Beam Energy Dependence of First and Higher-Order Flow Harmonics from the STAR Experiment at RHIC

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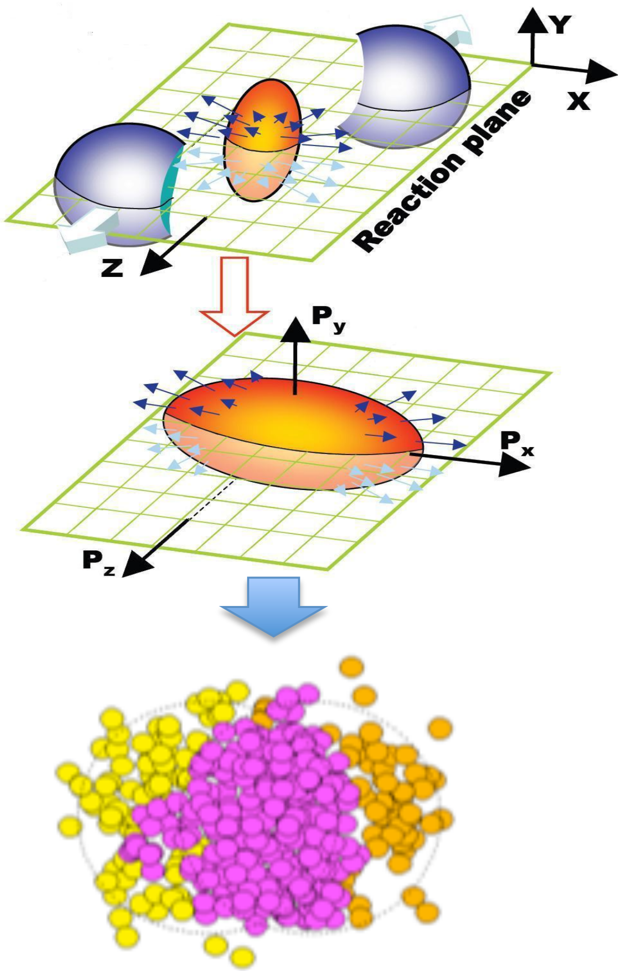
QM12 QuarkMatter

Outline:

- Introduction and motivation
- The Beam Energy Scan at RHIC
- The STAR experiment
- v_1 in 7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV Au+Au Collisions
- v_3 results in 7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV Au+Au and 62.4 and 200 GeV Cu+Cu Collisions.
- v_n (n=1-5) as a function of p_T in 200 GeV Au+Au Collisions
- Summary

Introduction: Anisotropic Flow in Heavy ion Collisions



$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos[n(\varphi - \psi_n)]\right)$$

$$v_n = \left\langle \cos n\left(\varphi - \psi_n\right)\right\rangle, \quad n = 1,2,3..,$$

