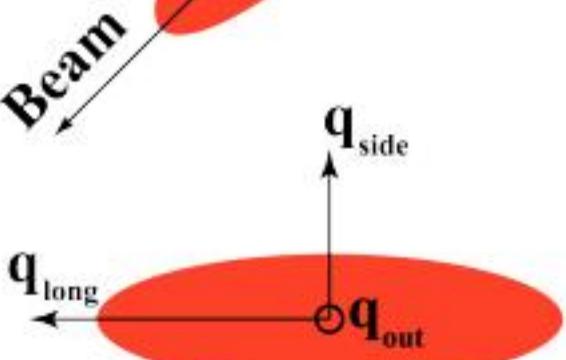
U.W. Heinz, A. Hummel, M.A. Lisa, U.A. Wiedemann:
 Phys. Rev. C66 (2002) 044903



$$R_o^2 = -\frac{1}{2}(\langle \tilde{y}^2 \rangle - \langle \tilde{x}^2 \rangle) \cos 2\phi + \frac{1}{2}(\langle \tilde{y}^2 \rangle + \langle \tilde{x}^2 \rangle) + \beta_\perp^2 \langle \tilde{t}^2 \rangle$$

$$R_s^2 = +\frac{1}{2}(\langle \tilde{y}^2 \rangle - \langle \tilde{x}^2 \rangle) \cos 2\phi + \frac{1}{2}(\langle \tilde{y}^2 \rangle + \langle \tilde{x}^2 \rangle)$$

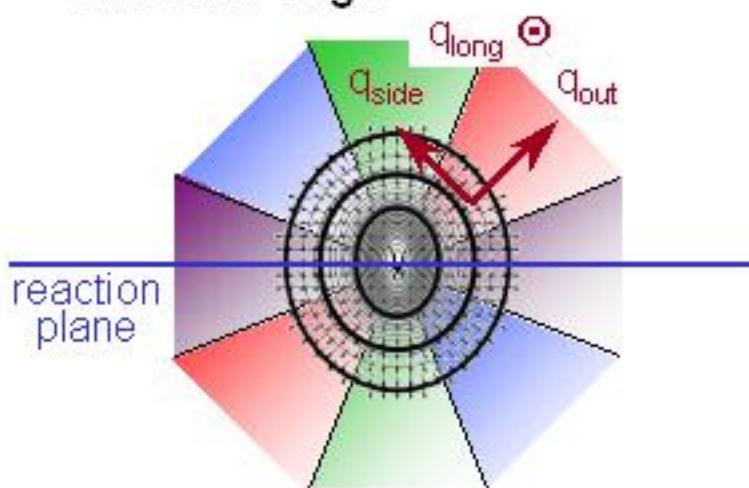
$$R_{os}^2 = +\frac{1}{2}(\langle \tilde{y}^2 \rangle - \langle \tilde{x}^2 \rangle) \sin 2\phi$$



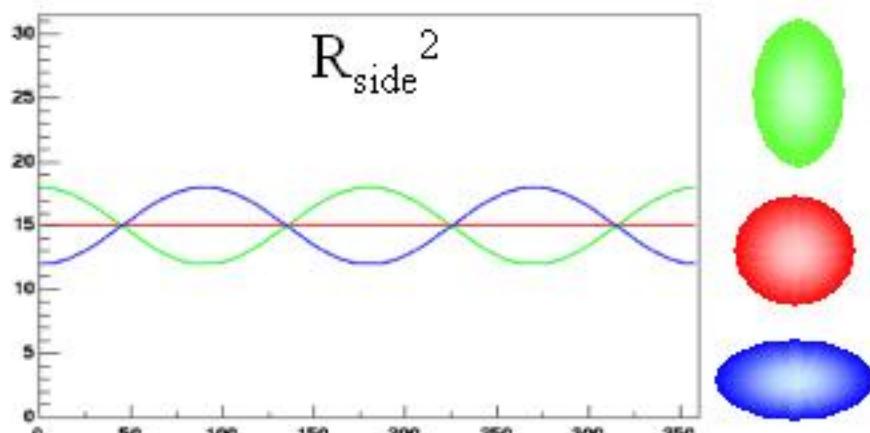
- In HBT versus the reaction plane, x and y can now be related to the source RMS in and out of the reaction plane

What do we expect to see?

HBT radii as a function of emission angle



2nd-order oscillations in HBT radii analogous to momentum-space (v_2)



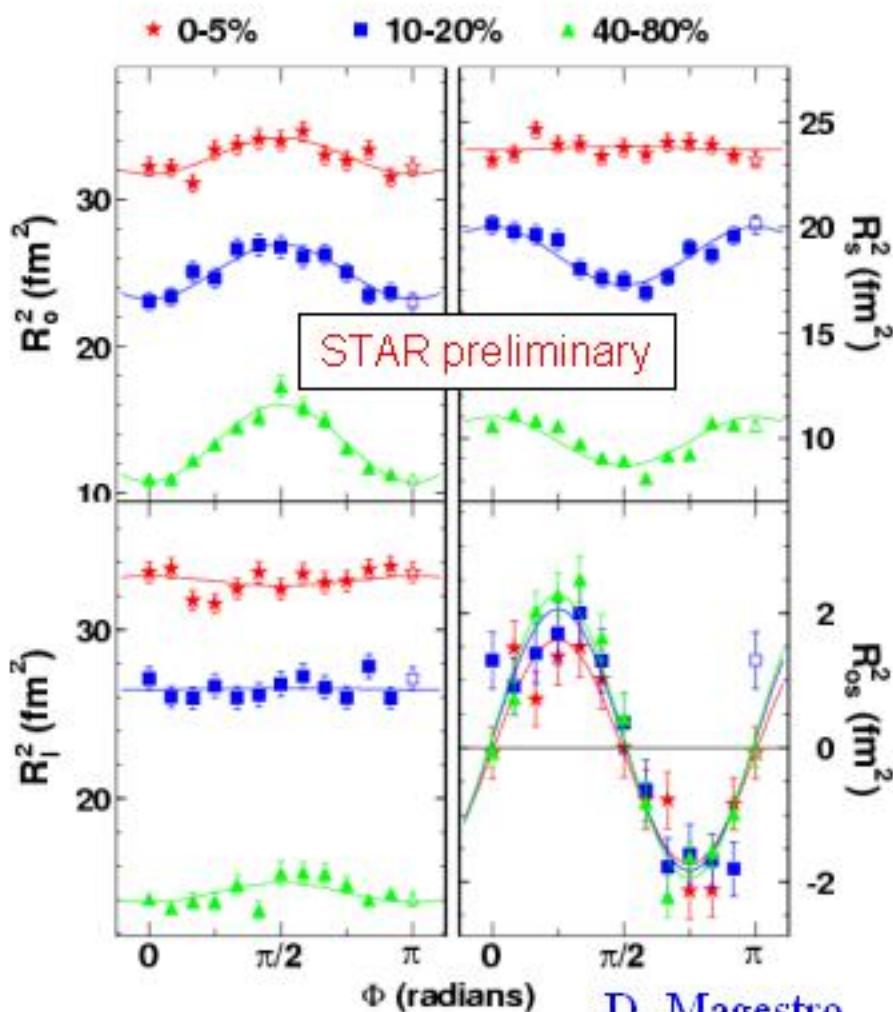
Centrality dependence of the oscillations

- 12 Φ -bin analysis, $0 < \Phi < \pi$
 $(0.15 < k_T < 0.65 \text{ GeV}/c)$

- 15° bins, 72 independent CF's

$$C(\bar{q}, \phi) = 1 + \lambda(\phi) \cdot e^{-\bar{q} \cdot q / R_s^2(\phi)}$$

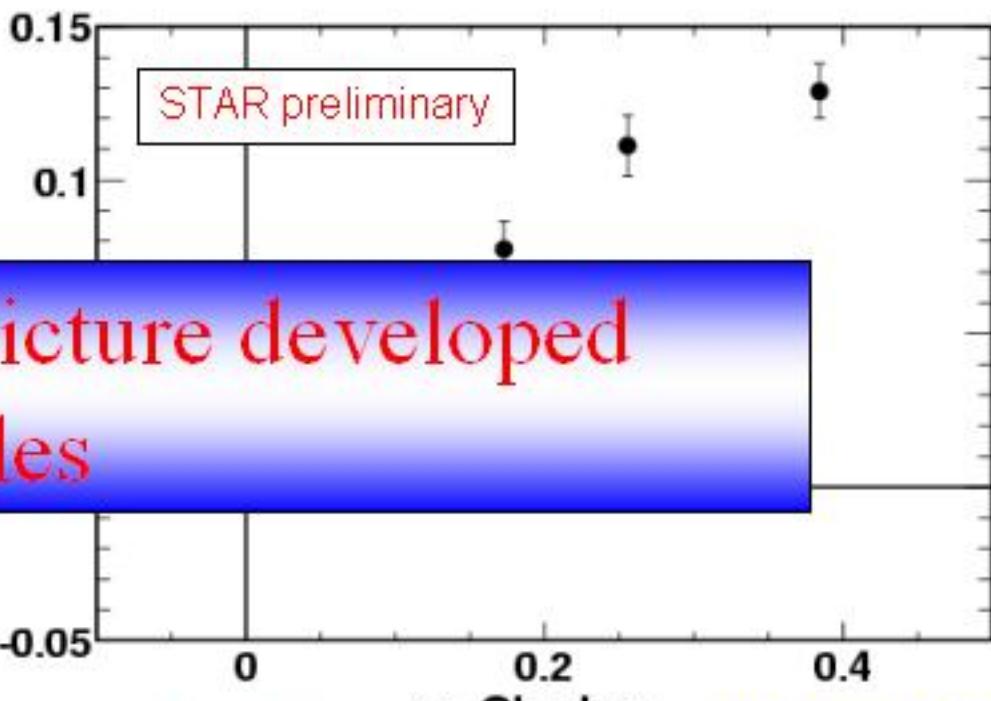
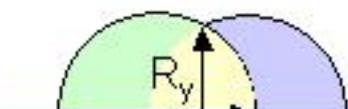
- 2nd-order oscillations of HBT radii are observed
- Lines are fits to allowed oscillations:
 - out, side, long go as $\cos(2\Phi)$
 - out-side goes as $\sin(2\Phi)$
- Amplitudes weakest for 0-5%
(makes sense in geometrical interpretation)



Initial versus final source shape

Initial eccentricity

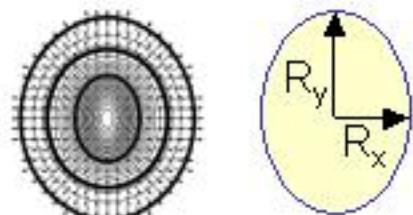
Glauber model: Initial geometry is related to number of participants



Final

HBT

relative amplitudes of oscillations



doesn't have temporal component

$$\varepsilon \equiv \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2} = 2\vartheta, \quad \vartheta = \frac{R_{os,2}^2}{R_{s,0}^2} = \frac{R_{s,2}^2}{R_{s,0}^2} = -\frac{R_{o,2}^2}{R_{s,0}^2}$$

D. Magestro

Calculating flow using multi particle correlations

$$v_n = \langle \cos n(\phi - \Psi_r) \rangle = \langle e^{in(\phi - \Psi_r)} \rangle$$

$$\langle e^{in(\phi_1 - \phi_2)} \rangle = \langle e^{in(\phi_1 - \Psi_r)} e^{in(\Psi_r - \phi_2)} \rangle \approx \langle e^{in(\phi_1 - \Psi_r)} \rangle \langle e^{in(\Psi_r - \phi_2)} \rangle = (v_n\{2\})^2$$

