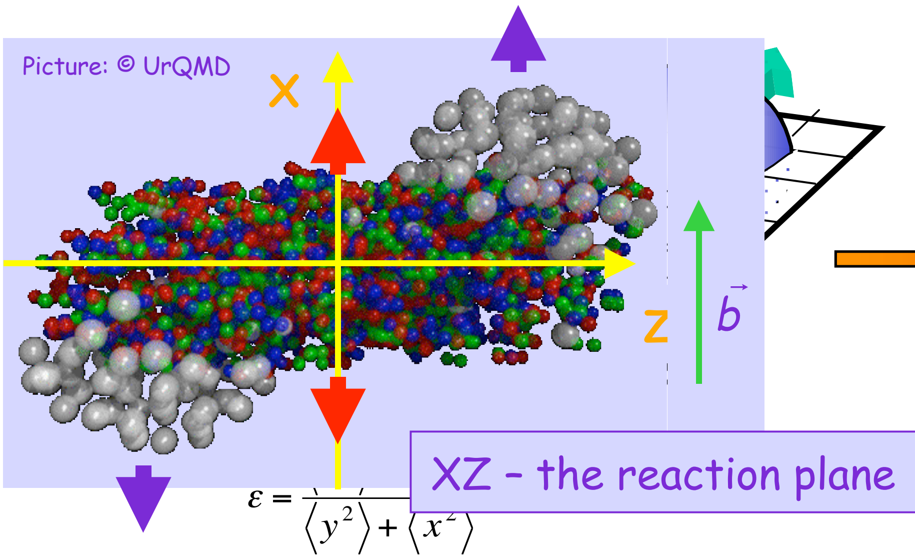
Directed and elliptic flow from Au+Au collisions at 200 GeV and azimuthal correlations in p+p and d+Au collisions at 200 GeV

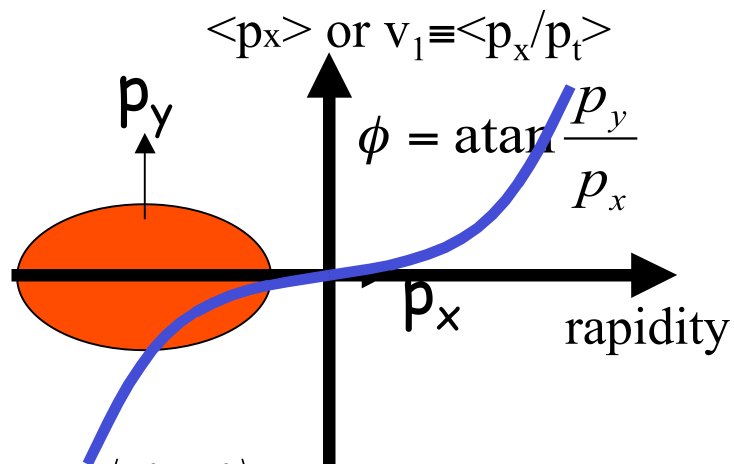
Aihong Tang for the STAR Collaboration

Outline

- Elliptic flow and Directed flow
  - An introduction
- Directed flow
  - Theoretical predictions (anti-flow/3rd flow component, v_1 wiggle)
  - v_1 at RHIC
- High p_t v_2 and correlation $\Rightarrow$ test of jet quenching
  - v_2 versus p_t
  - Comparisons to v_2 from jet energy loss in Hard Shell, Hard Sphere and Woods-Saxon.
  - In- and out- of plane suppression
- Azimuthal correlation in pp, dAu and AuAu
  - Comparison of azimuthal correlation in AuAu, dAu and pp
- Summary

Definitions: directed flow (v_1), elliptic flow (v_2)





$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

initial spatial anisotropy

anisotropy in momentum space

$$E\frac{dN^3}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2v_1\cos(\phi - \Psi_R) + 2v_2\cos(2(\phi - \Psi_R) + \ldots\right)$$

isotropic **directed** **elliptic**

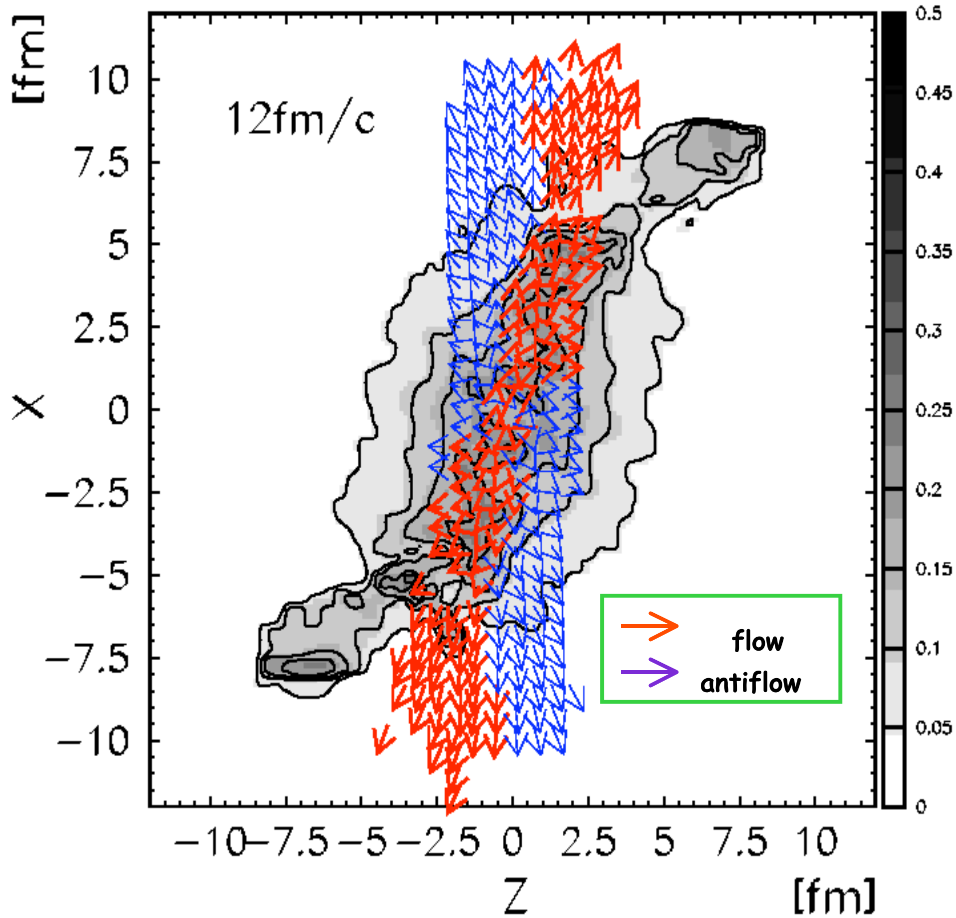
$$v_n = \left\langle \cos\left(n\left(\phi - \psi_{RP}\right)\right)\right\rangle = \left\langle e^{in(\phi - \psi_{RP})}\right\rangle$$

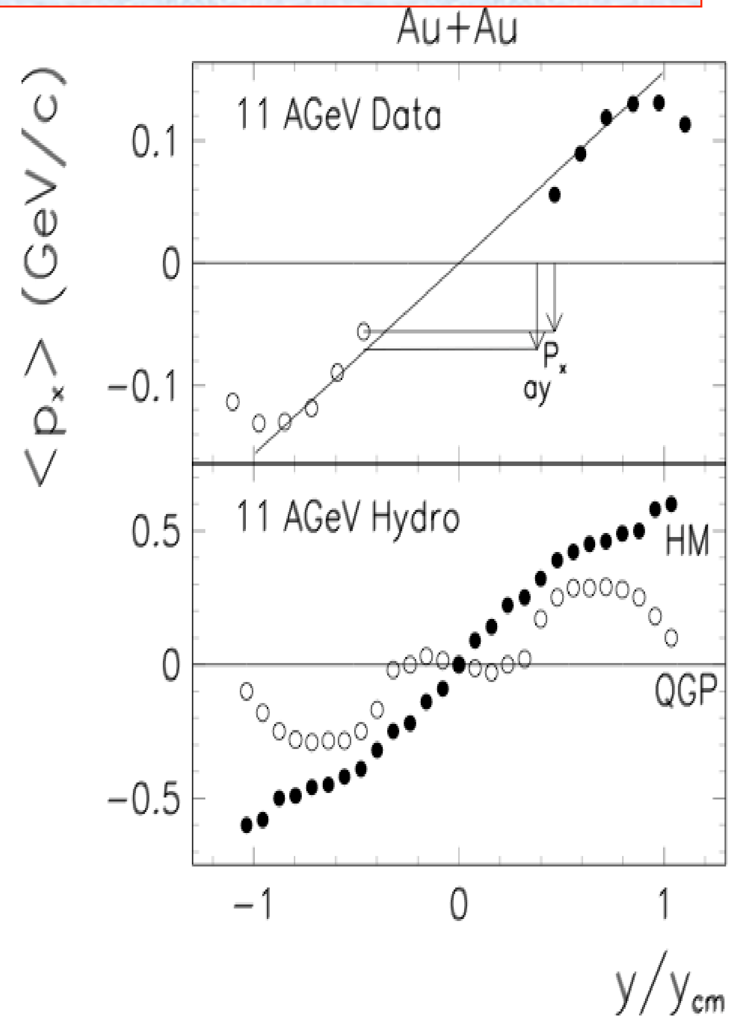
= Correlation to the reaction plane

≡" anisotropic flow "