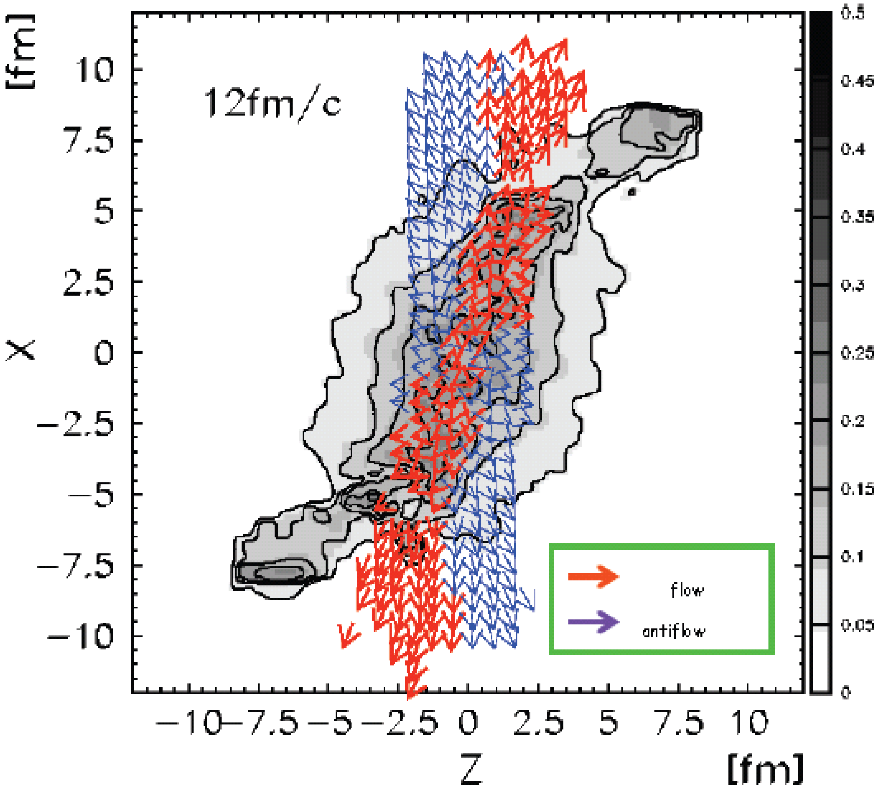
n=1 **Directed Flow**

- ❖ **conventional(rapidity odd)**
- ❖ **dipole asymmetry(rapidity even)**

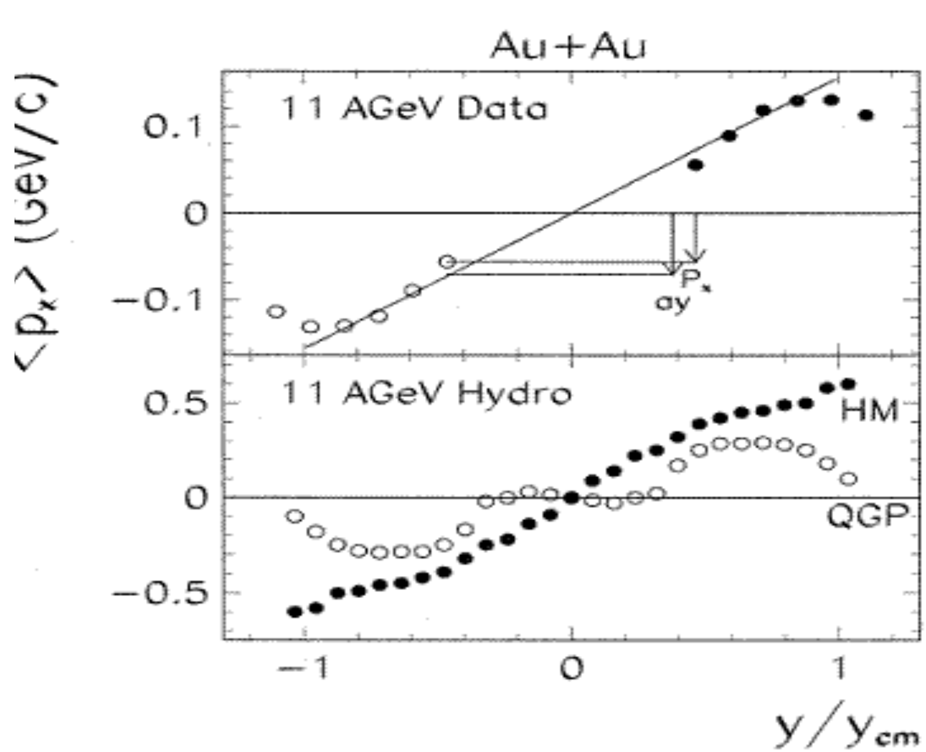
n=2 **Elliptic flow**
n=3 **Triangular flow**
n= 4, 5 **--------------------**

Anisotropy in position space (initial) → Anisotropy in momentum space (final)

Motivation: $v_1(y)$ Structure



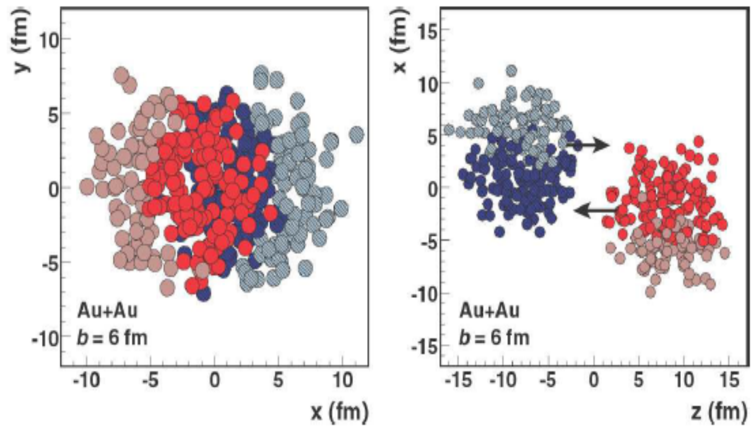
J. Brachmann et al., PRC 61, 24909 (2000).

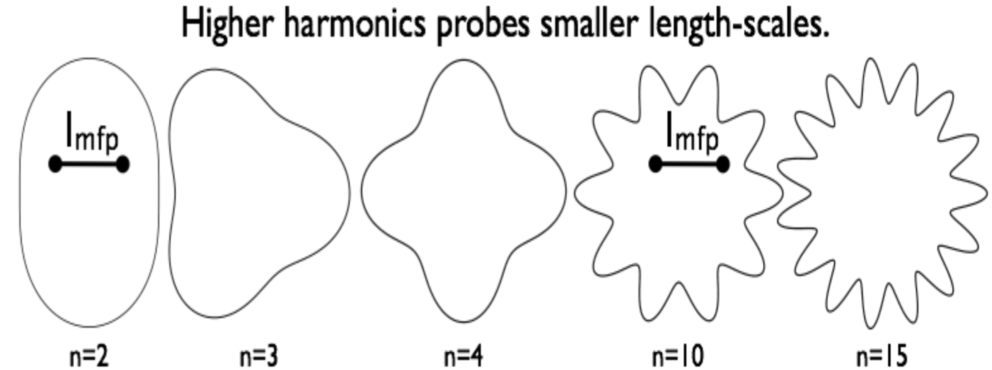


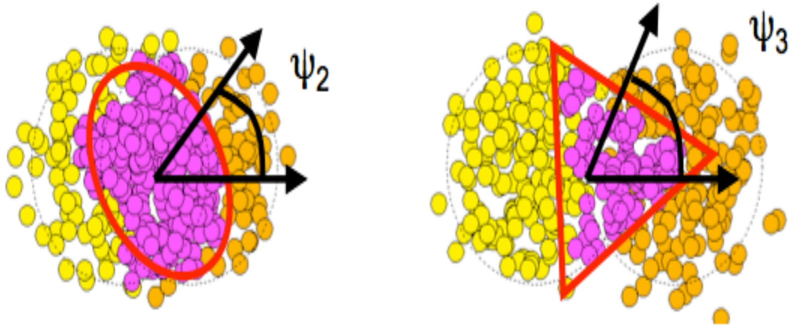
L.P. Csernai, D. Rohrich PLB 458, 454 (1999)

Anti-flow/3rd flow component: $v_1(y)$ of nucleons crosses zero 3 times (so-called “wiggle”) or flat v_1 at midrapidity due to 1st order phase transition.