Assumption all correlations between particles due to flow

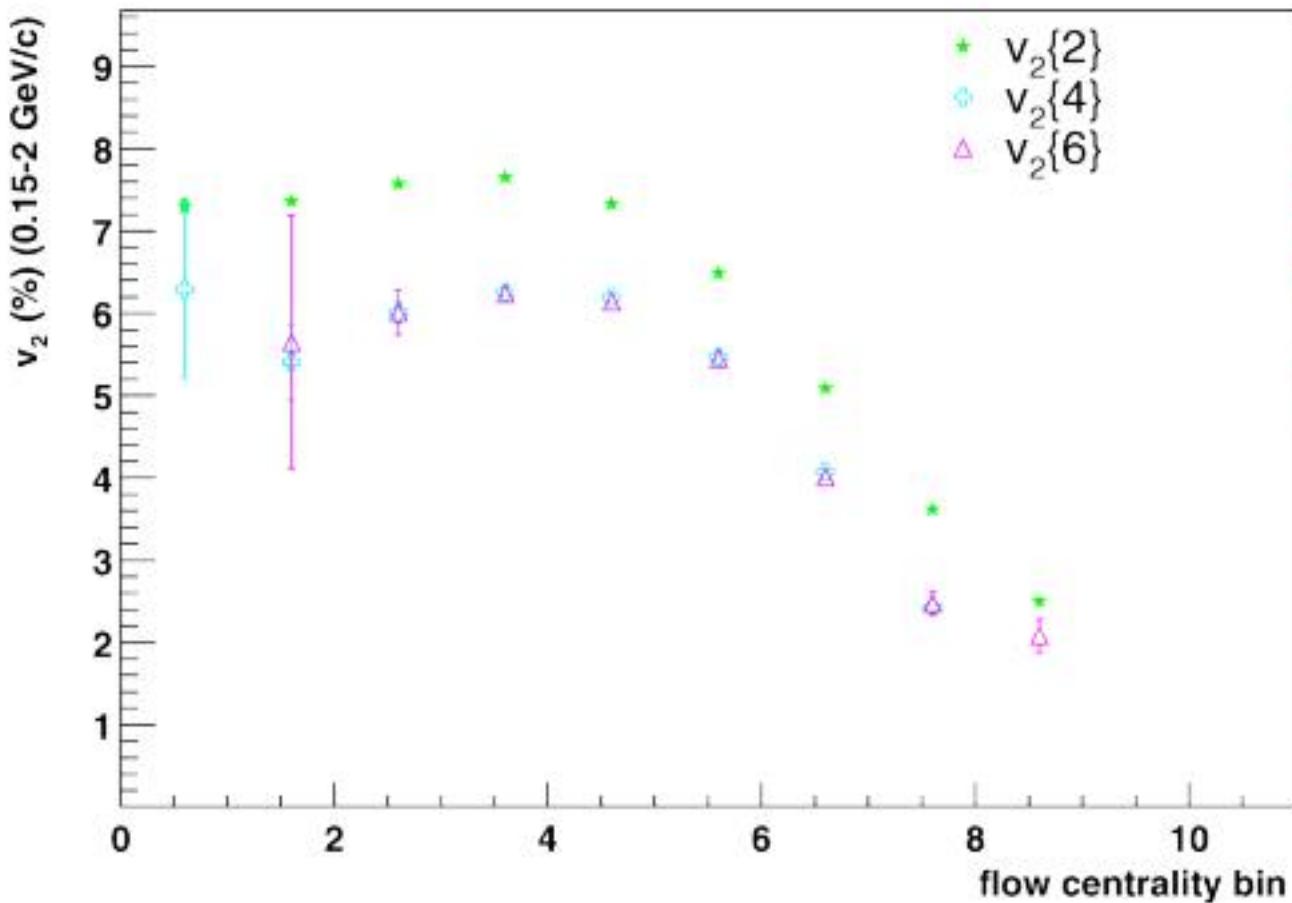
Non flow correlation contribute order (1/N), problem if $v_n \approx 1/N$

$$\langle e^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)} \rangle - \langle e^{in(\phi_1 - \phi_2)} \rangle \langle e^{in(\phi_3 - \phi_4)} \rangle - \langle e^{in(\phi_1 - \phi_4)} \rangle \langle e^{in(\phi_3 - \phi_2)} \rangle \approx -(v_n\{4\})^4$$

Non flow correlation contribute order (1/N³), problem if $v_n \approx 1/N^{3/2}$

N. Borghini, P.M. Dinh and J.-Y Ollitrault, Phys. Rev. C63 (2001) 054906

Integrated v_2 from cumulants



About 20% reduction from $v_2\{2\}$ to $v_2\{4\}$
 $v_2\{4\} \approx v_2\{6\}$

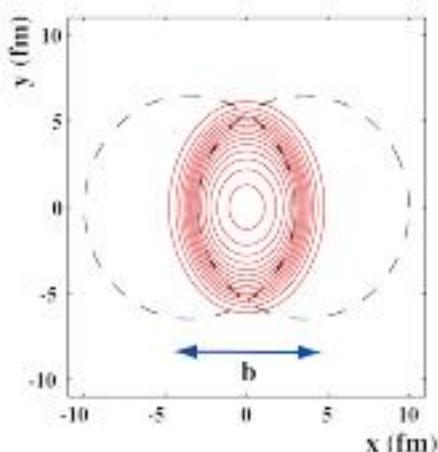
STAR, PRC 66,(2002) 034904

Raimond Snellings; CERN Heavy Ion Forum

Fluctuations

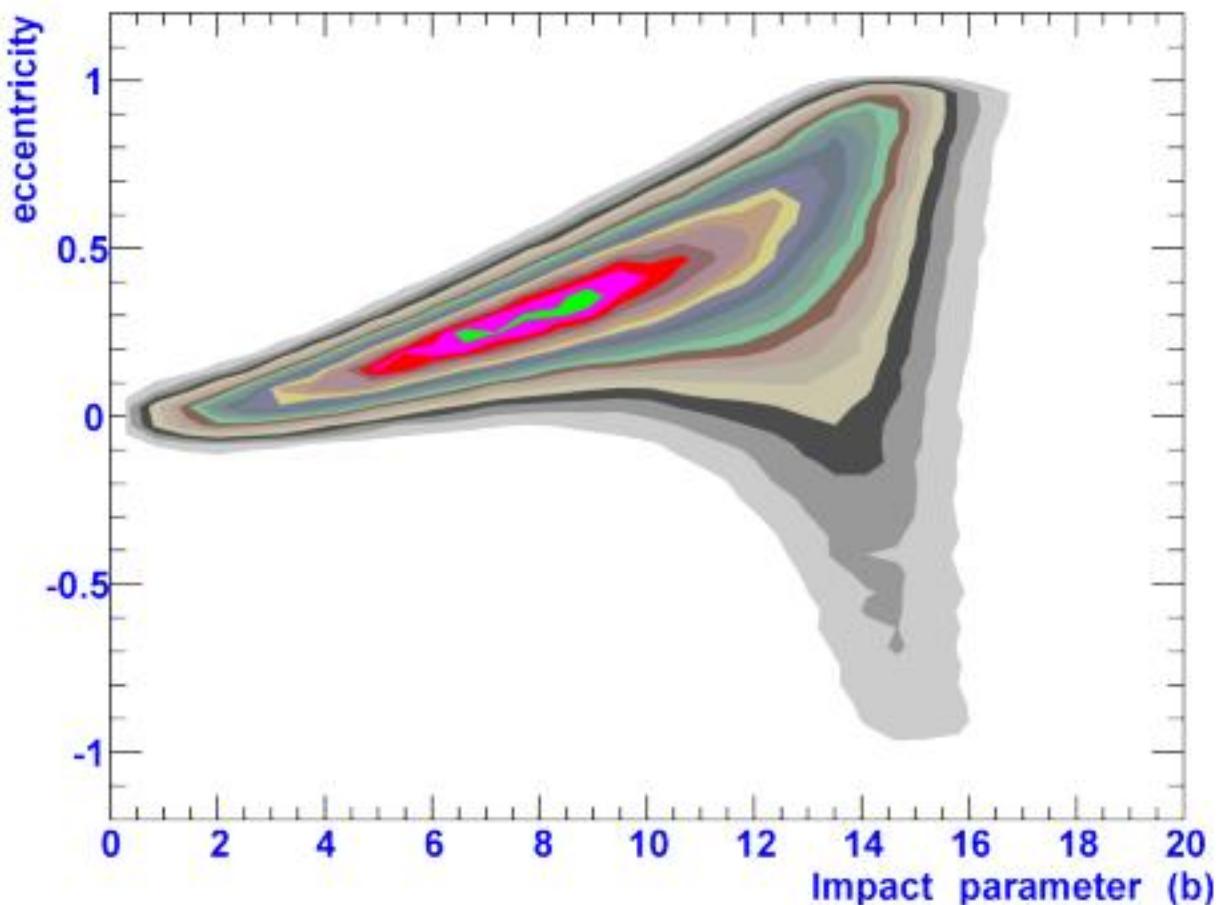
- Multi-particle correlations are used to give a better estimate of v_2 , because they are less sensitive to “non-flow”. They do however rely on higher powers of v_2 . In case of event-by-event fluctuations in v_2 in general $\langle v_2^n \rangle \neq \langle v_2 \rangle^n$ which will lead to an over correction of v_2 when using a cumulant approach
- Fluctuations in eccentricity, ε , are expected and due to the fact that $v_2 \otimes \varepsilon$ this will introduce fluctuations in v_2 . This can be estimated in the framework of a **Monte Carlo Glauber** calculation. This also gives an lower limit on how big v_2 fluctuations due to more interesting physics reasons should be before they can be used to argue for a solid physics case

non-flow or fluctuations?