Directed flow (v_1) and phase transition

Anti-flow/3rd flow component, with QGP $\Rightarrow$ v_1 flat at middle rapidity.

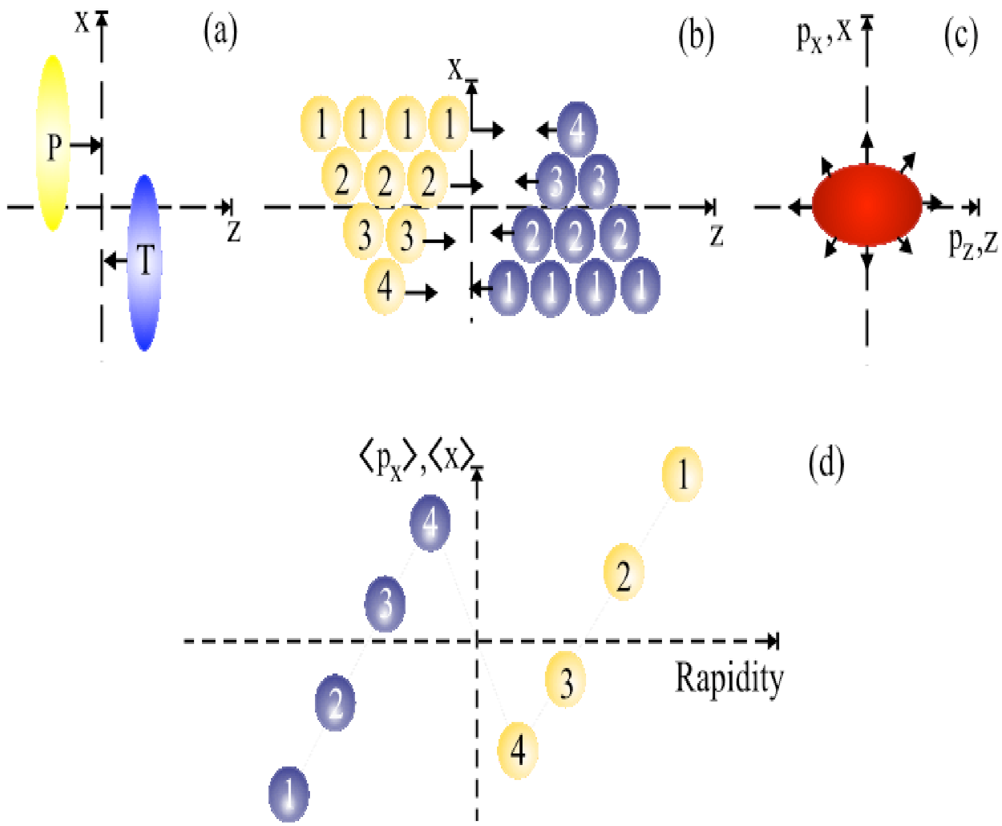


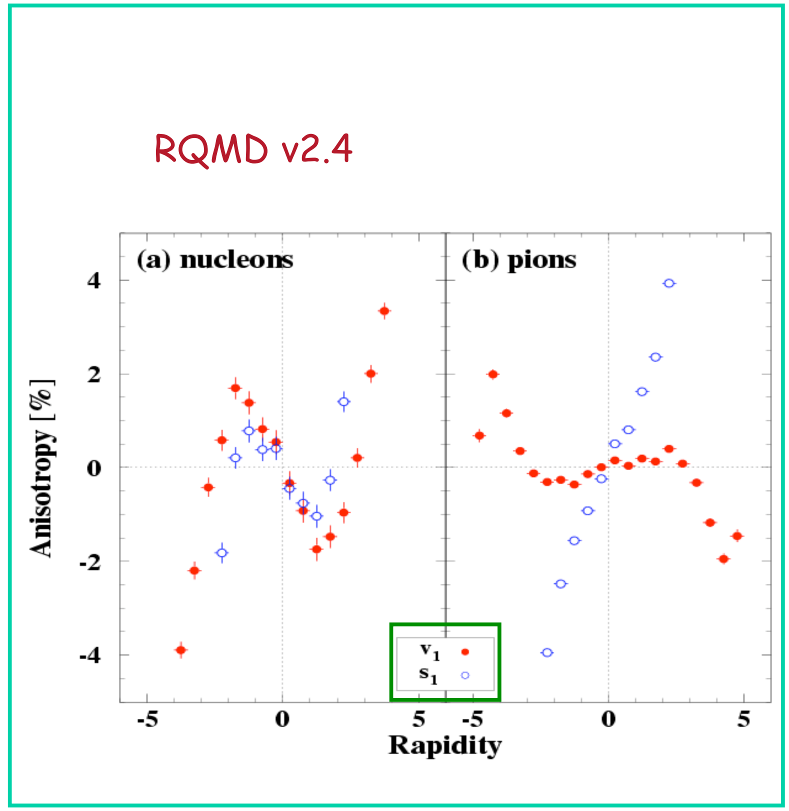


Brachmann, Soff, Dumitru, Stocker, Maruhn, Greiner Bravina, Rischke , PRC 61 (2000) 024909.
L.P. Csernai, D. Roehrich PLB 458, 454 (1999) M.Bleicher and H.Stocker, PLB 526,309(2002)

Directed flow (v_1) and baryon stopping

Positive space-momentum correlation, no QGP necessary ⇒ v_1 wiggle.





R.Snellings, H.Sorge, S.Voloshin, F.Wang, N. Xu, PRL (84) 2803(2000)

Directed flow (v_1) - three particle correlation method

$$\langle \cos(\phi_a - \psi_2)\cos(\phi_b - \psi_2) - \sin(\phi_a - \psi_2)\sin(\phi_b - \psi_2) \rangle \approx v_{1a} v_{1b} v_2$$