Motivation: v_3/v_n







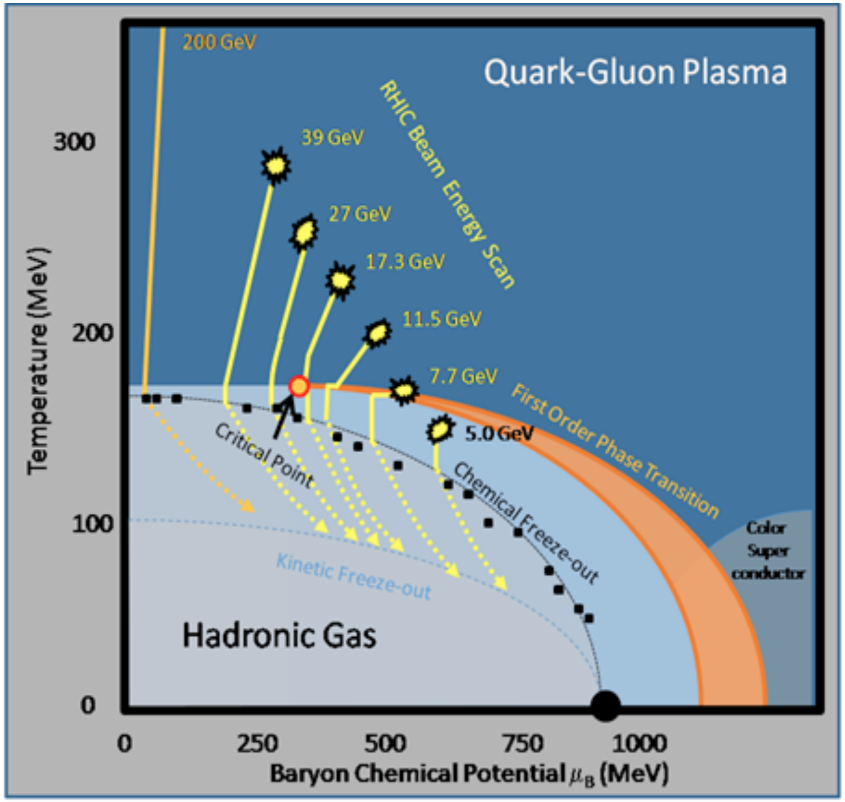
$$\varepsilon_2^2 = \frac{\langle r^2 \cos(2\varphi)\rangle^2 + \langle r^2 \sin(2\varphi)\rangle^2}{\langle r^2 \rangle^2}$$

$$\varepsilon_3^2 = \frac{\langle r^2 \cos(3\varphi)\rangle^2 + \langle r^2 \sin(3\varphi)\rangle^2}{\langle r^2 \rangle^2}$$

Triangular anisotropy in initial geometry can be quantified by "participant triangularity" analogous to participant eccentricity.

v_3 and higher harmonics (v_n) are sensitive to initial-state fluctuations and hydrodynamic evolution and they probe smaller length scale than v_2 .

RHIC Beam Energy Scan (BES) Program



Motivation:

Search for signals of phase boundary

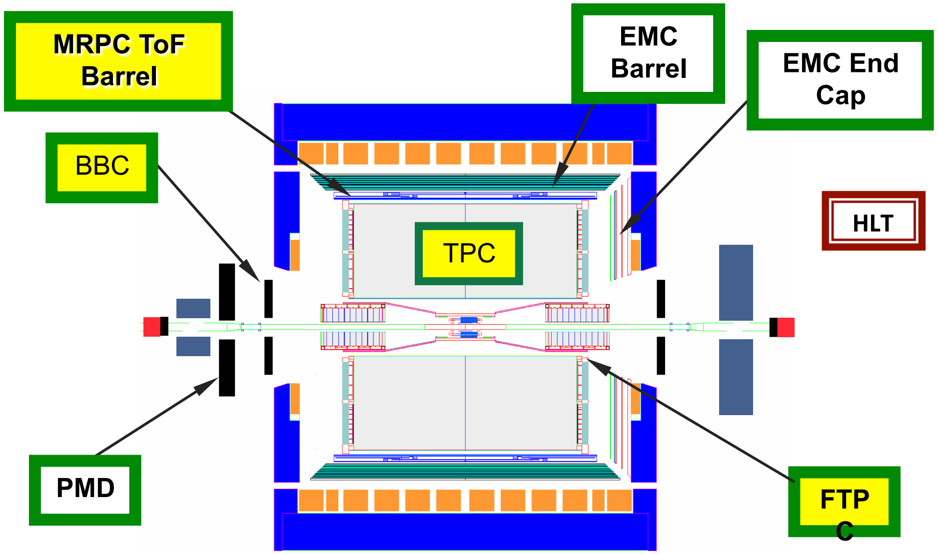
Search for signals for critical point

Established observables:

NCQ scaling of v_2	Partonic vs. hadronic degrees of freedom
Dynamical charge correlations	Partonic vs. hadronic degrees of freedom
Azimuthally sensitive HBT	Possible 1st order phase transition
v_1 vs. rapidity	Possible 1st order phase transition
Fluctuations	Possible critical point
v_3/v_n	Initial geometry/viscosity