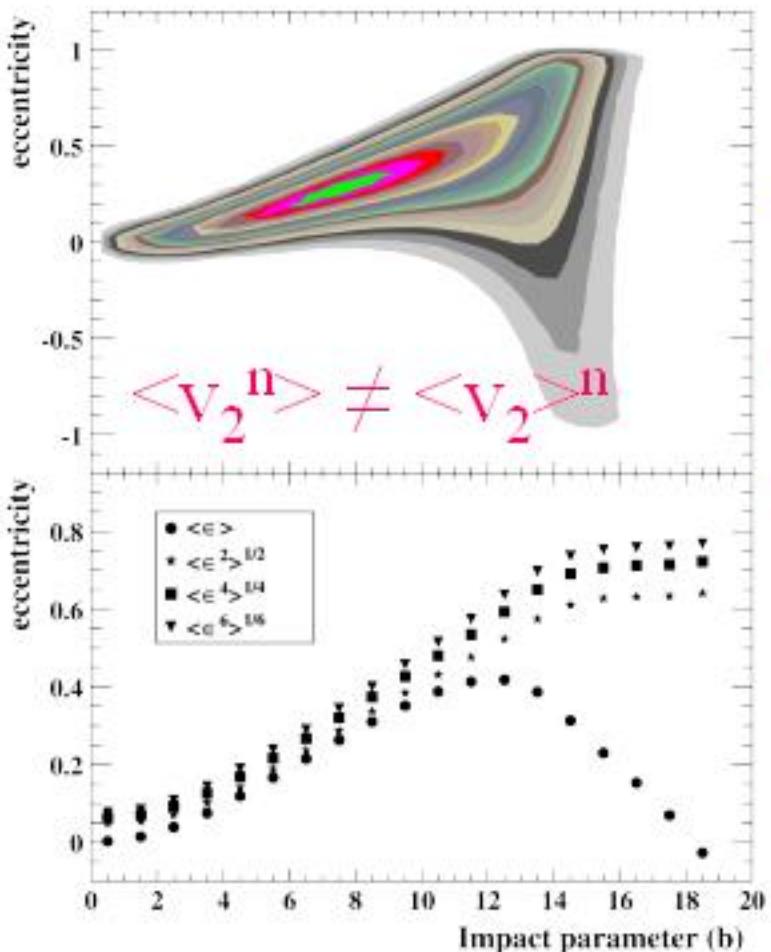


$$\varepsilon \equiv \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

$$v \propto \varepsilon$$



Higher moments

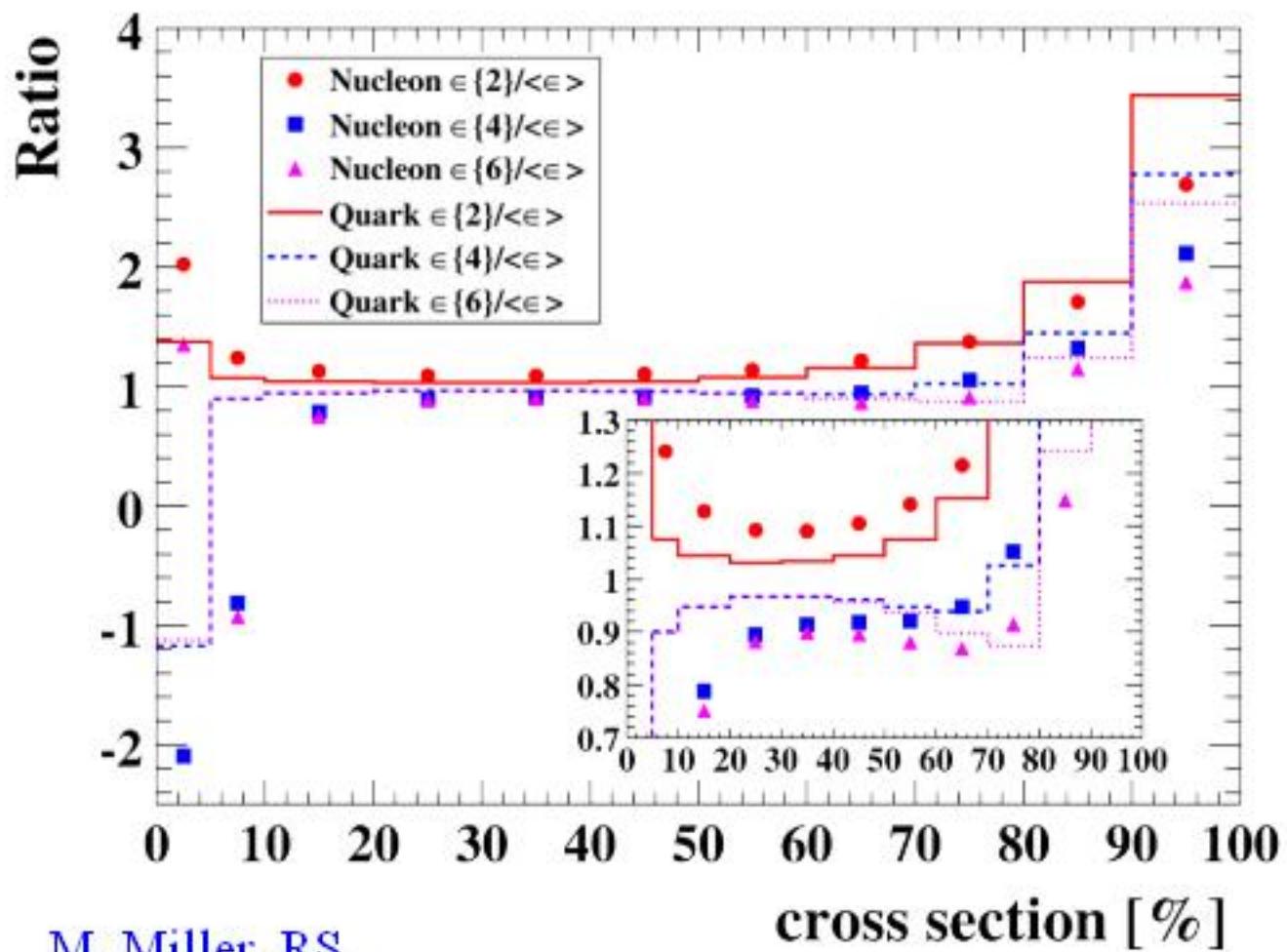


$$v_2\{2\} = \sqrt{\langle v_2^2 \rangle}$$

$$v_2\{4\} = \left(2 \langle v_2^2 \rangle^2 - \langle v_2^4 \rangle \right)^{1/4}$$

$$v_2\{6\} = \left(\frac{1}{4} \left(\langle v_2^6 \rangle - 9 \langle v_2^4 \rangle \langle v_2^2 \rangle + 12 \langle v_2^2 \rangle^3 \right) \right)^{1/6}$$

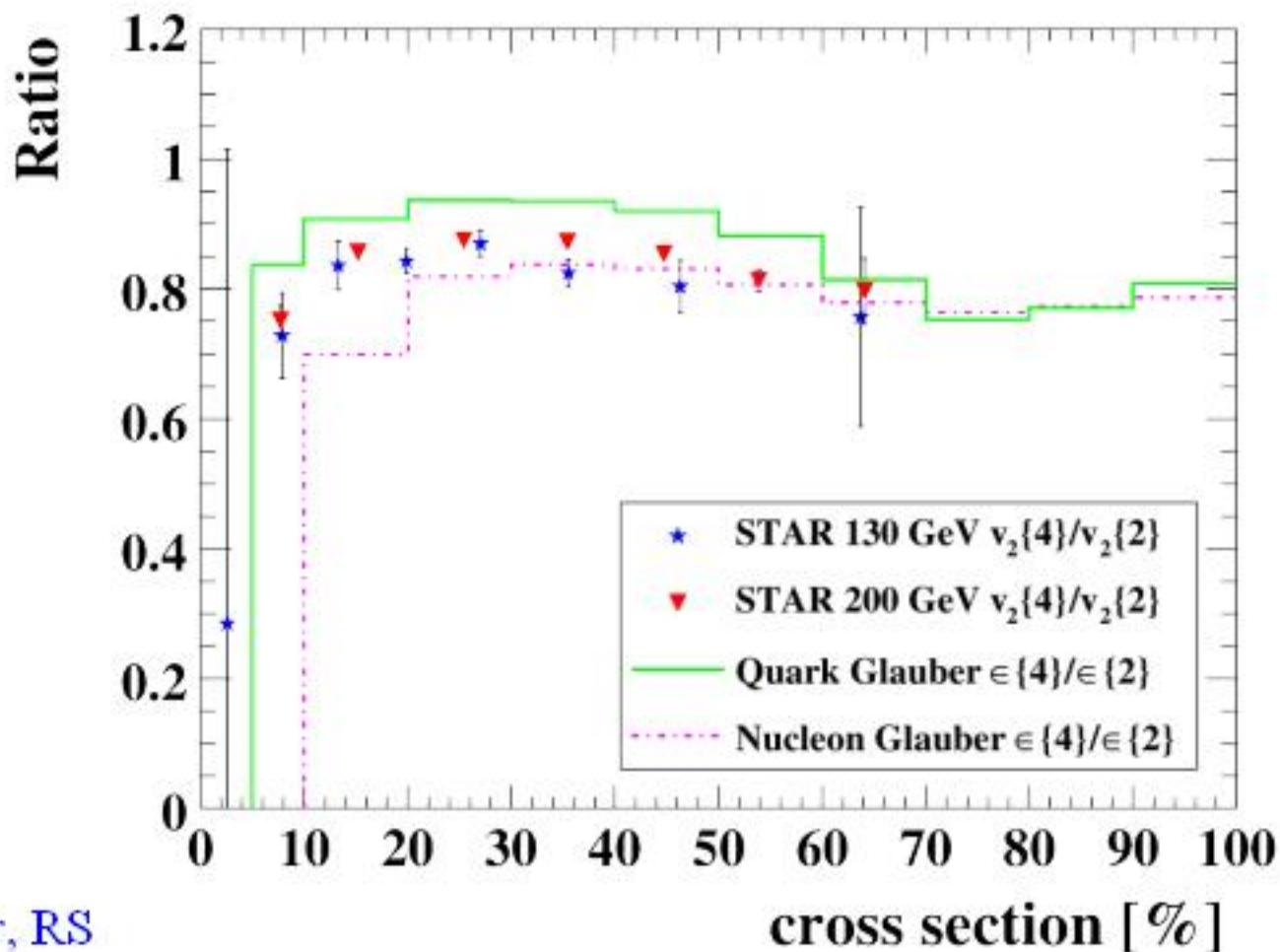
The fluctuation contribution to v_2



“standard”
 $v_2\{2\}$
 overestimates
 v_2 by 10%,
 higher order
 cumulant
 underestimate
 v_2 by 10% at
 intermediate
 centralities

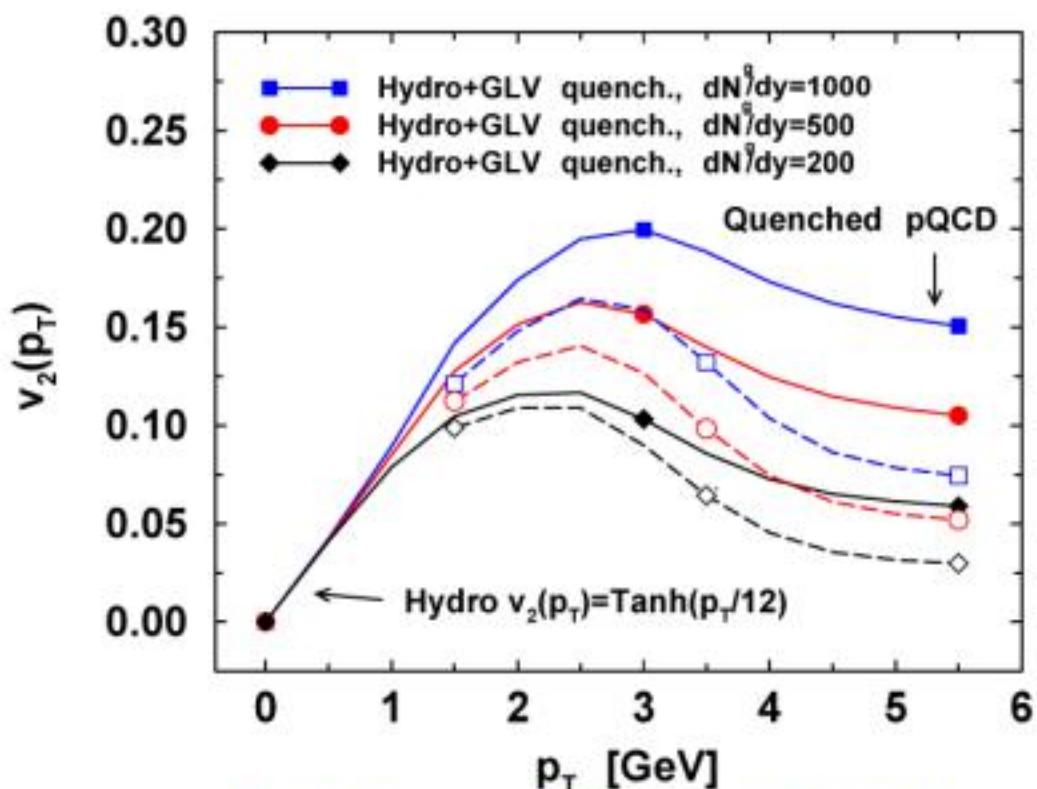
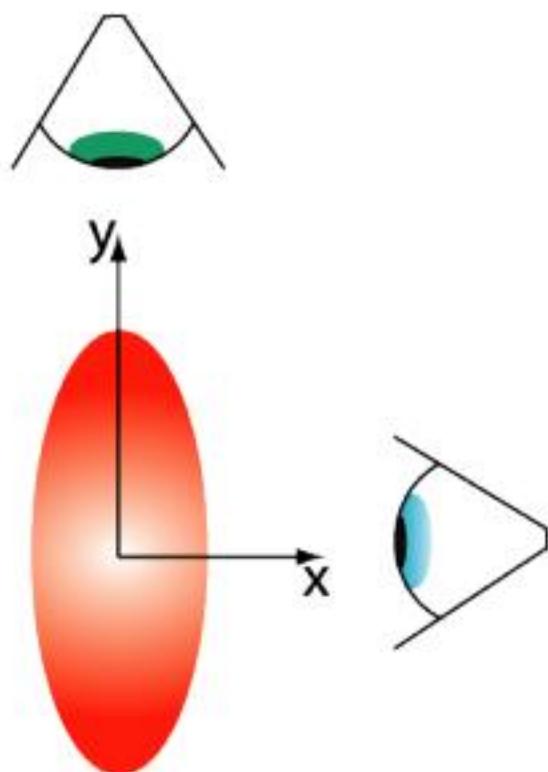
M. Miller, RS