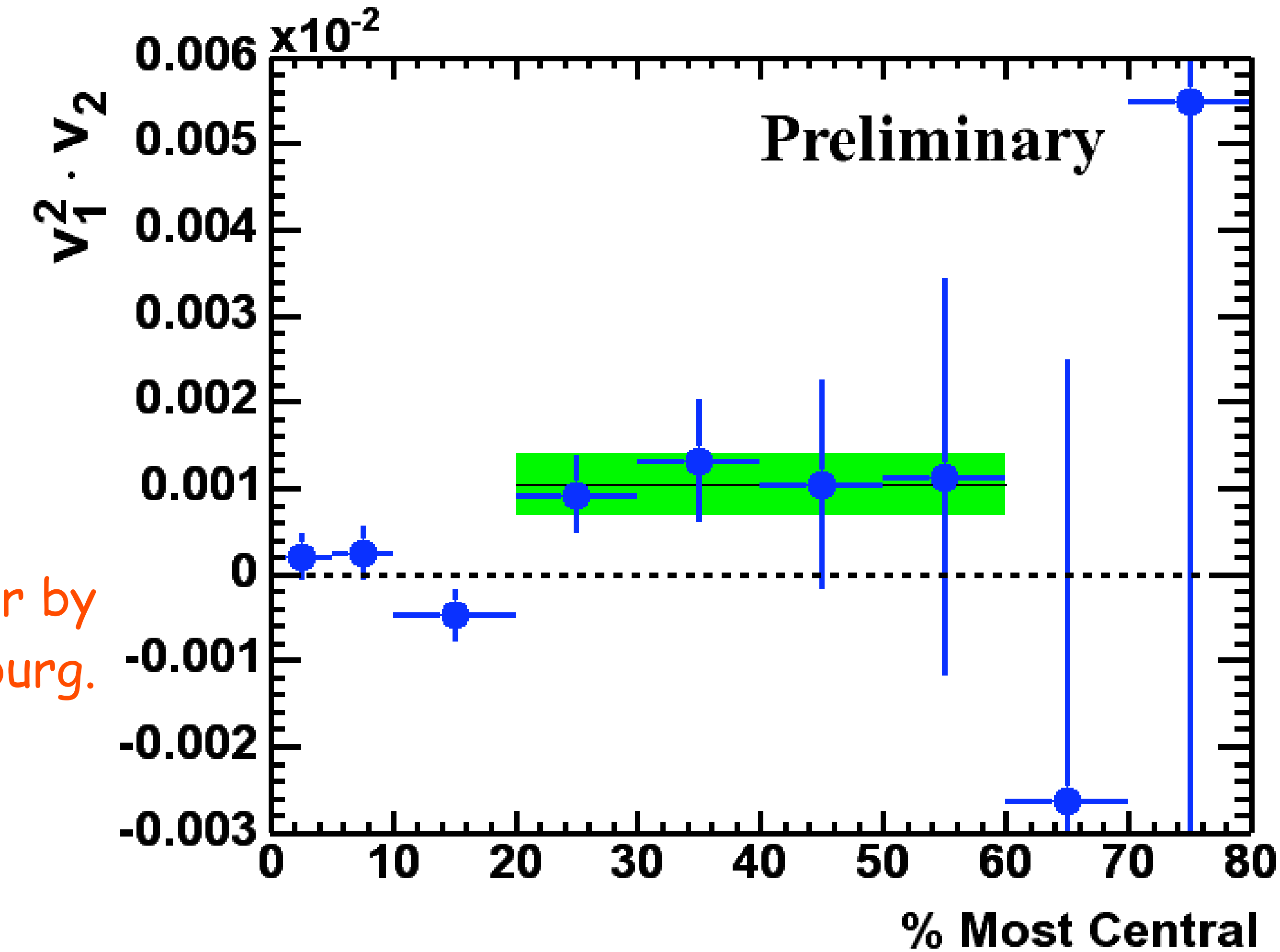
In-plane component of $Q_a Q_b$
Flow+nonflow

Out-of-plane component of $Q_a Q_b$
Nonflow

Basic formula of three particle cumulant method
N.Borghini, P.M.Dihn,J-Y.Ollitrault, PRC 014905(2002)

- The same of the use of mixed harmonics
- Takes advantage of the knowledge about the reaction plane derived from the large elliptic flow - minimizes nonflow effect
- Can measure the sign of v_2

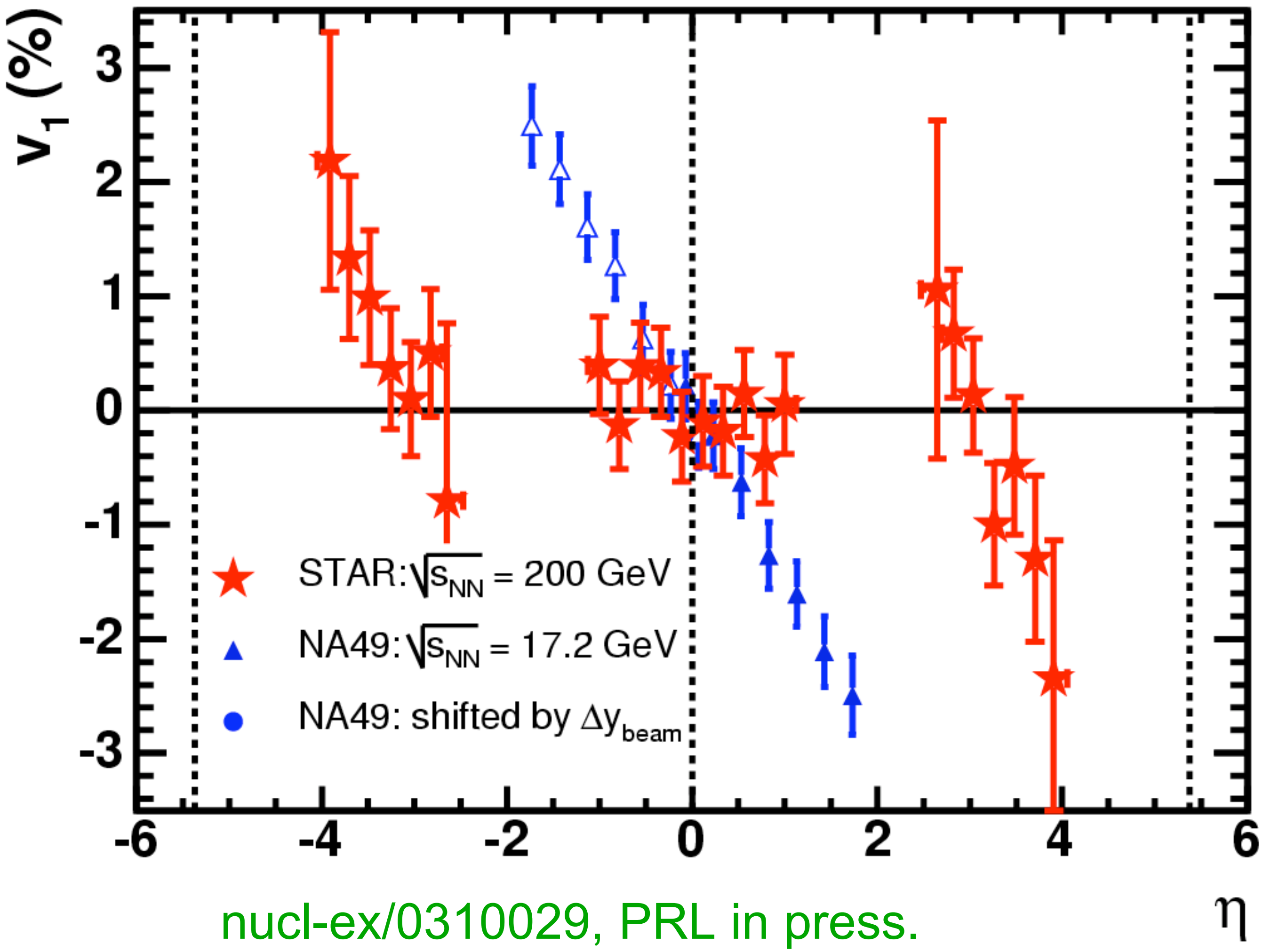
The evidence of *in-plane* elliptic flow



See poster by M. Oldenburg.

In this analysis, we measured $v_1^2 v_2$ to be positive ⇒ *In-plane* elliptic flow confirmed

The first measurement of directed flow at RHIC !



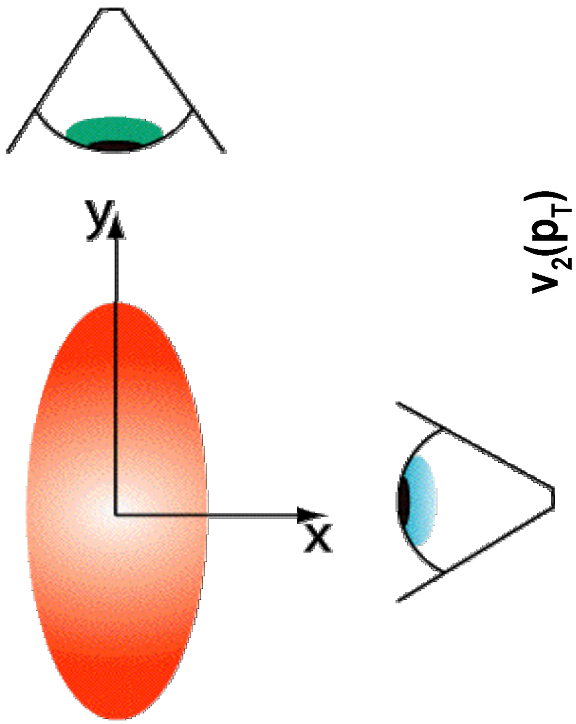
Shows no sign of a "wiggle" (although does not exclude the magnitude as predicted)