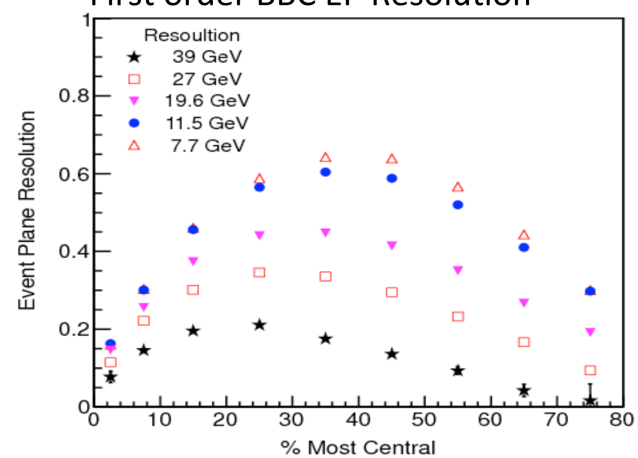
- RHIC successfully completed first phase of BES program in 2011.
- Directed flow results at $\sqrt{s_{NN}}$= 7.7, 11.5, 19.6, 27 and 39 GeV are presented here.
- v_3 results in 7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV Au+Au and 62.4 and 200 GeV Cu+Cu collisions are presented.
- Transverse momentum dependence of higher harmonics (n = 1-5) at 200 GeV Au+Au collisions are presented

STAR Experiment

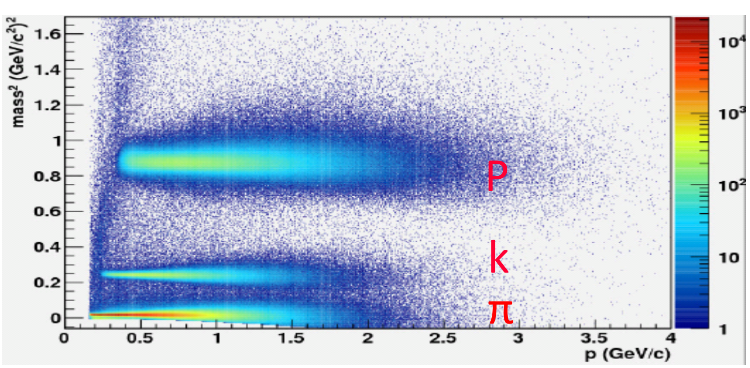


- Time Projection Chamber (TPC) is main tracking detector at STAR.
- Forward TPC (FTPC) ($2.5 < |\eta| < 4.0$) also provides tracking at forward rapidity