Compare fluctuations to data



M. Miller, RS

$v_2(p_t)$ for high p_t particles (self normalizing tomography of dense matter)



<http://www.lbl.gov/nsd/annual/rbf/nsd1998/rnc/RNC.htm>

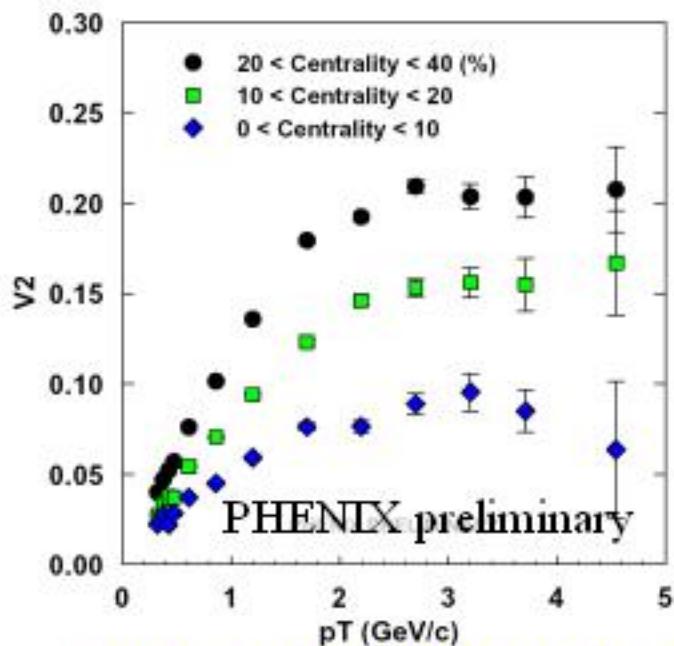
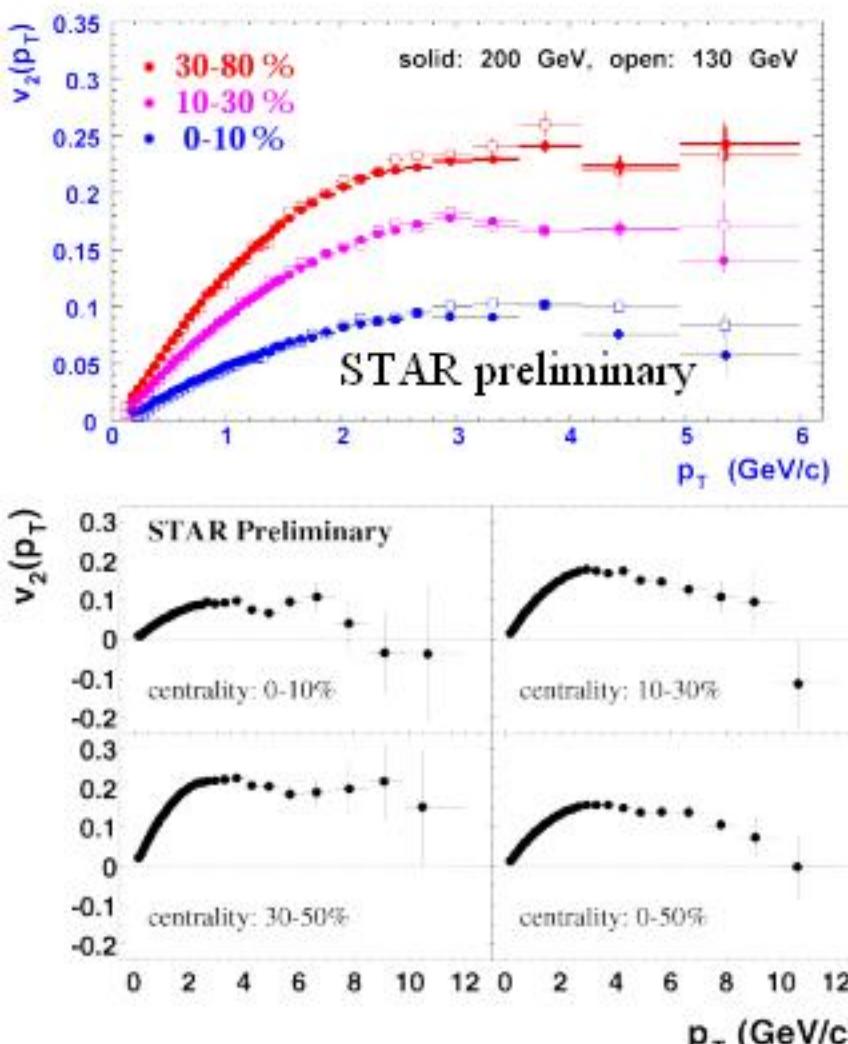
R17. Event Anisotropy as a Probe of Jet Quenching

R.S and X.-N. Wang

R.S, A.M. Poskanzer, S.A. Voloshin, STAR note, nucl-ex/9904003

M. Gyulassy, I. Vitev and X.N. Wang

Charged particle v_2 at high- p_T



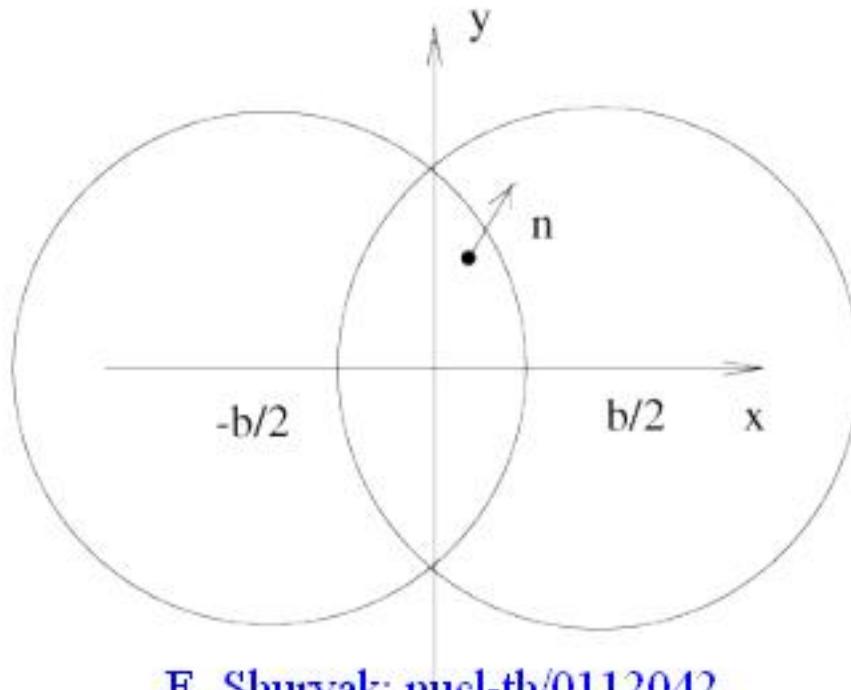
N. N. Ajitanand: Nucl.Phys. A715
(2003) 765-768

K. Filimonov: Nucl.Phys. A715 (2003) 737-740

Raimond Snellings; CERN Heavy
Ion Forum

Why is v_2 so large at higher- p_t ?

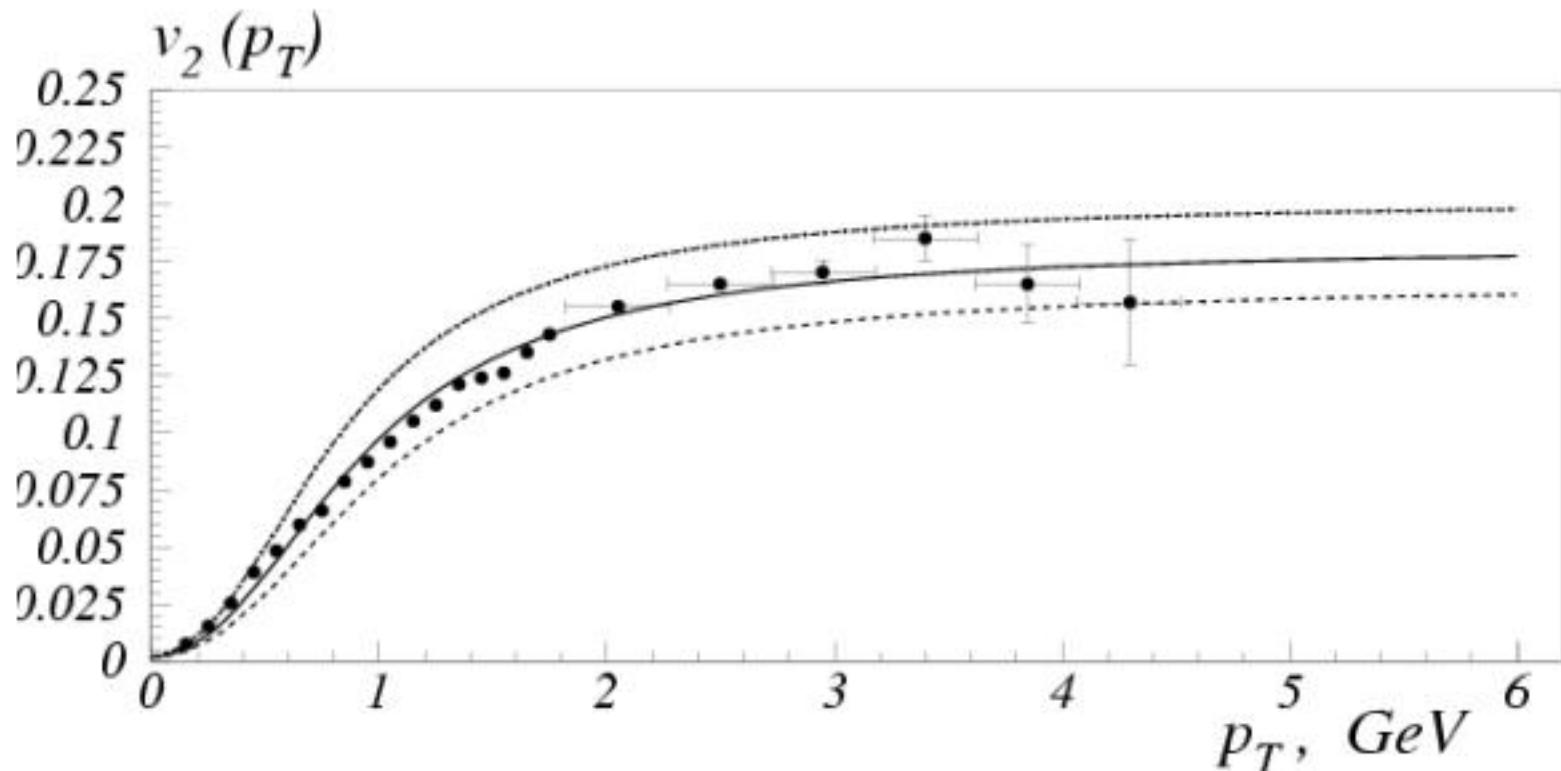
Measured v_2 values seem to be larger than the maximum values in the case of extreme quenching \rightarrow surface emission