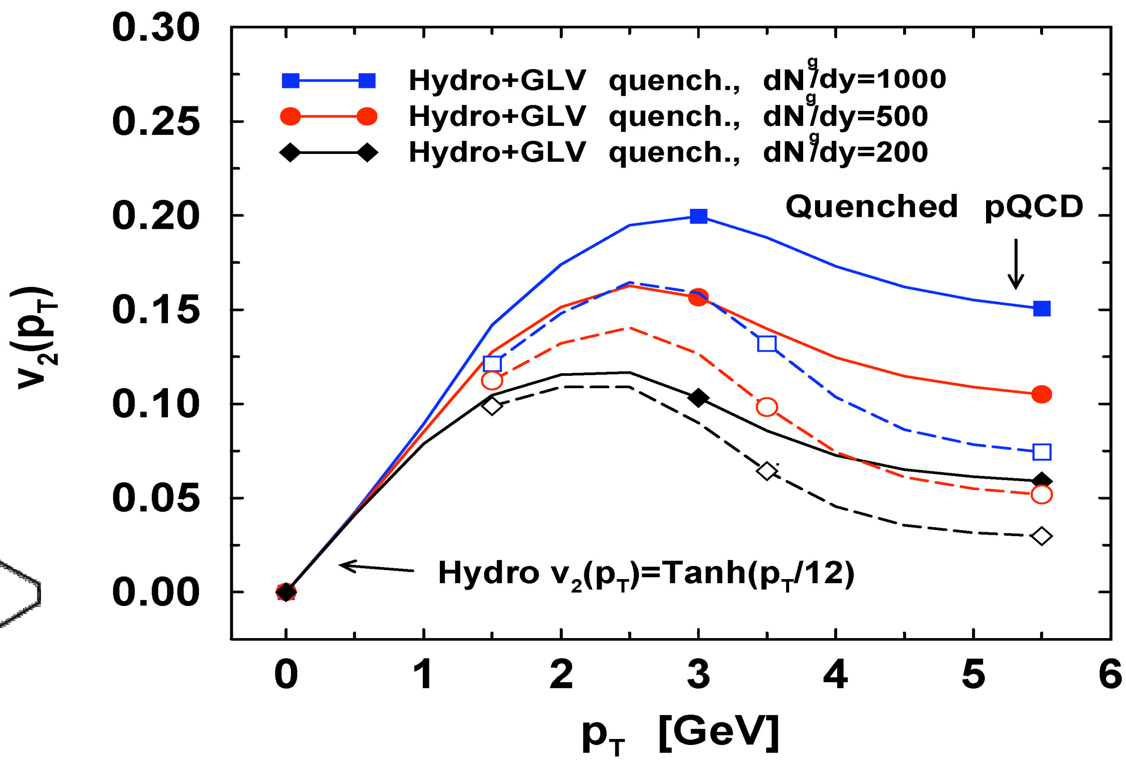
nucl-ex/0310029, PRL in press.

v_1 Conclusions

- Mixed harmonic correlations and 3 particle cumulant analysis of v_1 confirms the *in-plane* elliptic flow
- v_1 is found to be flat at middle rapidity $\Rightarrow$ consistent with theoretical predictions.
- Viewed in the projectile frame, v_1 at RHIC agrees with NA49 result.
- The wiggle structure / anti-flow around midrapidity needs more statistics to study.

High p_t v_2 and correlation : the test of jet quenching

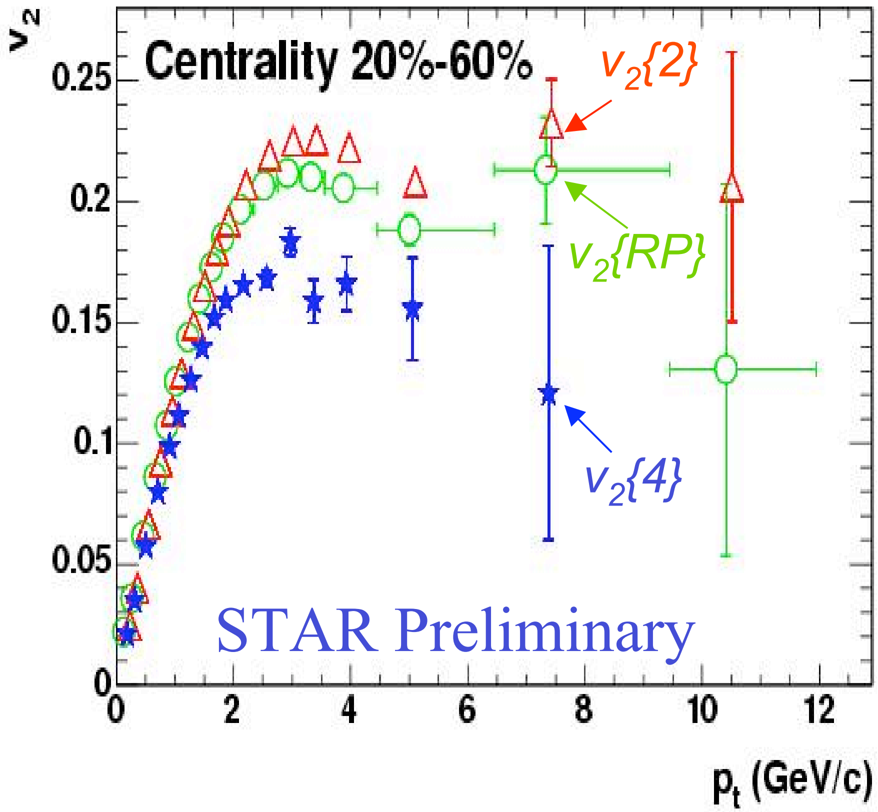


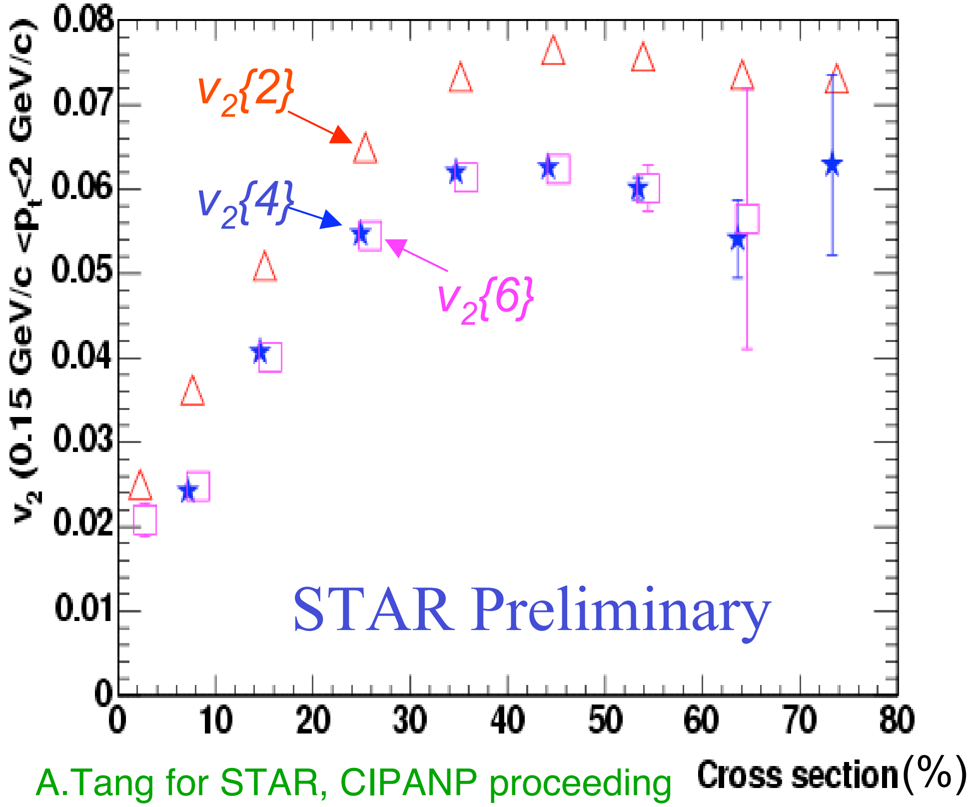


M. Gyulassy, I. Vitev and X.N. Wang
PRL 86 (2001) 2537

Results from jet energy loss from different emission angles with respect to the reaction plane. Sensitive to the medium density.