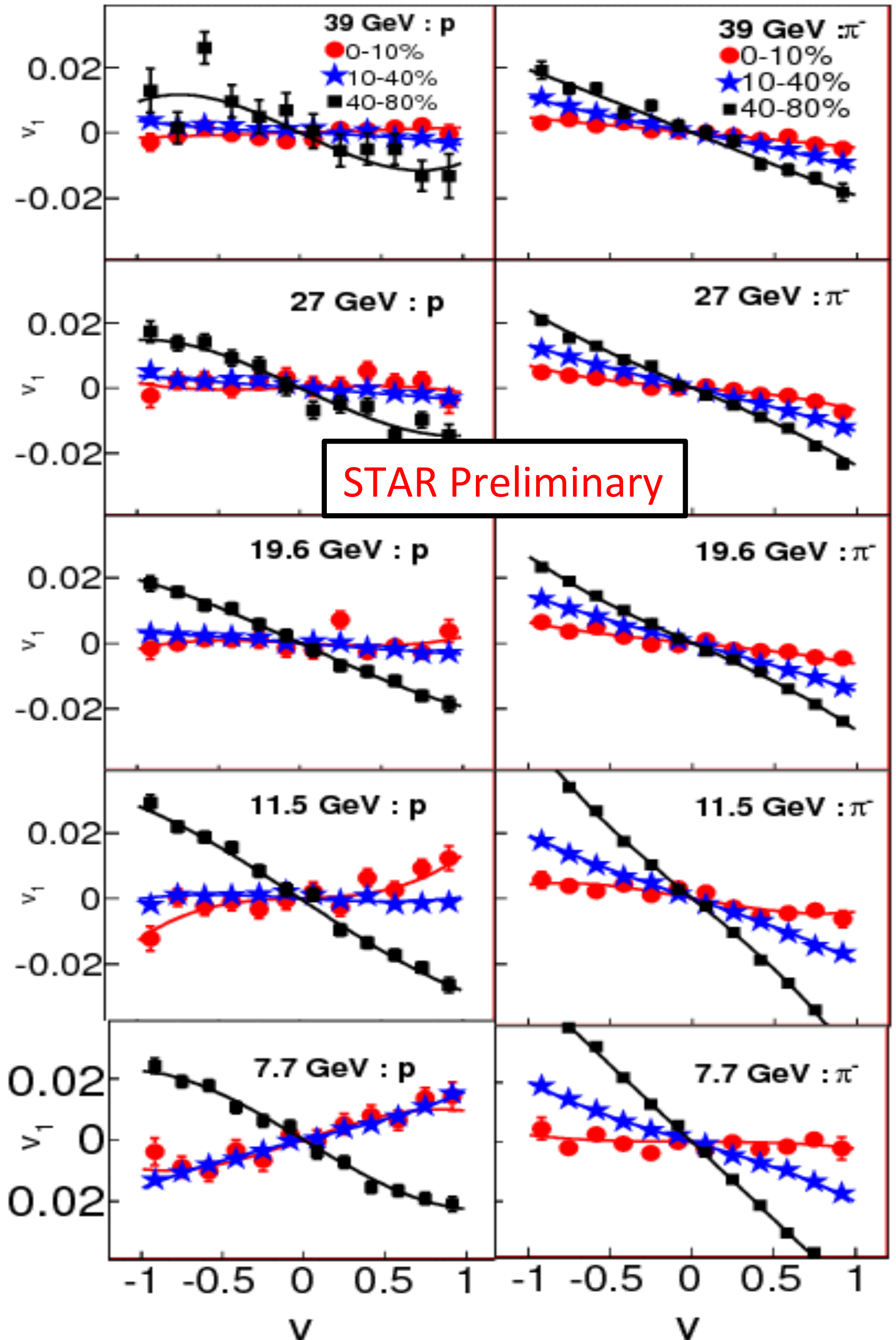
First order BBC EP Resolution



- Time of Flight (TOF) provides excellent particle identification $p_T < 1.6$ GeV/c for pions ($0<m^2<0.10$ (GeV c^2)^2), kaons ($0.20<m^2<0.35$ (GeV/c^2)^2) and $p_T<2.8$ GeV/c for protons ($0.8<m^2<1.0$ (GeV/c^2)^2)



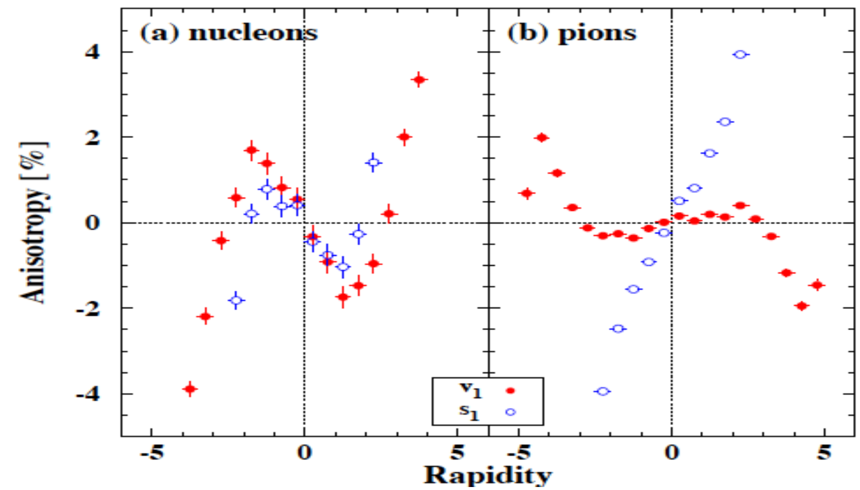
- Beam Beam Counters (BBC) ($3.3<|\eta|<5.0$) are used to reconstruct the first-order event plane at 39 GeV and lower beam energies. BBC provides adequate event plane resolution.
- Greatly reduced non-flow effects in v_1 study because of η gap between TPC and BBC.



Proton and pion v_1

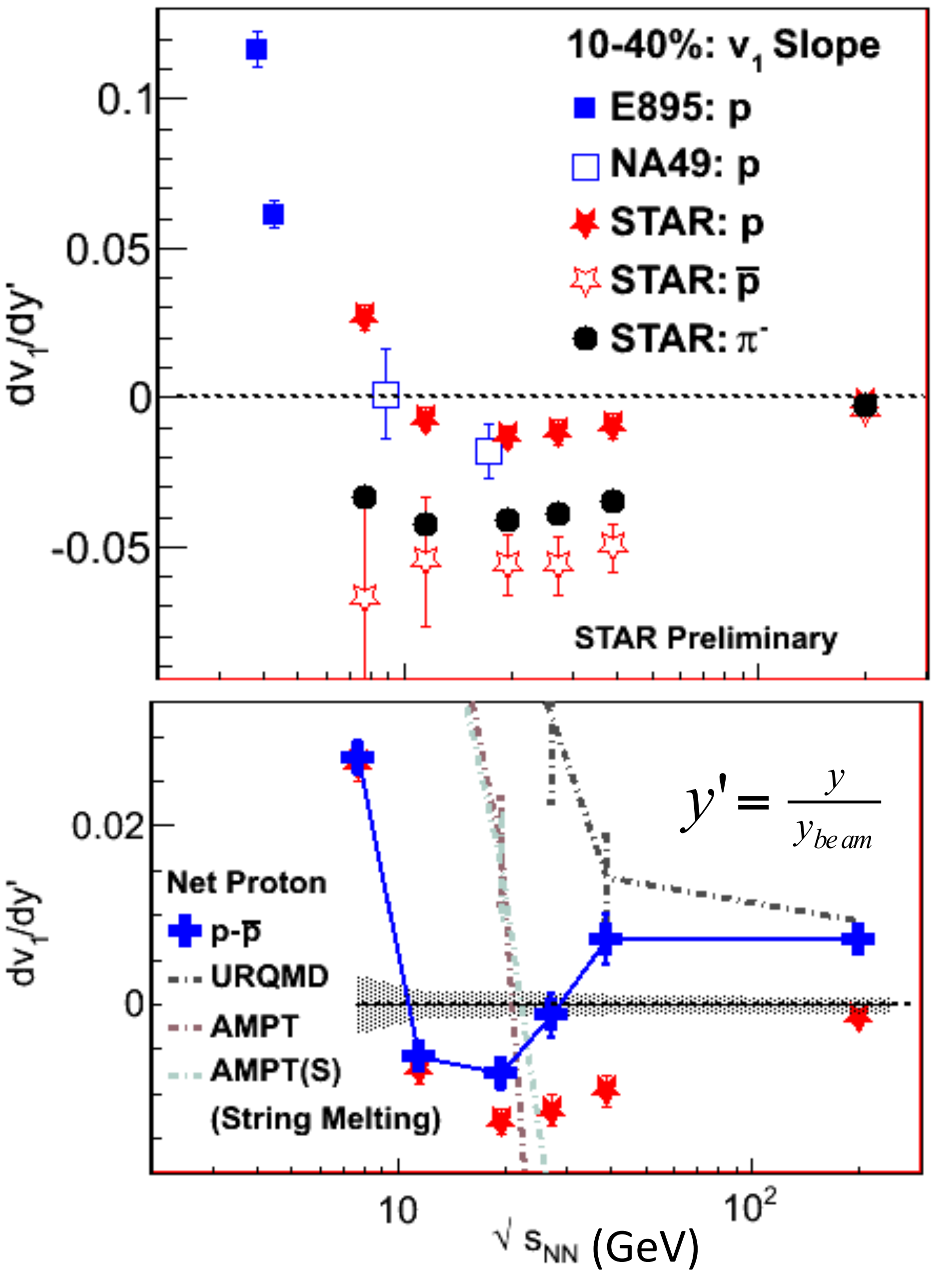
Directed flow of protons and pions at five different energies in central (0-10%), mid-central (10-40%) and peripheral (40-80%) collisions near midrapidity.