E. Shuryak: nucl-th/0112042

Centrality %	$< f >$	v_2^*/s_2	v_2^*	v_2^{STAR}
0-11	.018	.32	.042	.12 \pm 0.02
11-34	.027	.35	0.12	.16 \pm 0.02
34-85	.046	.31	0.16	.22 \pm 0.02

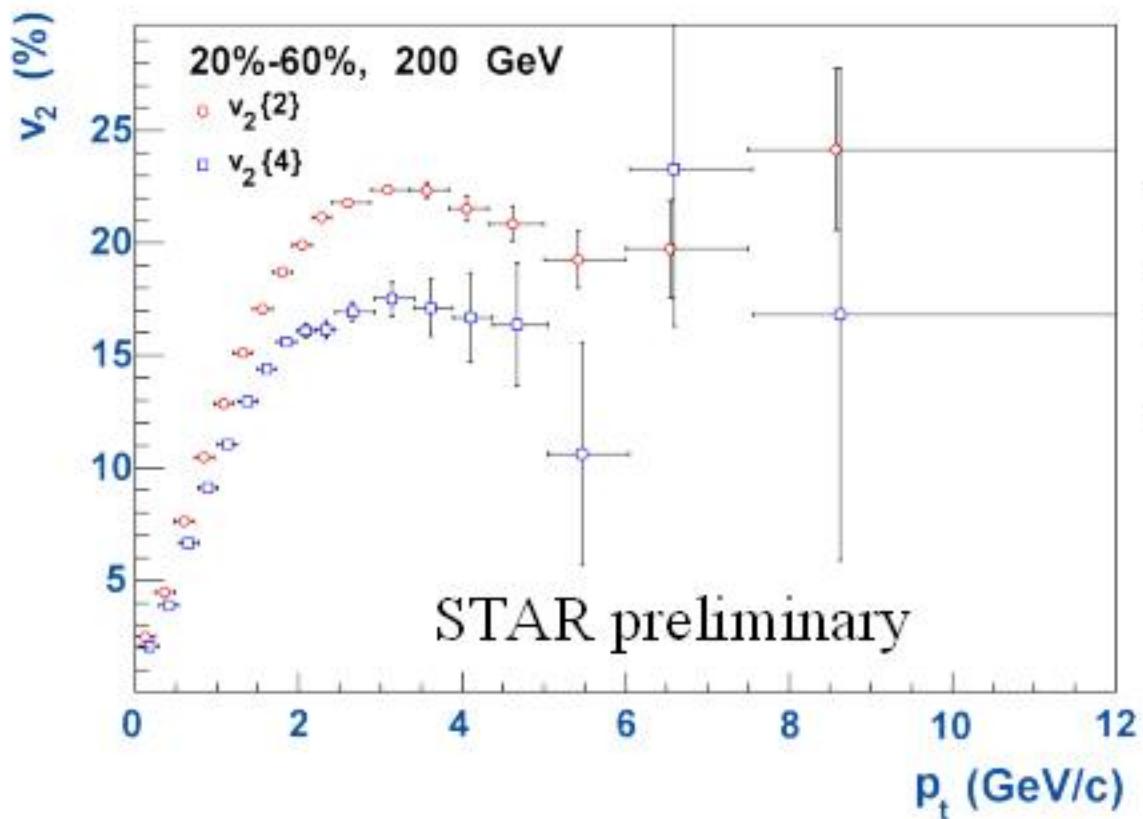
Is it all non-flow?



Yuri V. Kovchegov and Kirill L. Tuchin hep-ph/0203213

STAR data: RS, Nucl.Phys. A698 (2002) 193-198

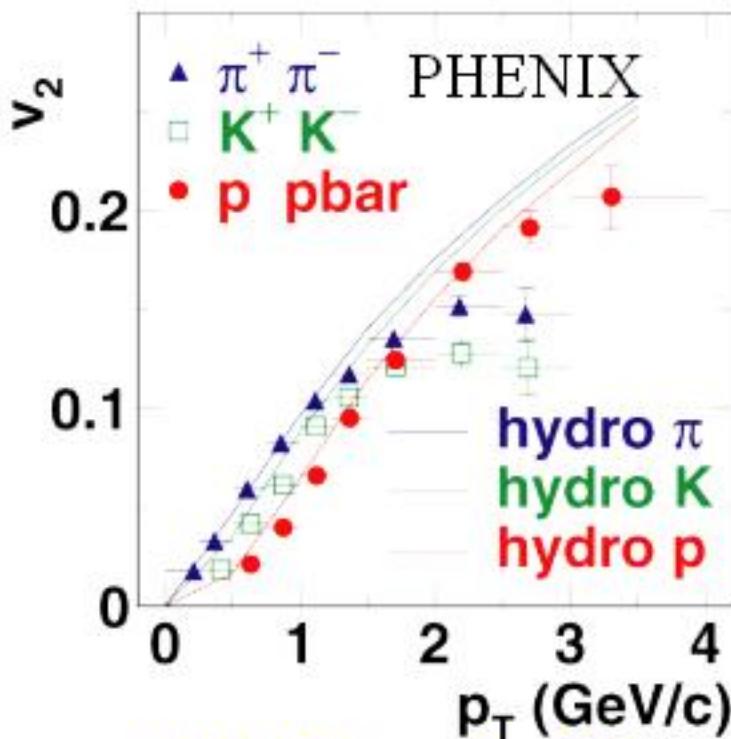
Is it all non-flow at high- p_t ?



Above 6 GeV we do not have a reliable answer (yet)
what the real flow contribution is

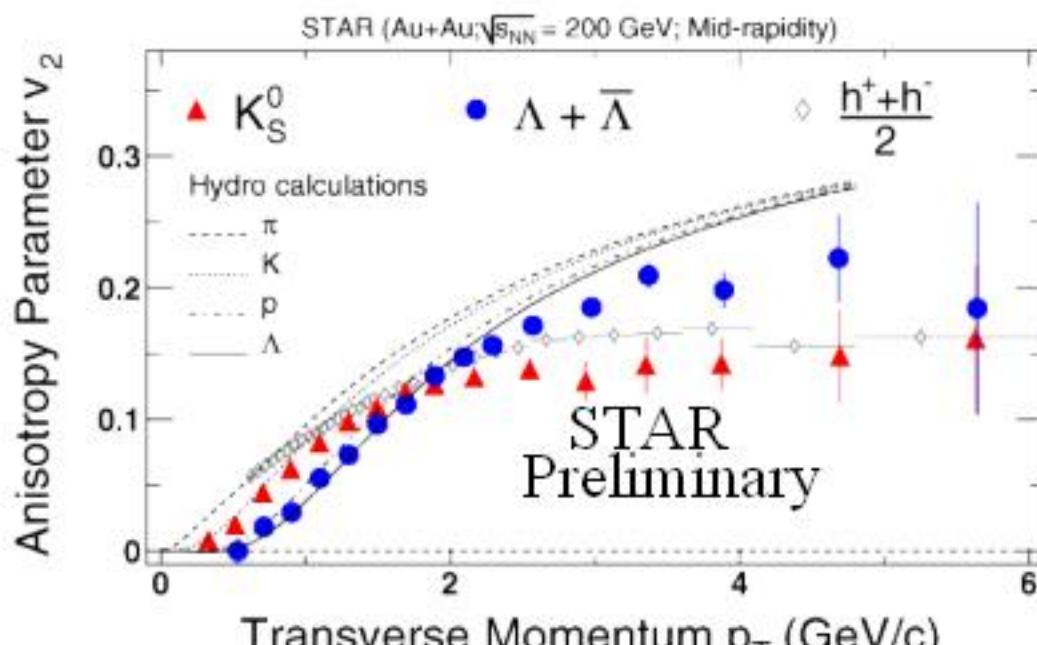
A. Tang

More detailed information: $v_2(p_t)$ for identified particles at higher- p_t



Shinichi Esumi: Nucl.Phys.

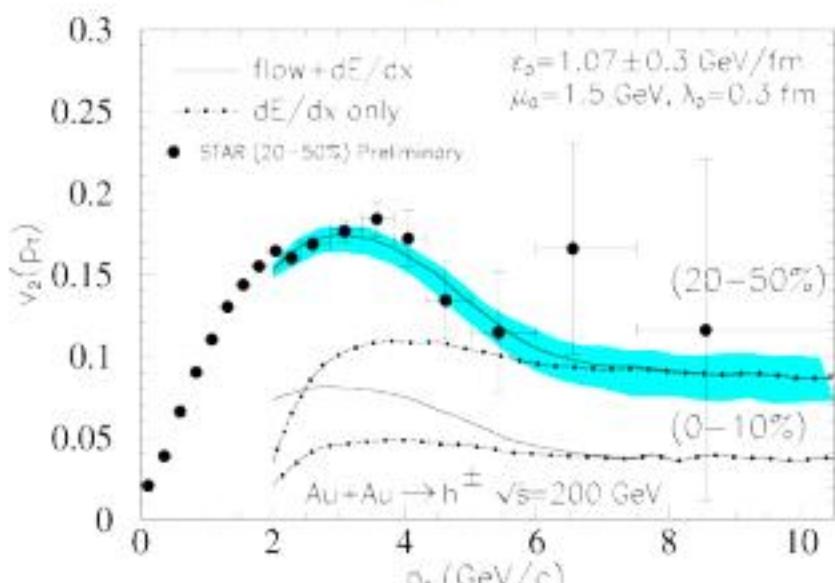
A715 (2003) 599-602



STAR Preliminary

P. Sorensen

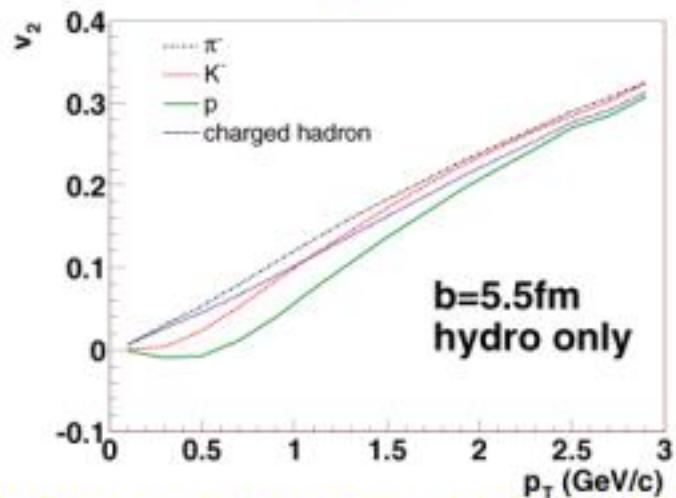
Hydro + Jet Quenching?