High p_t v_2 and correlation : the test of jet quenching

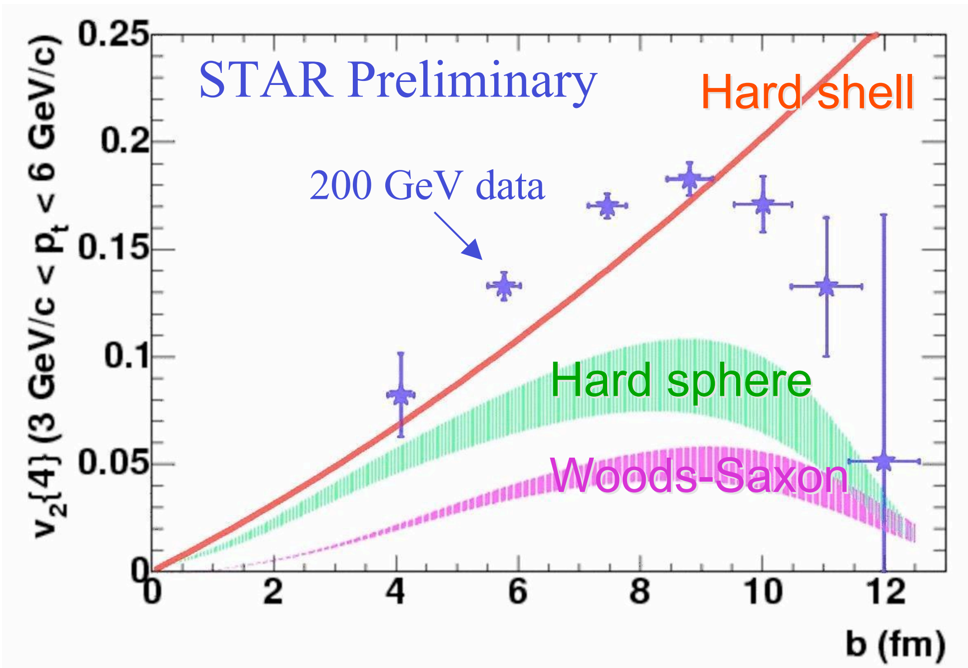


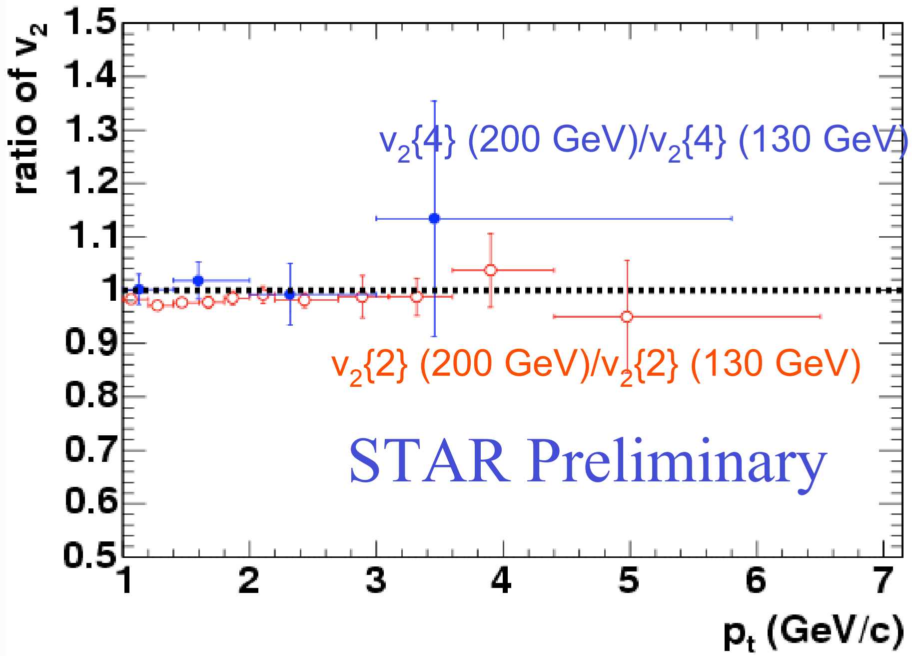


A.Tang for STAR, CIPANP proceeding
nucl-ex/0308020

Significant v_2 up to ~7 GeV/c in pt, the region where hard scattering begins to dominate. Nonflow from 4 particle correlation, $v_2\{6\}$-$v_2\{4\}$ is negligible.

High p_t v_2 and correlation : the test of jet quenching

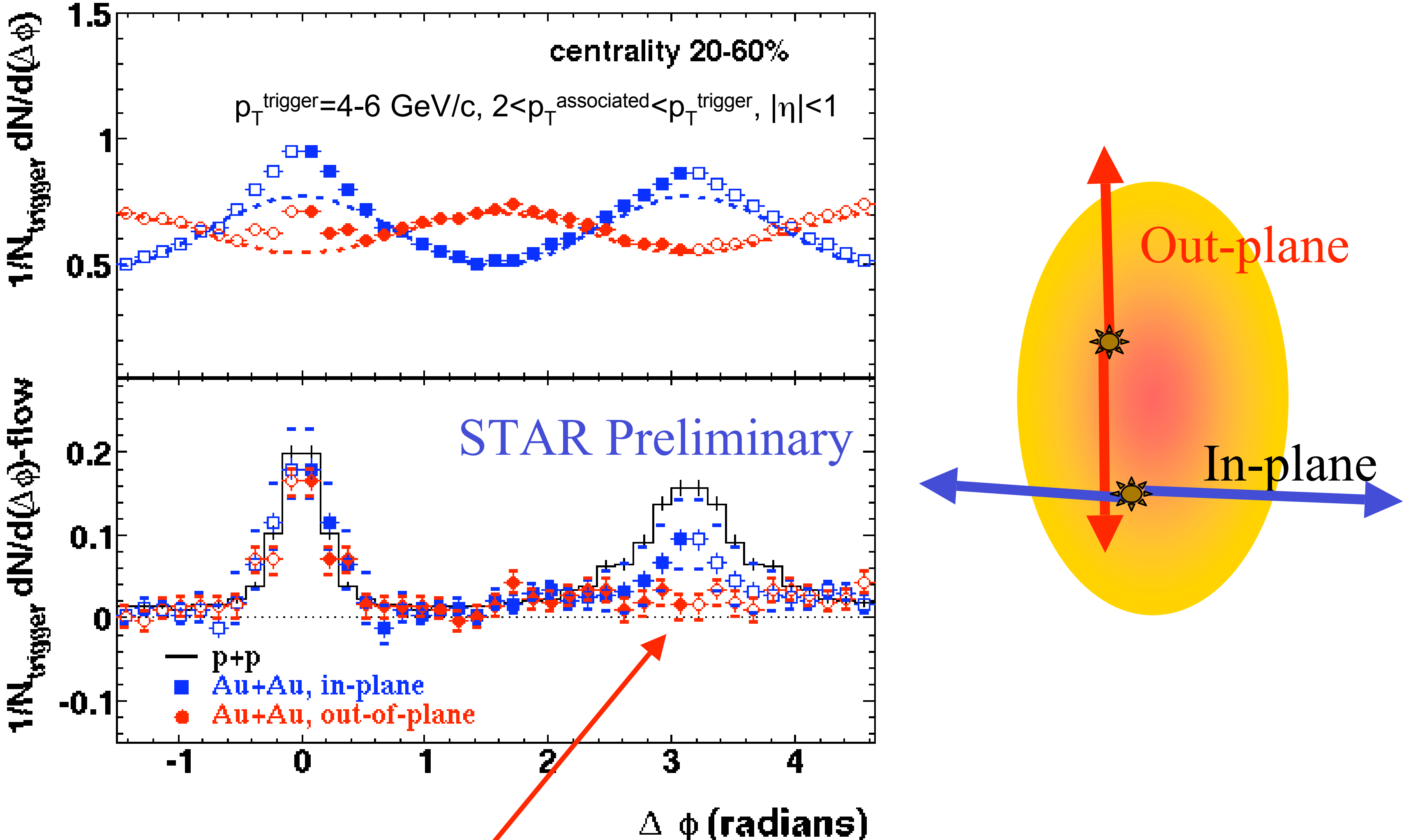




v_2 curve from Woods-Saxon and Hard Sphere are our calculations based on ideas of X.N.-Wang and Jiayong Jia.

v_2 is large ⇒exceeds the upper limit set by hard shell emission - Coalescence?
Little dependence on collision energy ⇒ dominated by geometry?