Baryon stopping + positive space-momentum correlation cannot explain both proton and pion flow simultaneously.



1. P. Huovinen in *Quark-Gluon Plasma 3*, eds: R. C. Hwa, X. N. Wang (World Scientific, Singapore, 2003), p. 616.
2. R. J. Snelling *et al.*, PRL **84**, 2803 (2000).
3. M. Bleicher and H. Stöcker, PLB **526**, 309 (2002).

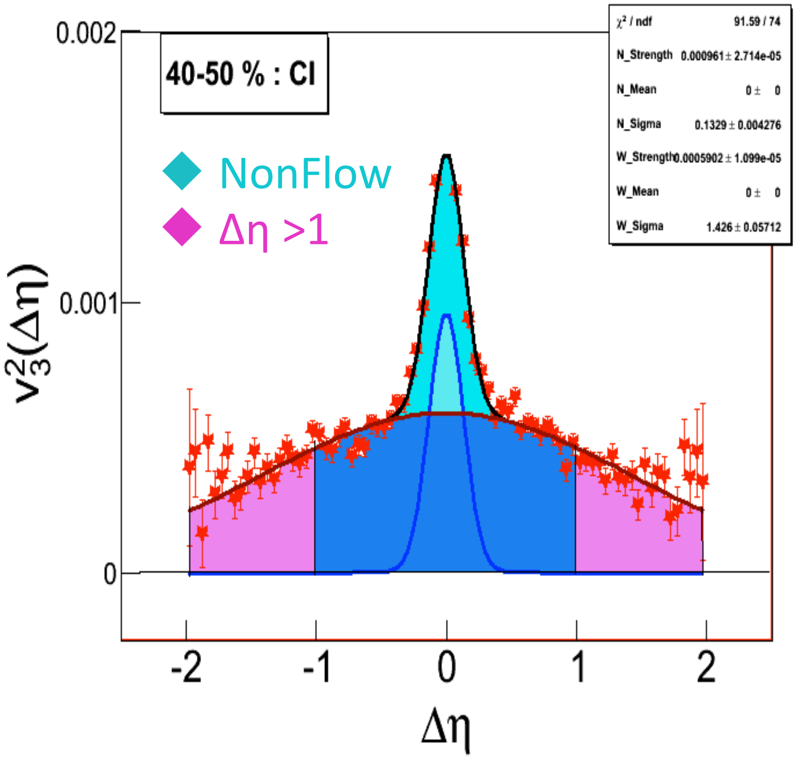
Beam energy dependence of v_1 slope ($F = dv_1/dy'$)