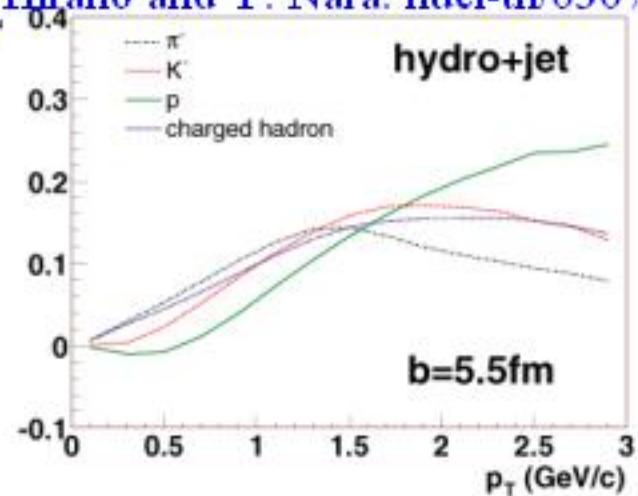
X.-N. Wang: nucl-th/0305010

Coupling of hydro and parton energy loss gives a reasonable description of the data and also has a mass dependence at higher- p_t

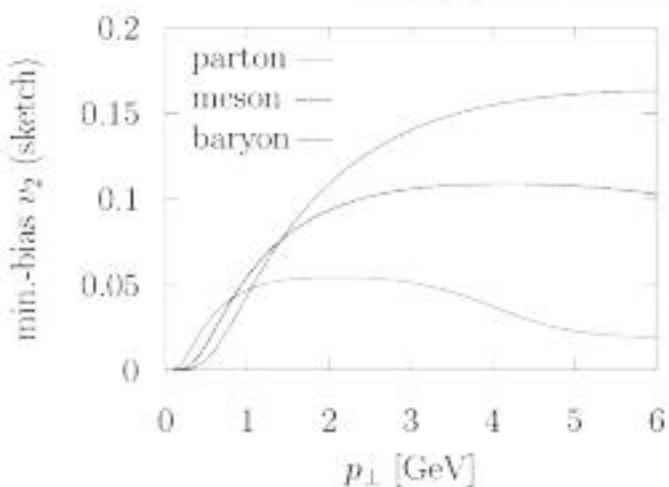
Raimond Snellings; CERN Heavy Ion Forum



T. Hirano and Y. Nara: nucl-th/0307015

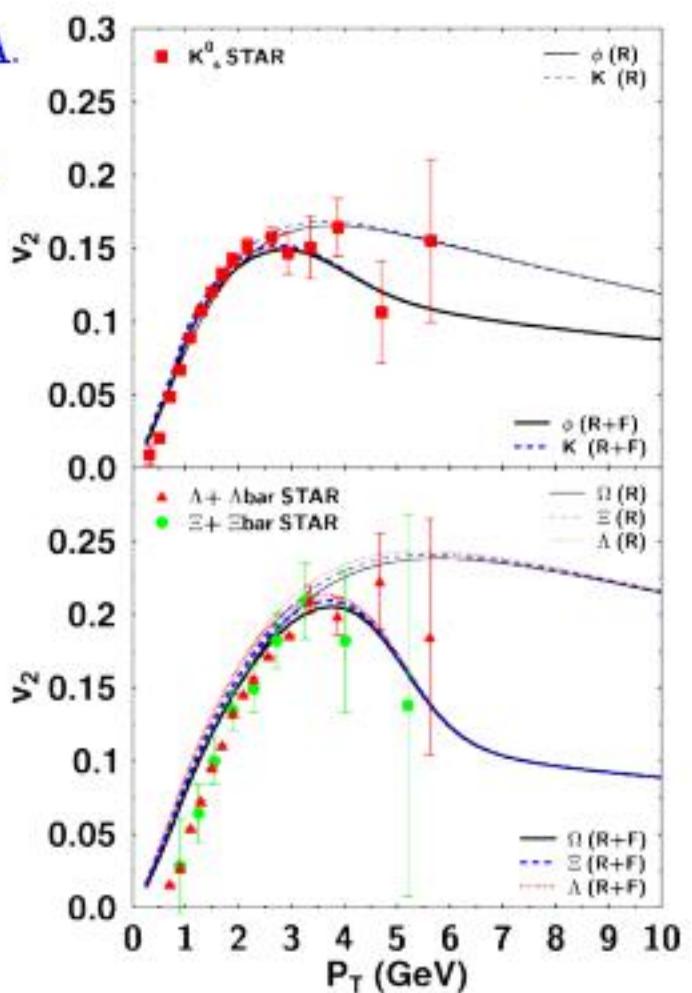
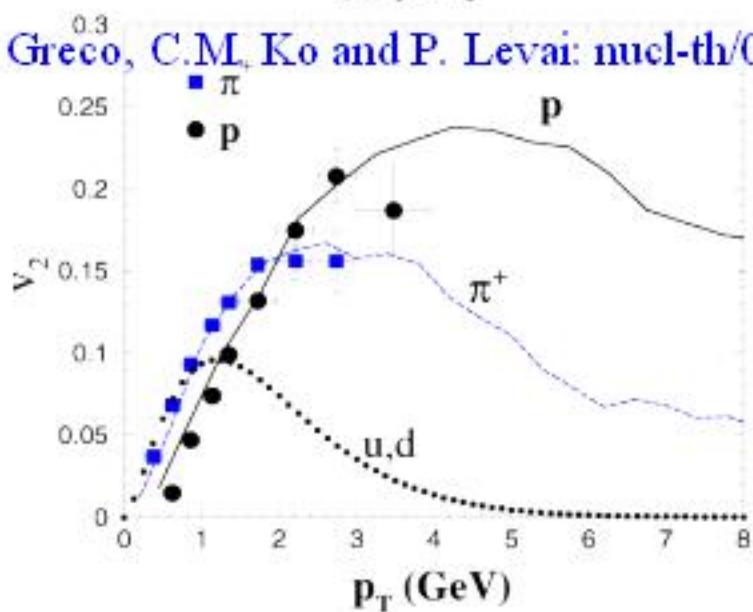


Parton Coalescence?



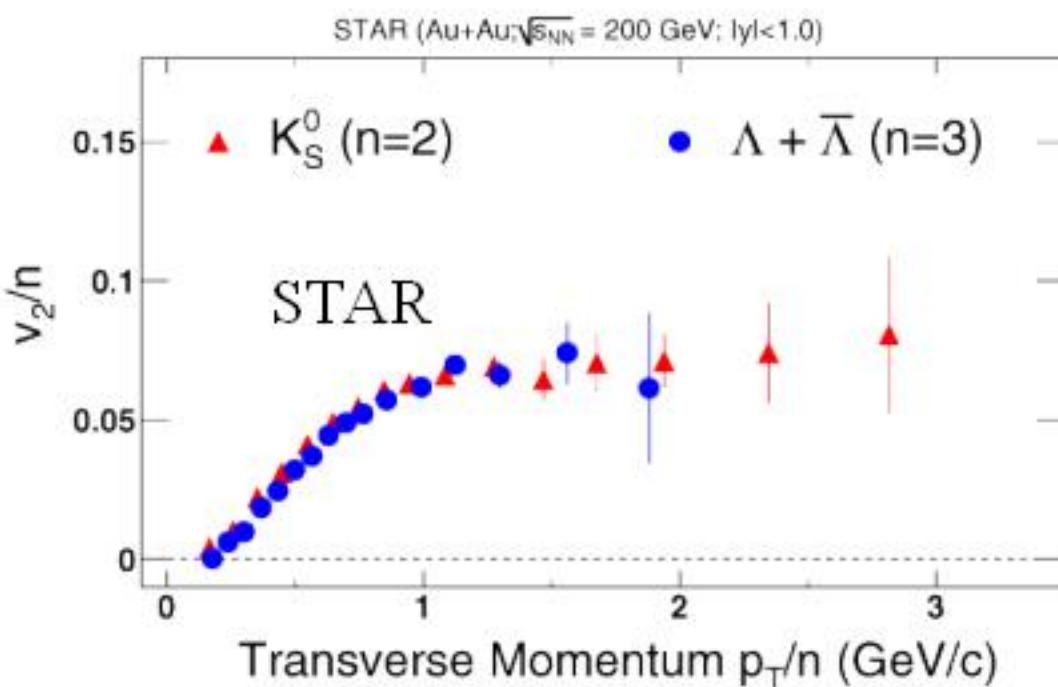
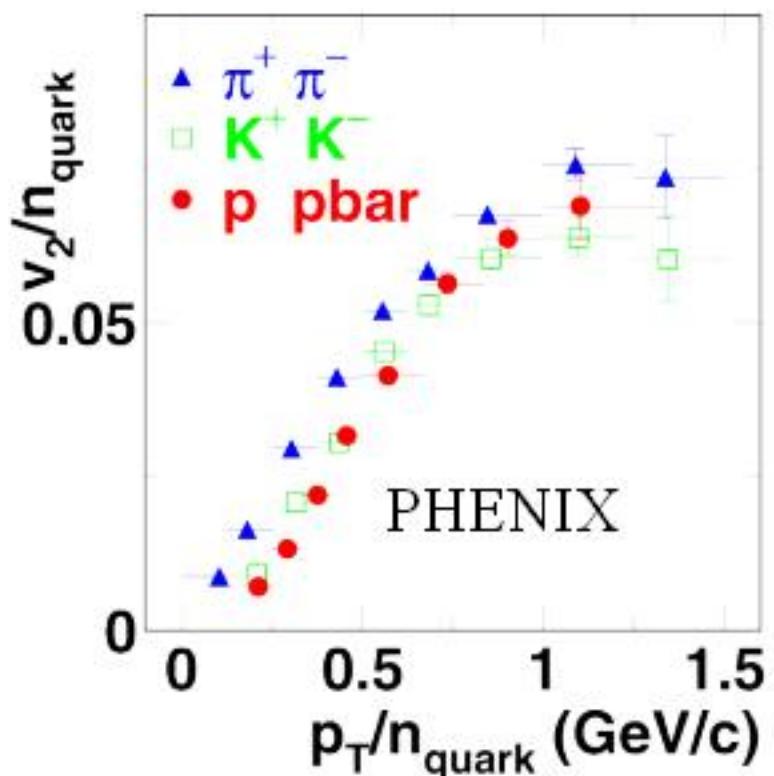
D. Molnar, S.A.
Voloshin:
Phys.Rev.Lett.
91 (2003)
092301

V. Greco, C.M. Ko and P. Levai: nucl-th/0305024



C. Nonaka, R.J. Fries, S.A. Bass
nucl-th/0308051

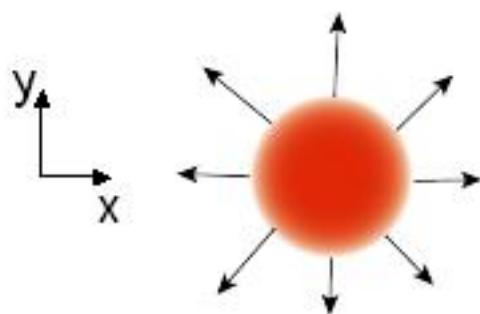
Parton Coalescence



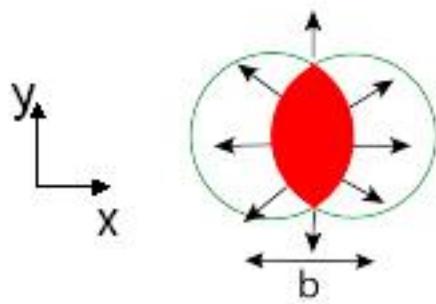
Summary: v_2 at intermediate p_t

- v_2 up to 6 GeV/c is large; consistent with energy loss picture
- Charged particle v_2 up to 6 GeV/c is not dominated by non-flow effects
- Identified particle v_2 shows “fine splitting” at intermediate p_t
- Particle dependence at intermediate p_t is expected both in hydro + jet picture as in parton coalescence. Parton coalescence also provides a “natural” way to get the large v_2 values
- Real test which picture is more correct will come with a measurement of v_2 at intermediate p_t of the ϕ -meson and the Ω

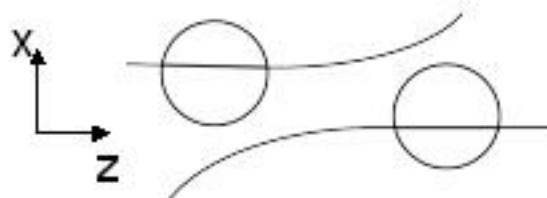
Flow (radial, directed and elliptic)



- Only type of transverse flow in central collision ($b=0$) is transverse flow.
- Integrates pressure history over complete expansion phase