High p_t v_2 and correlation : the test of jet quenching



Method paper : J. Bielcikova, S.Esumi, K. Filimonov, S.Voloshin, J.P.Wurm. Nucl-ex/0311007

Back-to-back suppression is larger in the out-of-plane direction

High p_t v_2 and correlation : conclusions

- Sizable v_2 is found up to 7 GeV/c in pt.
- Nonflow contribution to 4 particle correlations is negligible.
- v_2 at moderate pt increases little from 130 GeV to 200 GeV-qualitatively consistent with geometrical v_2
- v_2 at moderate pt is too high to be explained by "jet quenching" alone.
- Back-to-back suppression is larger in the out-of-plane direction

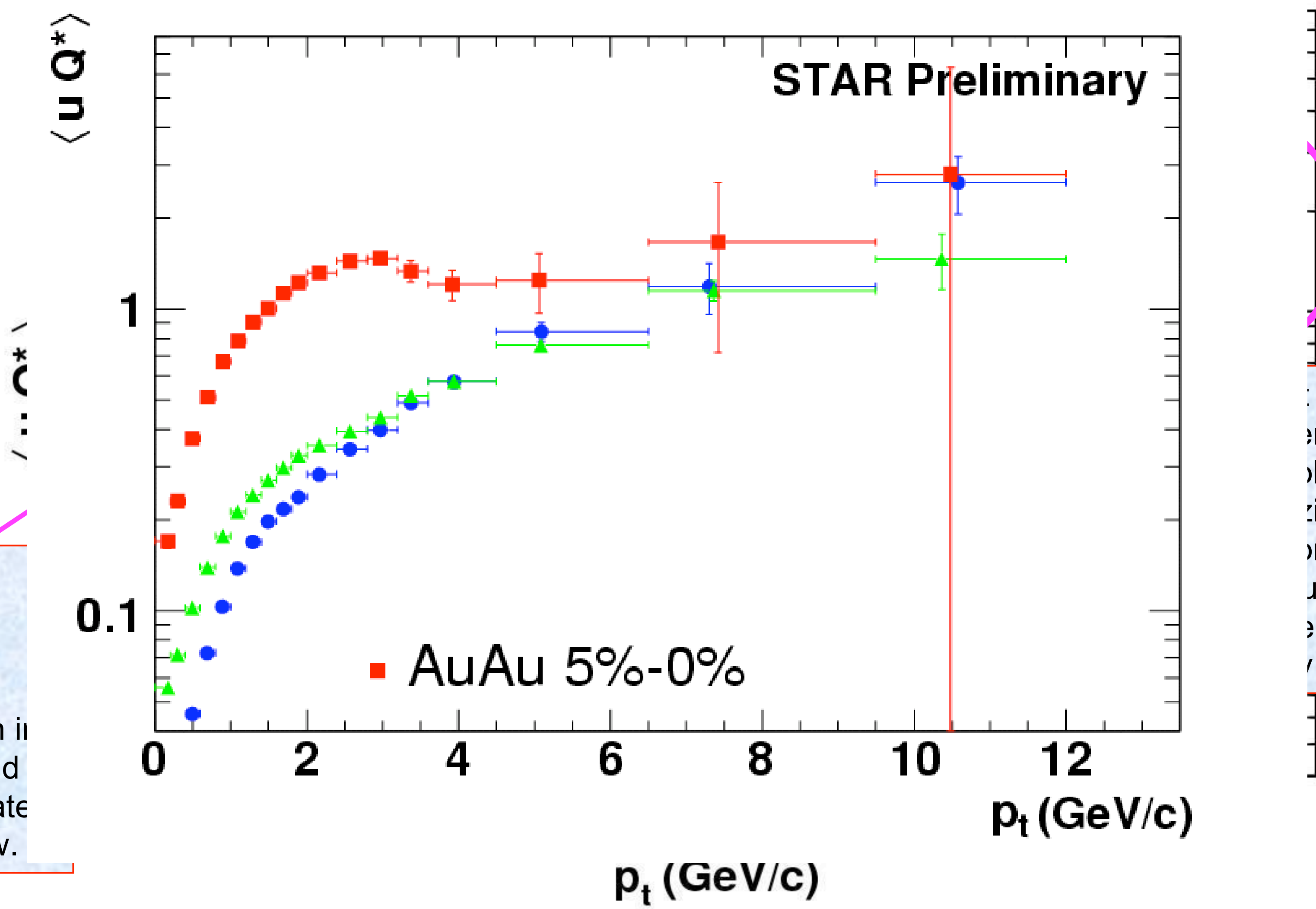
How to compare " elliptic flow " in AuAu, dAu and pp collisions ?

v_2 does not scale --- need to find a multiplicity (or Nbinary) independent quantity to compare azimuthal correlations between two different systems.

$$M\left\langle e^{in(\phi_1-\phi_2)}\right\rangle = \underbrace{\left\langle uQ^*\right\rangle}_{\text{Multiplicity independent non-flow}} = \tilde{\delta}_2$$

Azimuthal correlation in AuAu, dAu and pp collisions

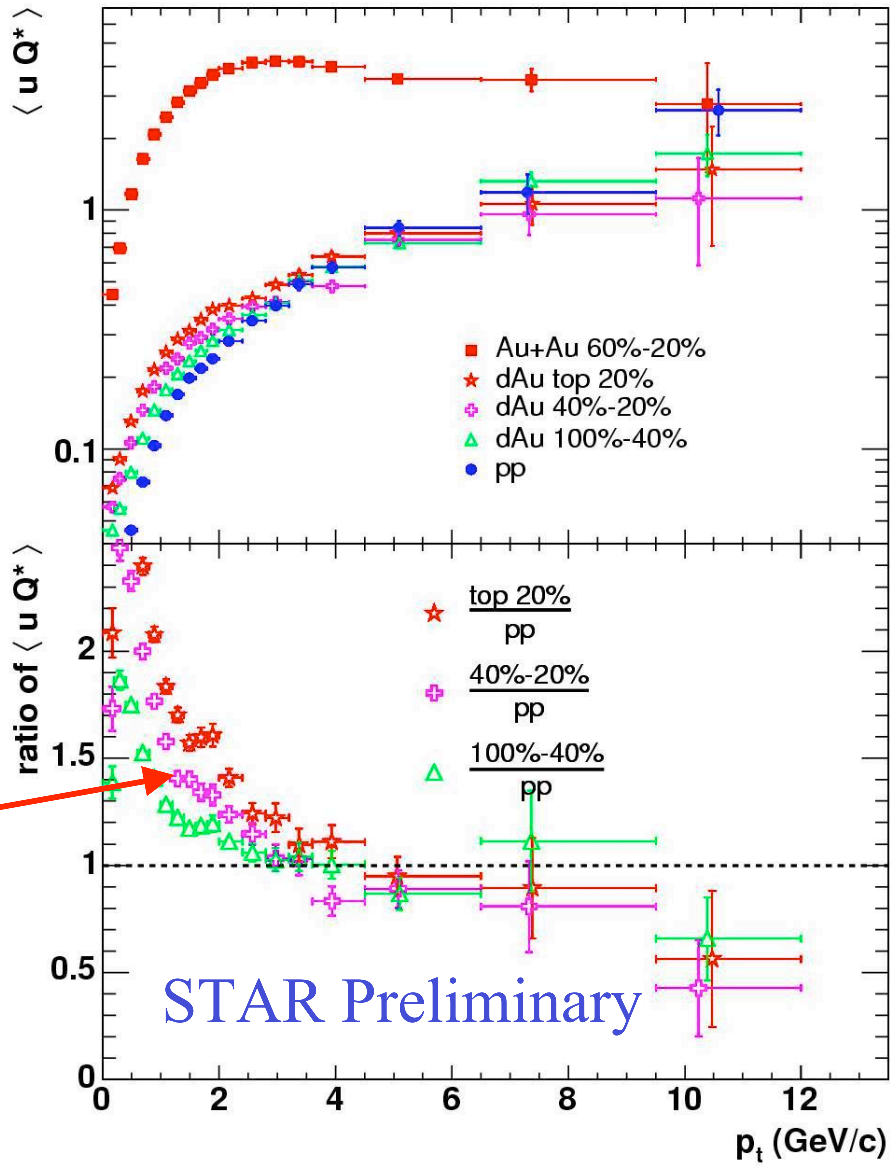
$$\langle u\, Q^* \rangle^{AA} \approx v\, v\, M^{AA} + \langle u\, Q^* \rangle^{pp}$$



In VERY peripheral collisions, azimuthal correlation i[n] AuAu could be dominate[d] by nonflow.