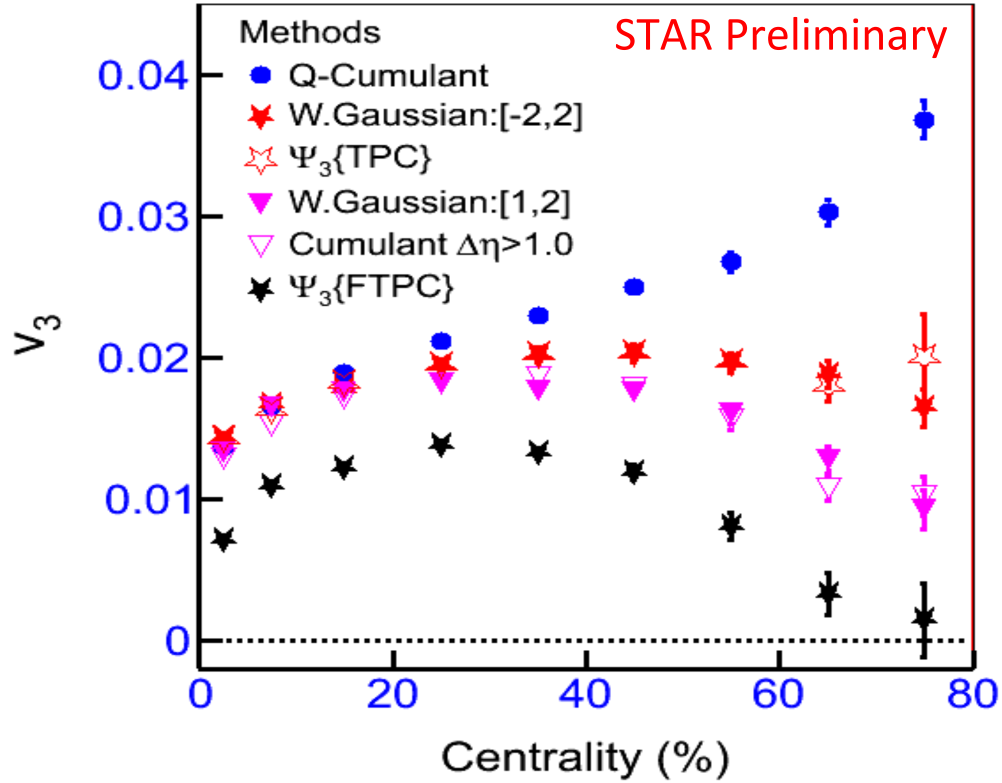


$F = r\, F_{anti\text{-}p} + (1 - r)\, F_{trans}$, where r is the observed ratio of antiprotons to protons.

- Possible signature of EOS softening.
- F_{trans} (labeled $p - \bar{p}$ in Fig.) is also called "net-proton" v_1 slope.
- We observe non-monotonic behavior of net-proton v_1 slope.
- UrQMD and AMPT cannot explain even the sign of the net proton data.
- Need more input from theory and more statistics to accurately measure centrality dependence to fully understand underlying physics.

Triangular flow: Method of Measurement



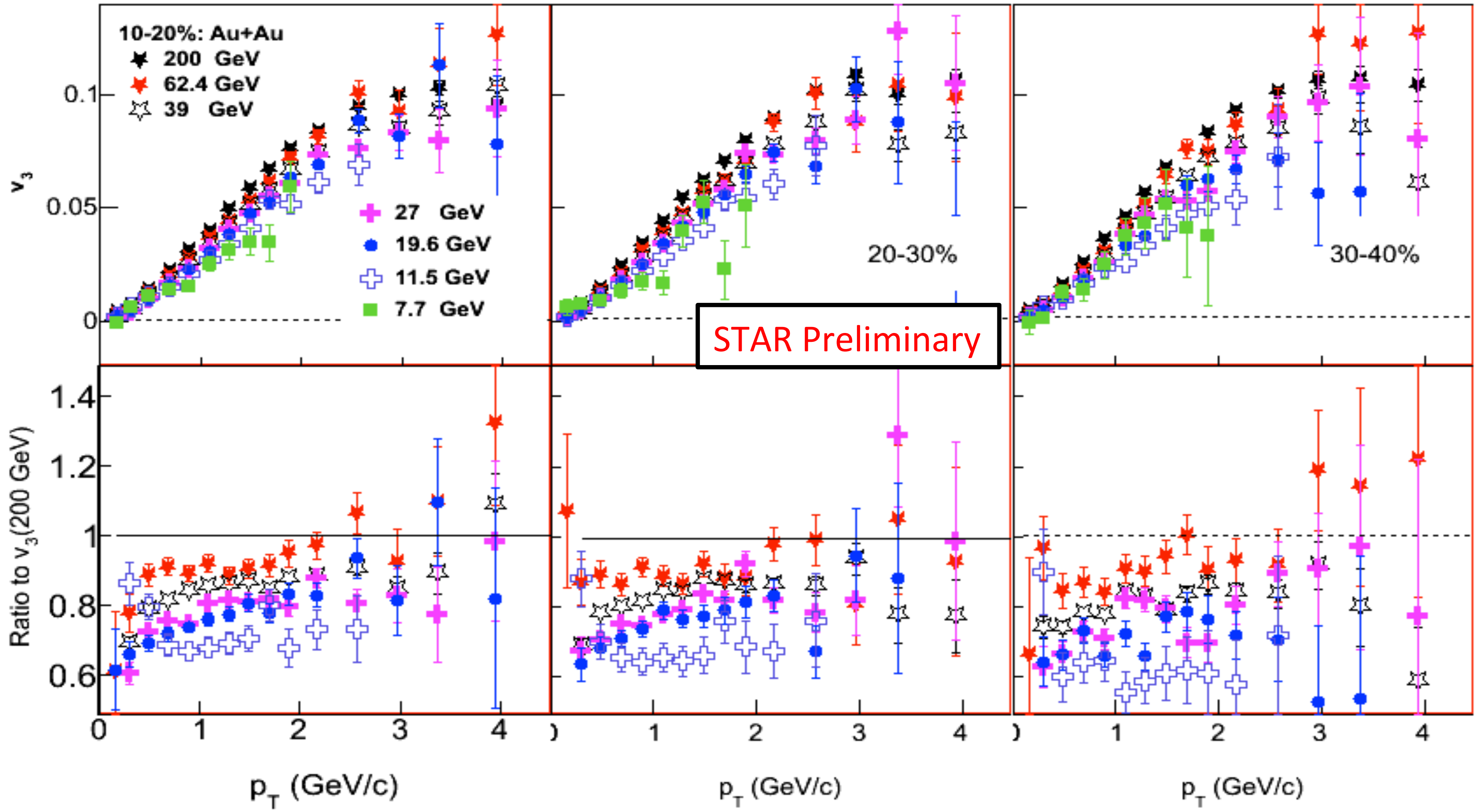


$$\left\langle v_3^2\{2\}\right\rangle = \frac{\int_{\Delta\eta=a}^{\Delta\eta=b} v_3^2\{2,\Delta\eta\}\frac{dn}{d(\Delta\eta)}d(\Delta\eta)}{\int_{\Delta\eta=a}^{\Delta\eta=b} \frac{dn}{d(\Delta\eta)}d(\Delta\eta)}$$

The differences among methods are due to different Δη windows used to measure v_3.