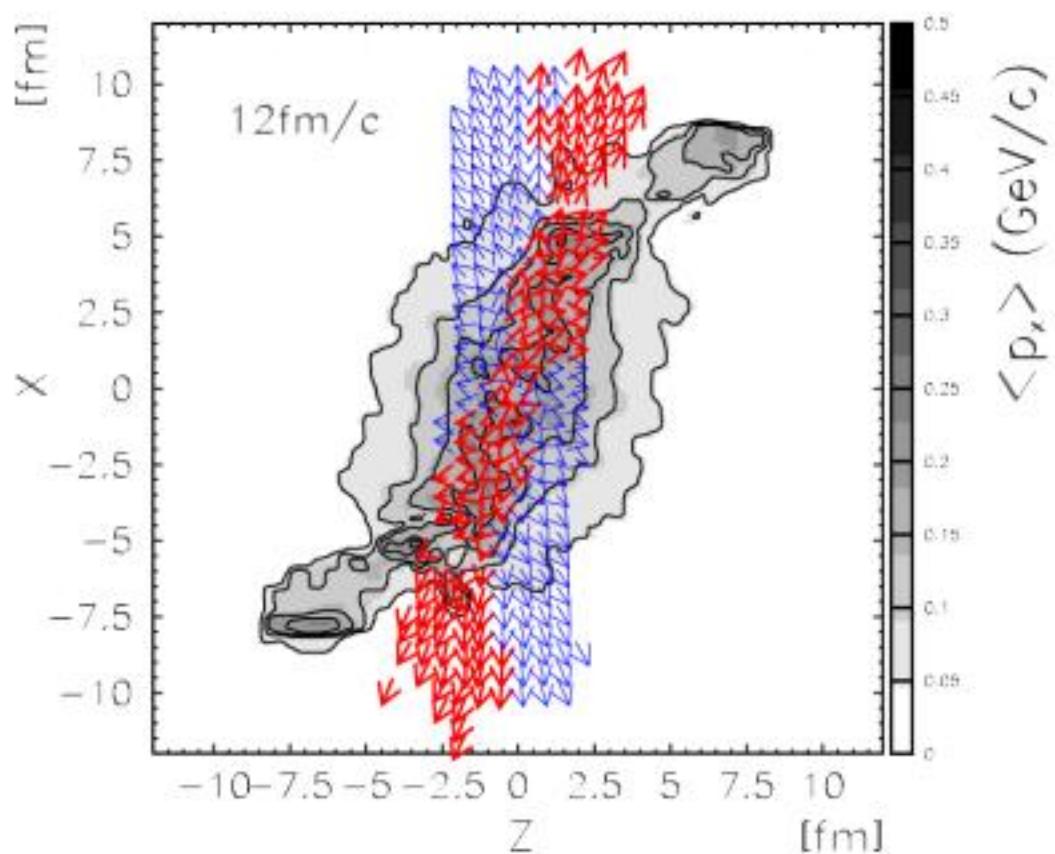


- Elliptic flow, caused by anisotropic initial overlap region ($b > 0$).
- More weight towards early stage of expansion.

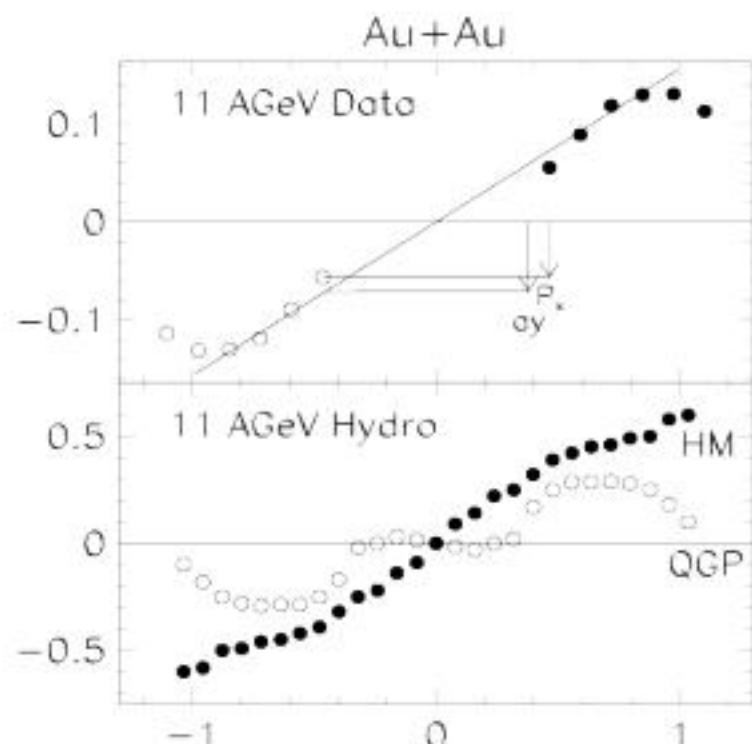


- Directed flow, sensitive to earliest collision stage (pre-equilibrium, $b > 0$)

v_1 predictions (QGP invoked)

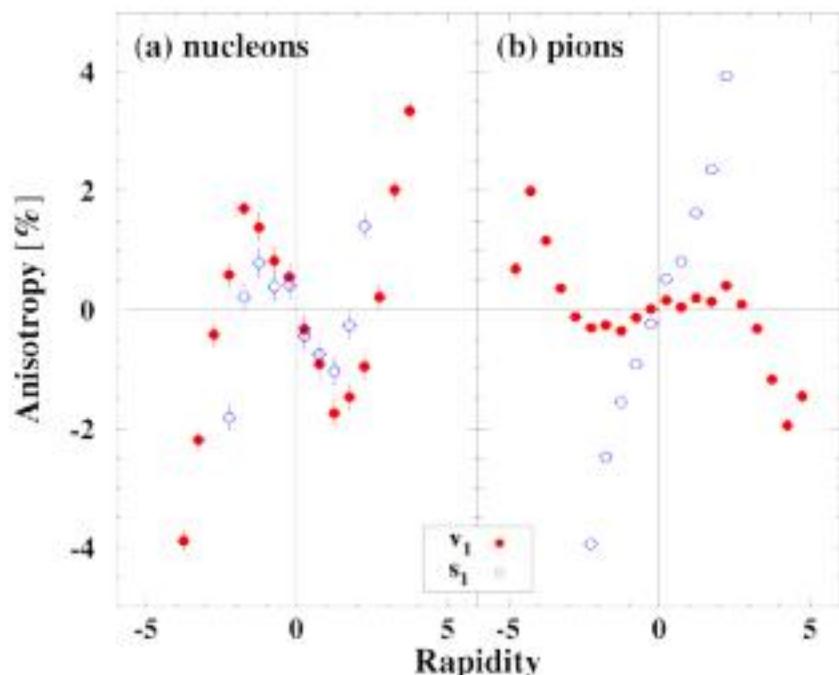
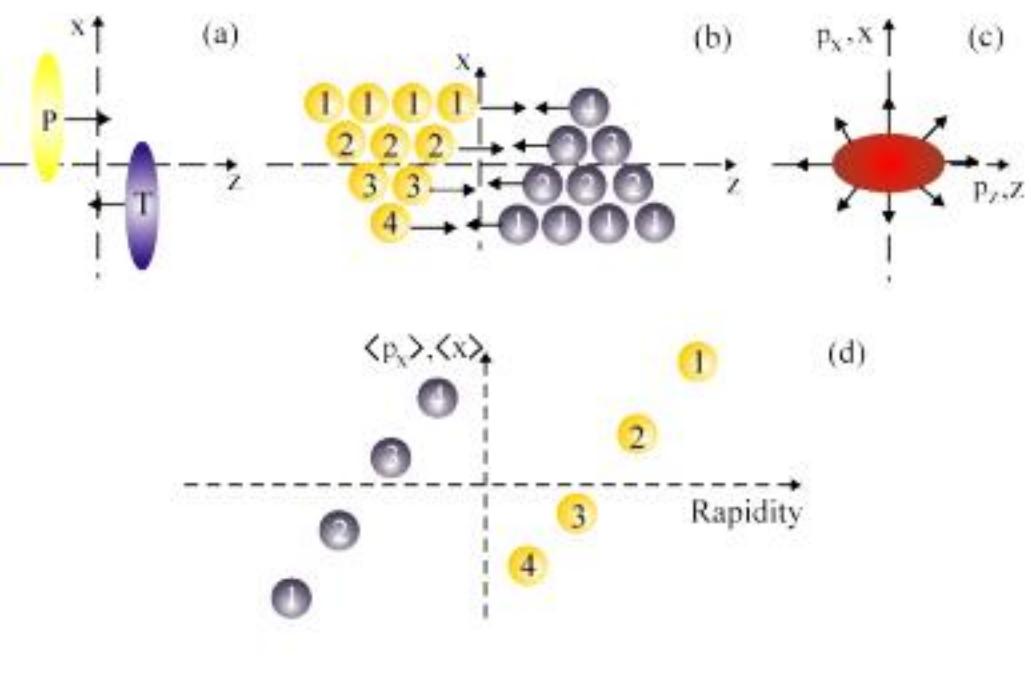


J. Brachmann et al., Phys. Rev. C 61 024909 (2000)



L.P. Csernai, D. Rohrich:
Phys. Lett. B 458 (1999)
454

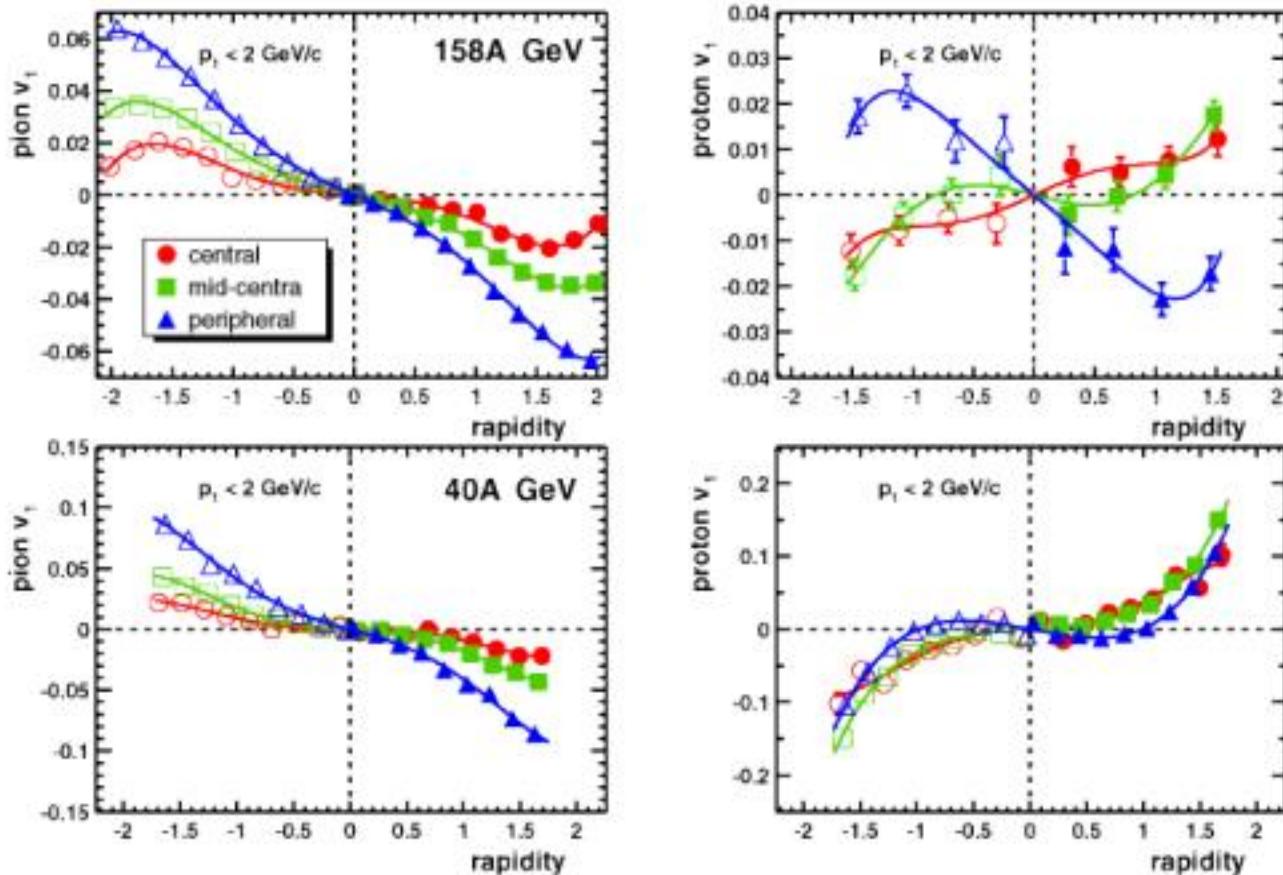
v_1 predictions (more general, QGP interpretation not necessary)