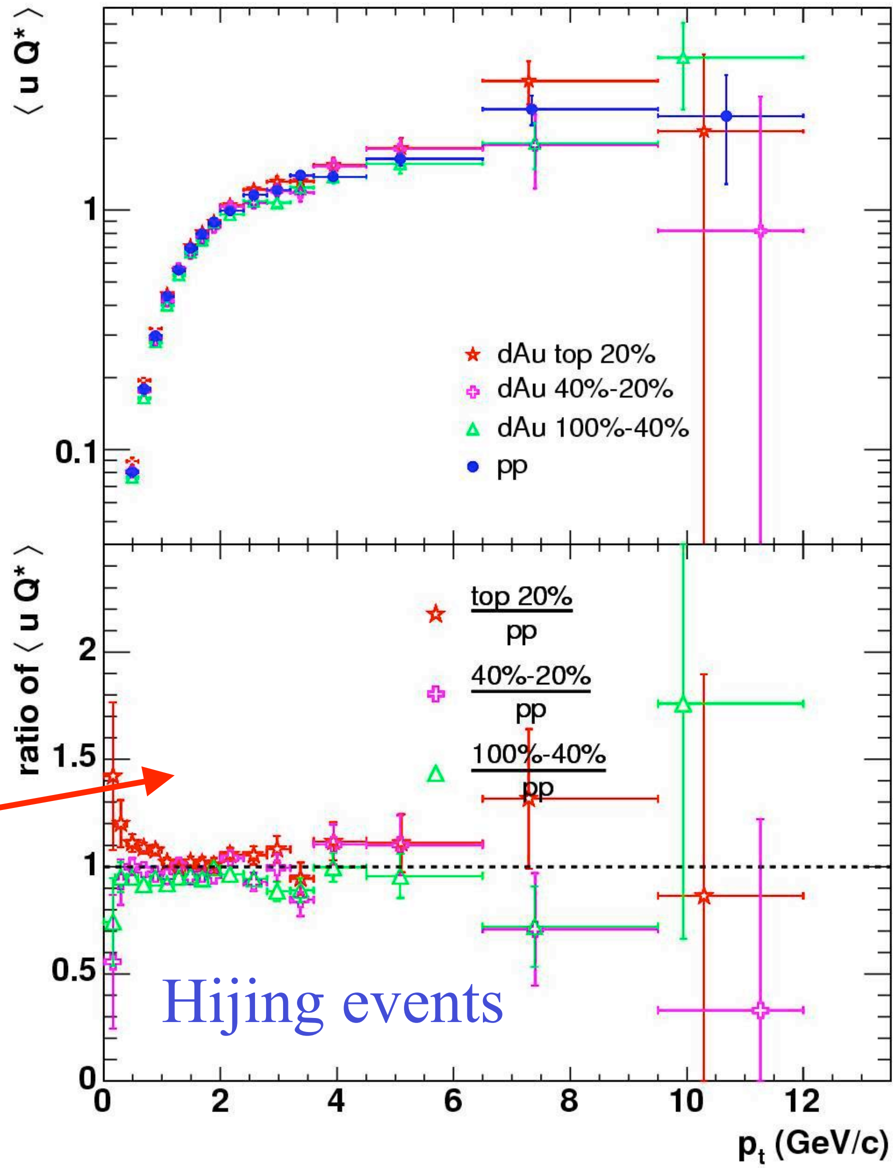
[At] high p$_t$ in [c]entral [c]ollisions, [a]zimuthal [c]orrelation in [A]uAu could [b]e dominated [b]y nonflow.

Is there “ elliptic flow ” in dAu collisions ?



collective motion at low p_t

Is there " elliptic flow " in HIJING dAu collisions ?



collective motion not seen in Hijing

Conclusion of azimuthal correlation in AuAu dAu and pp

- We can compare azimuthal correlation in three different collision systems by Scalar Product method.
- Azimuthal correlations in AuAu collisions show strong real collective motion.
- Azimuthal asymmetry is observed at low pt in dAu collisions, and such asymmetry is larger in high multiplicity events than that is in low multiplicity events. It could be due to multiple hadronic rescattering.
- As expected, such azimuthal asymmetry is not found in Hijing due to the fact that Hijing does not have collectivity.

Summary

- In-plane elliptic flow is confirmed.
- Directed flow is found to be flat at middle rapidity.
- Finite v_2 is found up to 7 GeV/c in p_t.
- v_2 at moderate p_t is too large for “jet quenching”.
- Back-to-back suppression is larger in the out-of-plane direction.
- Scalar product of AuAu collisions shows strong real collective motions if compared to pp and dAu collisions.
- Collective motion in dAu collisions is found to be larger in high multiplicity events if compared to that in low multiplicity events.

THE END

High pt v2 and correlation : the test of jet quenching

LBNL-52533

High-p_T Hadron Spectra, Azimuthal Anisotropy and Back-to-Back Correlations in High-energy Heavy-ion Collisions

Xin-Nian Wang
Nuclear Science Division, MS70R0319,
Lawrence Berkeley National Laboratory, Berkeley, CA 94720

Such a phenomenon, known as jet quenching …, one also observes the disappearance of back-to-back jet-like hadron correlations and finite azimuthal anisotropy of high pt hadron spectra. These three seemingly unrelated high pt phenomena are all predicted as consequences of jet quenching. Together they can provide unprecedented information on the properties of dense matter produced at RHIC

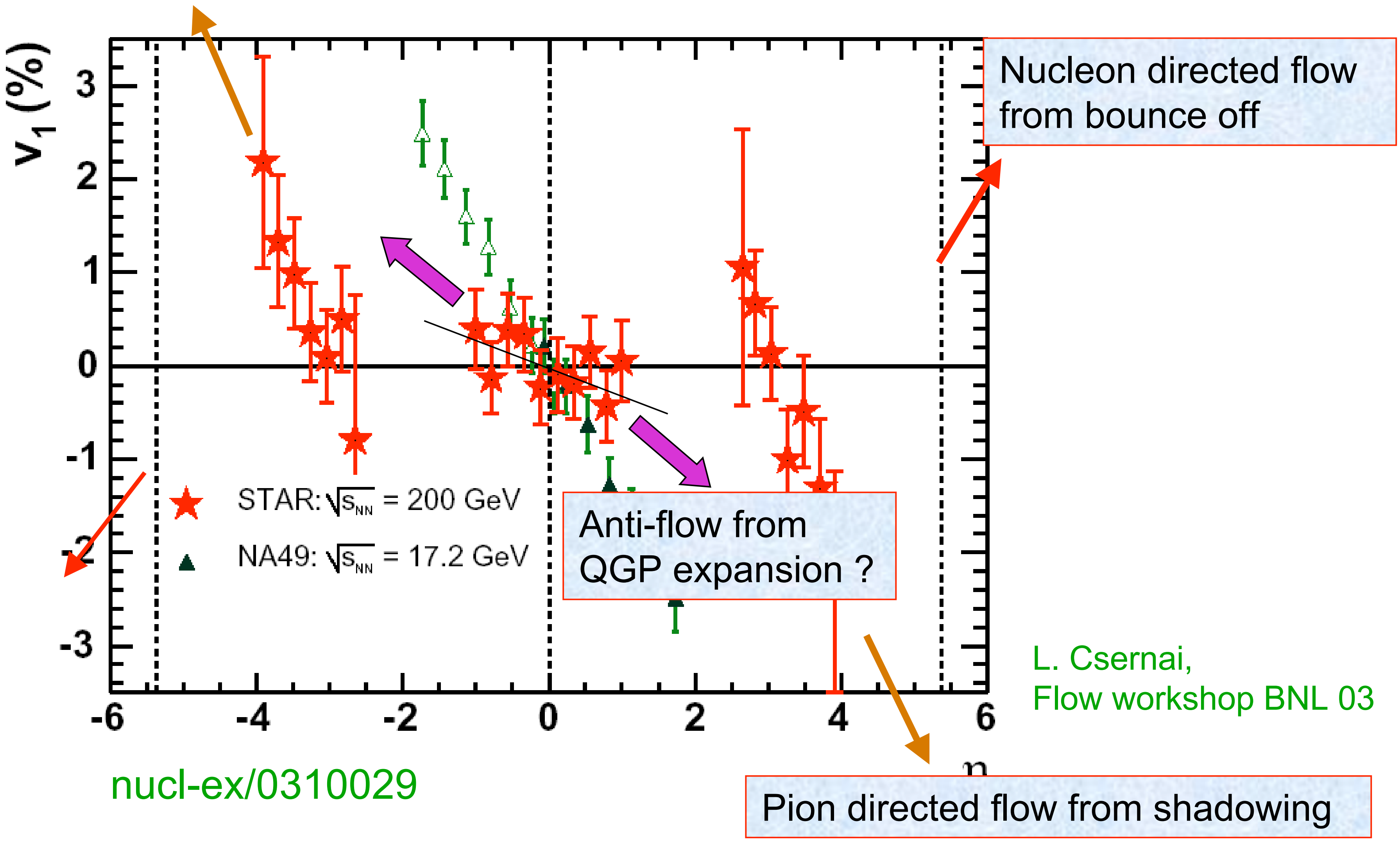
The degradation … agation in the dens… mation necessary f… the strongly interacting matter produced in high-energy heavy-ion collisions. Because of radiative parton energy loss induced by multiple scattering, the final high-p_T hadron spectra from jet fragmentation are expected to be significantly suppressed [1]. Such a phenomenon, known as jet quenching, was observed for the first time in $Au+Au$ collisions at the Relativistic Heavy-ion Collider (RHIC) [2,3]. One also observes the disappearance of back-to-back jet-like hadron correlations [4] and finite azimuthal anisotropy [5] of high-p_T hadron spectra. These three seemingly unrelated high-p_T phenomena are all predicted as consequences of jet quenching [1,6–8]. Together, they can provide unprecedented information on the prop-

pQCD corrections. The parton distributions per nucleon $f_{a/A}(x_a, Q^2, r)$ inside the nucleus are assumed to be factorizable into the parton distributions in a free nucleon given by the MRS D−′ parameterization [11] and the impact-parameter dependent nuclear modification factor [12,13]. The initial transverse momentum distribution $g_A(k_T, Q^2, b)$ is assumed to have a Gaussian form with a width that includes both an intrinsic part in a nucleon and nuclear broadening. Details of this model and systematic data comparisons can be found in Ref. [9].

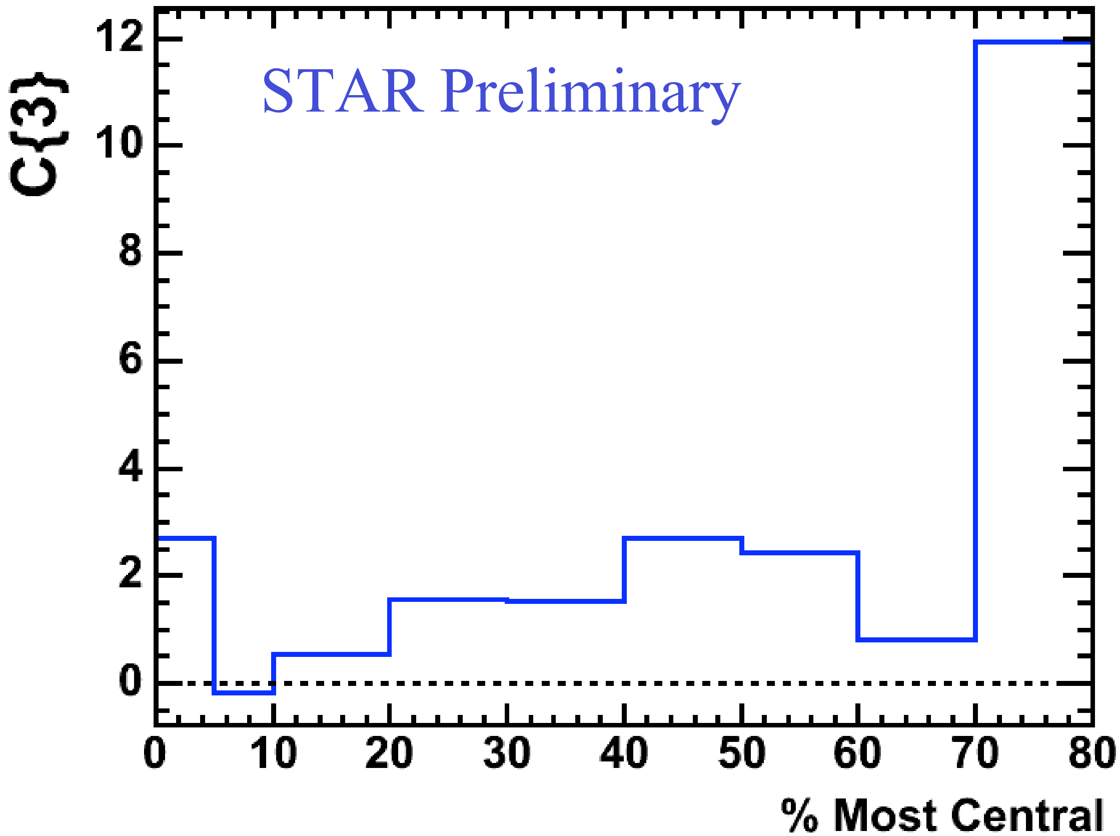
As demonstrated in recent studies, a direct consequence of parton energy loss is the medium modification of FF's [14,15] which can be well approximated by [16]

![STAR logo]

Directed flow at RHIC -> cut?



Directed flow at RHIC -> CHANGE THIS.



In this analysis, we measured $v_1^2v_2$ to be positive ⇒ *In-plane* elliptic flow confirmed

In S. Voloshin's language (Scalar product)

$$\left\langle u_b Q^* \right\rangle = \left(v_b v_p + \delta_{bp}^{AA} \right) M^{AA}$$

$$\delta_{bp}^{AA} \approx \frac{\delta_{bp}^{pp}}{N_{coll}} \approx \frac{\delta_{bp}^{pp} M^{pp}}{M^{AA}}$$

$$\longrightarrow \quad \left\langle u_b Q^* \right\rangle^{AA} \approx v_b v_p M^{AA} + \left\langle u_b Q^* \right\rangle^{pp}$$

$$Q = \sum_{i \in "pool"} u_i; \quad u_i = e^{i2\phi_i}$$

v_p - Flow in a particle pt/eta "bin"

v_b - Average flow for particles used ("pool particles") to define RP

δ_{bp}^{pp} - Azimuthal correlations in pp ($\left\langle u_a u_b^* \right\rangle$, $u = e^{i2\phi}$)

In language of J.-Y Ollitrault et al

The format of generating function used in cumulant analyses is:

$$G_n(z) = \prod_{j=1}^{M} \left(1 + \frac{z^* e^{in\phi_j} + z e^{-in\phi_j}}{M}\right)$$

It is good for extracting v2, but it does not scale. If we change it to

$$G_n(z) = \prod_{j=1}^{M} \left(1 + z^* e^{in\phi_j} + z e^{-in\phi_j}\right)$$

Then for a system that is superposition of two independent system 1 and 2, and only "nonflow" correlations are present, we have

$$G(z) = G1(z)G2(z)$$

So if a Nucleus-Nucleus is a simple superposition of N independent pp collisions, then

$$G(z) = \left[G_{pp}(z)\right]^N$$

Log(G(z)) then should scale linearly with the number of pp collisions, so should cumulants, which is the coefficient of z of Log(G(z)).

In the case of a second order cumulant, this is

$$M^2 \left\langle e^{in(\phi_1 - \phi_2)} \right\rangle = M \bullet M \left\langle e^{in(\phi_1 - \phi_2)} \right\rangle = M \bullet \left\langle uQ^* \right\rangle = M \tilde{\delta}_2$$