R.S., H. Sorge, S.A. Voloshin, F.Q. Wang, N. Xu: Phys. Rev. Lett 84 2803 (2000)

M. Bleicher, H. Stocker: Phys. Lett. B 526 (2002) 309 (UrQMD)

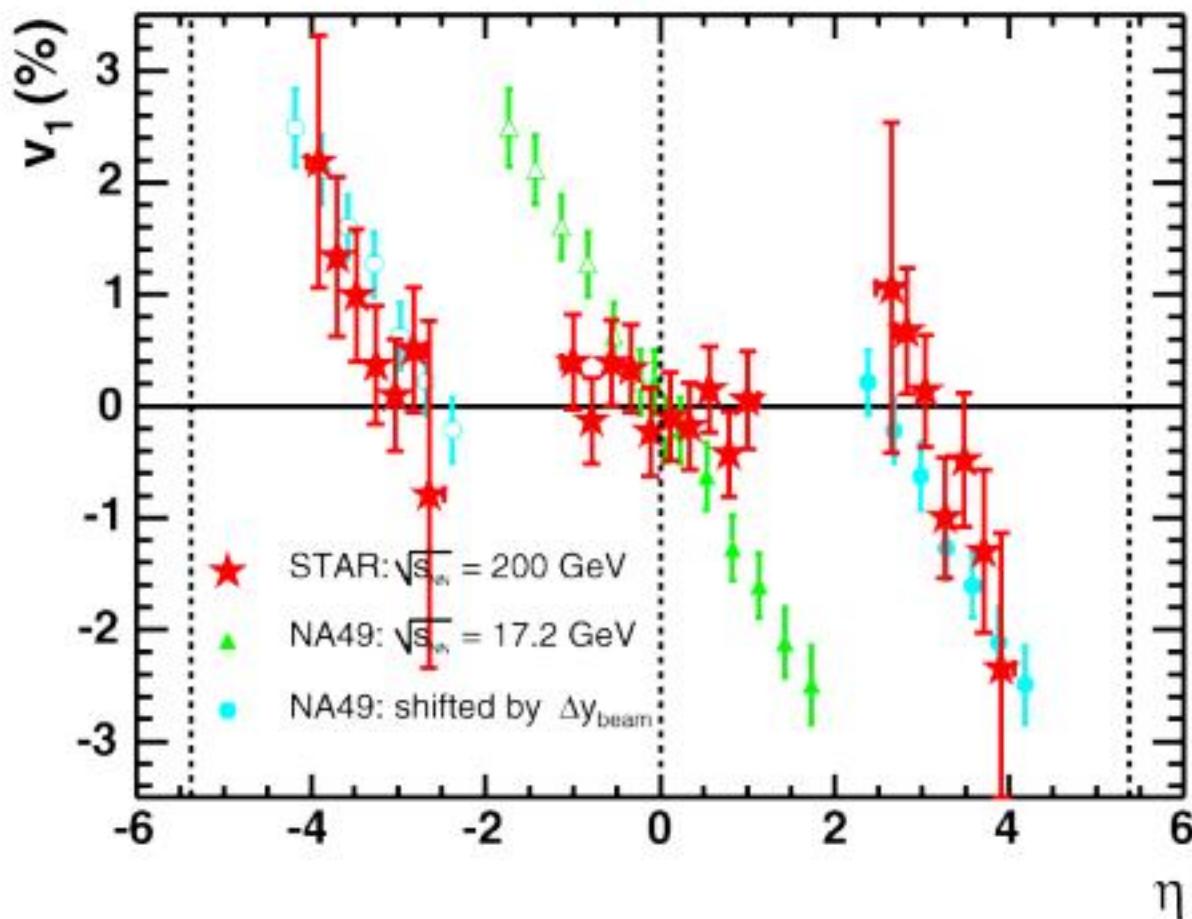
Directed flow at the SPS (NA49)



NA49: Phys.Rev. C68 (2003) 034903

First measurement of v_1 at RHIC

- Confirms v_2 is in-plane at RHIC
- Suggestive of limiting fragmentation picture
- Consistent with theory predictions
- The data with current statistics shows no sign of a wiggle (also does not exclude the magnitude of the wiggle as predicted)



A. Tang, M. Oldenburg, A. Poskanzer, J. Putschke, RS, S. Voloshin

What have we learned from elliptic flow at RHIC

- **L. McLerran**: one needs very strong interactions amongst the quark and gluons at very early times in the collision (hep-ph/0202025).
- **U. Heinz**: resulting in a well-developed quark-gluon plasma with almost ideal fluid-dynamical collective behavior and a lifetime of several fm/c (hep-ph/0109006).
- **E. Shuryak**: probably the most direct signature of QGP plasma formation, observed at RHIC (nucl-th/0112042).
- **M. Gyulassy**: The most powerful probe of the QGP equation of state: the mass dependence of v_2

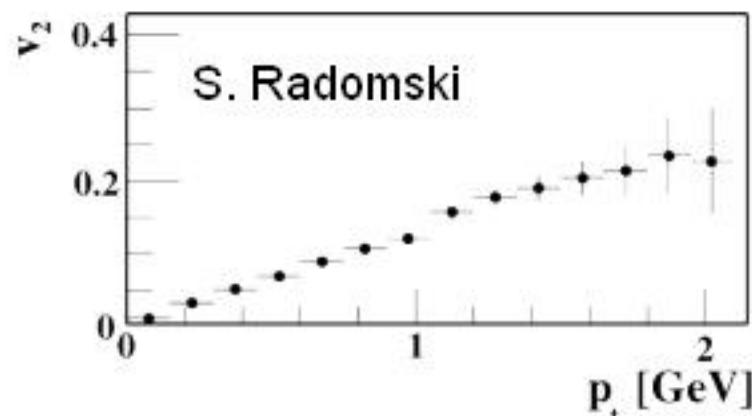
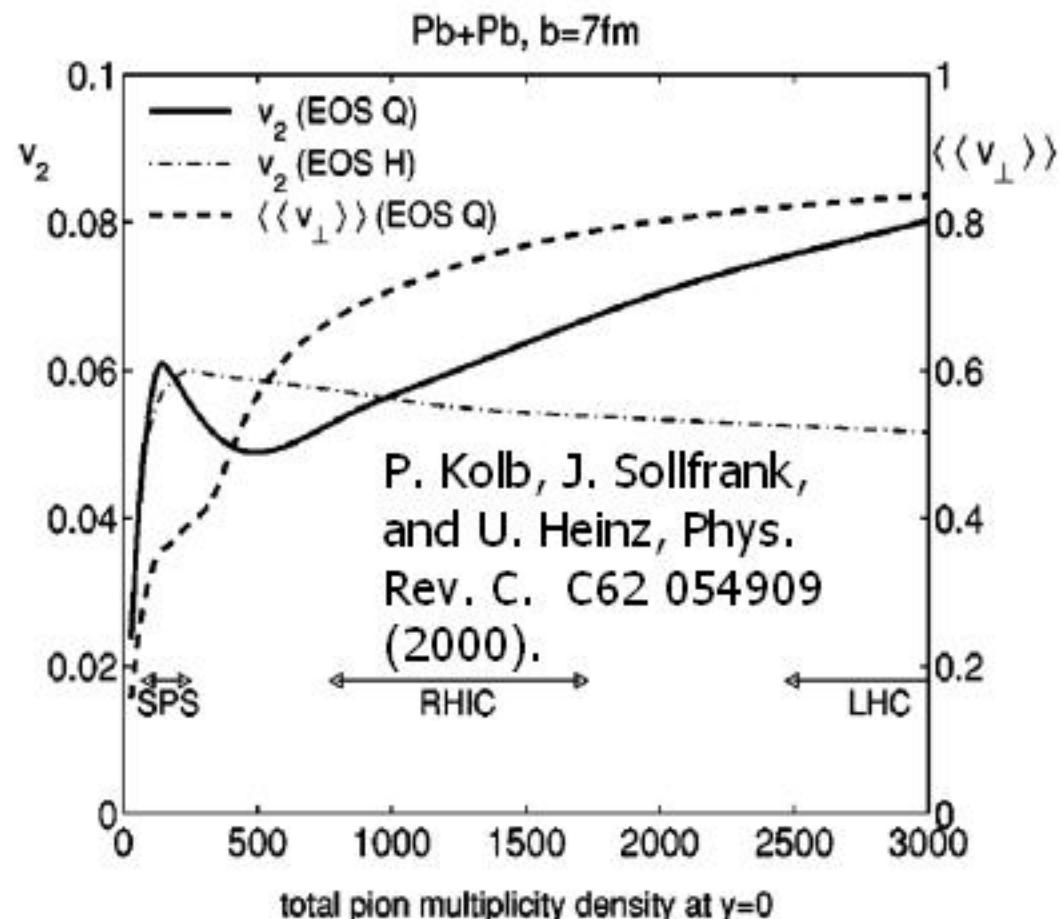
How has elliptic flow defined our view of physics at RHIC?

- **Charged particle elliptic flow at low p_t ; one of the first papers from RHIC**
 - First time quantitative agreement with hydrodynamics -> suggestive of early thermalization, strongly interacting parton phase
- **Identified particle elliptic flow at low p_t**
 - QGP equation of state (phase transition) provides accurate description
- **Charged particle elliptic flow at higher p_t**
 - First indications of jet quenching (later R_{AA})
 - Strongly dissipative system -> limiting surface emission (later back to back suppression). Suggested by Shuryak for high- p_t v_2 , earlier already by Huovinen for whole p_t range -> Not the whole answer at low p_t shown by mass dependence of $v_2(p_t)$ for π , K, p.
- **Identified particle elliptic flow at higher p_t**
 - Surface emission, not whole answer at higher p_t either shown by mass dependence of v_2 of pion, Kaon, proton and Lambda
 - pion, Kaon, proton and Lambda v_2 give indication for parton coalescence. First suggested at QM2002 by Voloshin (later also used for R_{AA} intermediate p_t mass dependence)

Conclusion

- Comparable measurements of elliptic flow from PHENIX, PHOBOS and STAR
- Elliptic flow for all measured particles at low- p_t well described by boosted thermal particle distributions
- Flow is large; indicative of strong partonic interactions at early stage of the collision
- Fluctuation could be main contribution to non-flow; At mid-central collisions the maximum effect is 10%. IMO best estimate of the true flow are in between $v_2\{2\} + v_2\{4\}/2$ and $v_2\{4\}$
- Up to $p_t = 6$ GeV/c sizable elliptic flow, indicative of energy loss
- Parton coalescence does a reasonable job at intermediate p_t ; important tests the v_2 of the ϕ -meson and the Ω
- Directed flow observed at RHIC, after scaling forward rapidity match SPS measurements
- Directed flow proves that elliptic flow is in-plane at RHIC energies

v_2 at LHC energy



(PPR) ALICE simulations and reconstruction, show that we will be in a beautiful position to do this physics at LHC