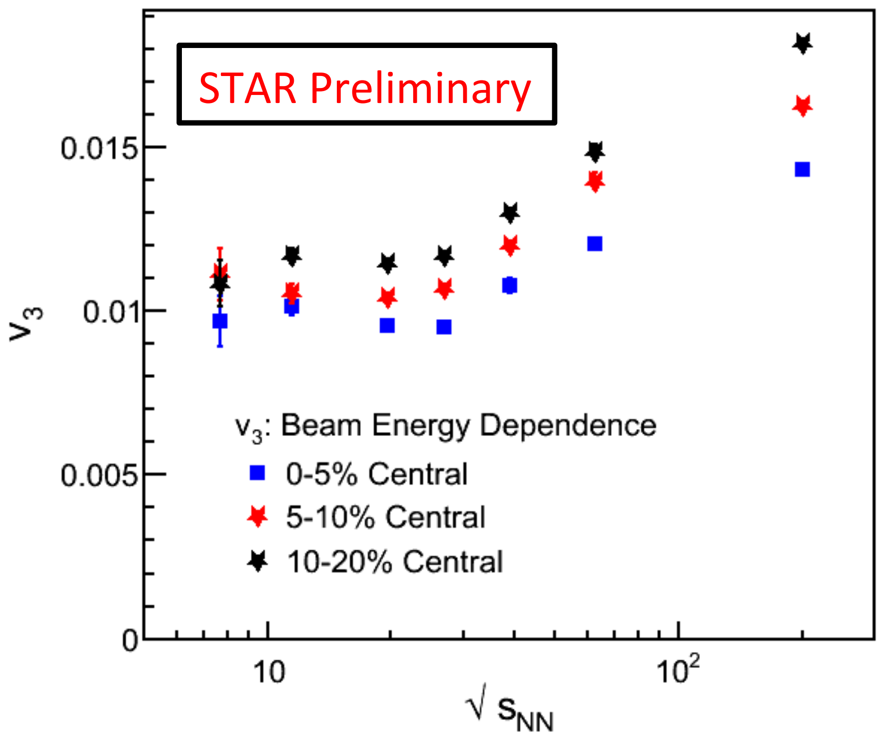
We use TPC η sub-event plane method, with η gap of 0.05 between the two sub-events.

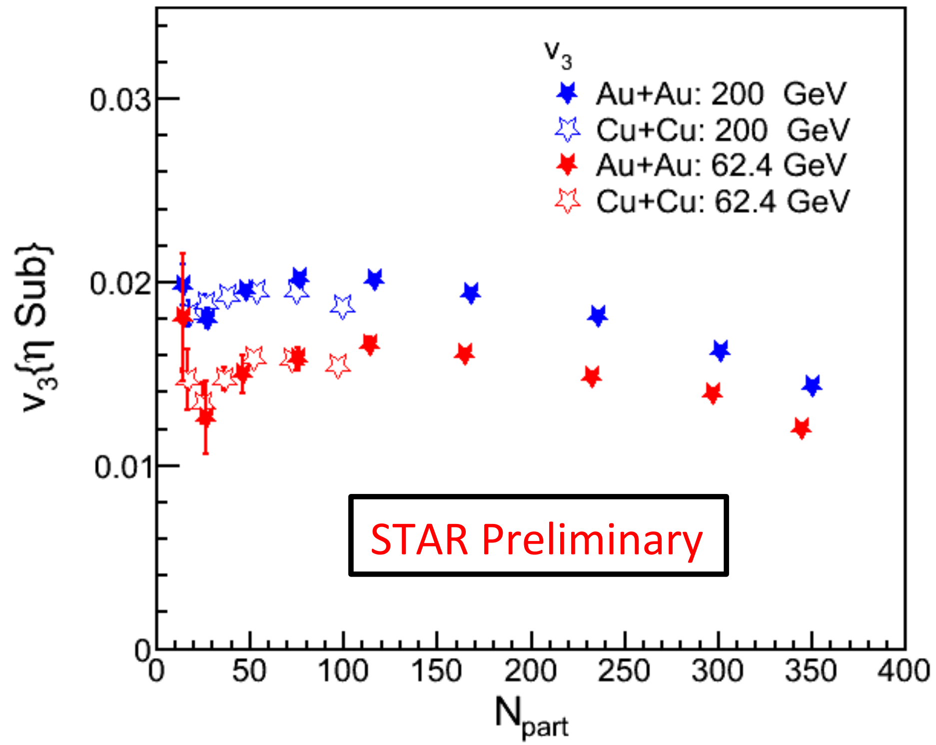
Beam Energy Dependence : 7.7-200 GeV Au+Au Collisions



- Triangular flow as a function of p_T: measurements at 7.7, 11.5, 19.6, 27 & 39 GeV lie below 200 GeV points at low p_T but difference is less at higher p_T.

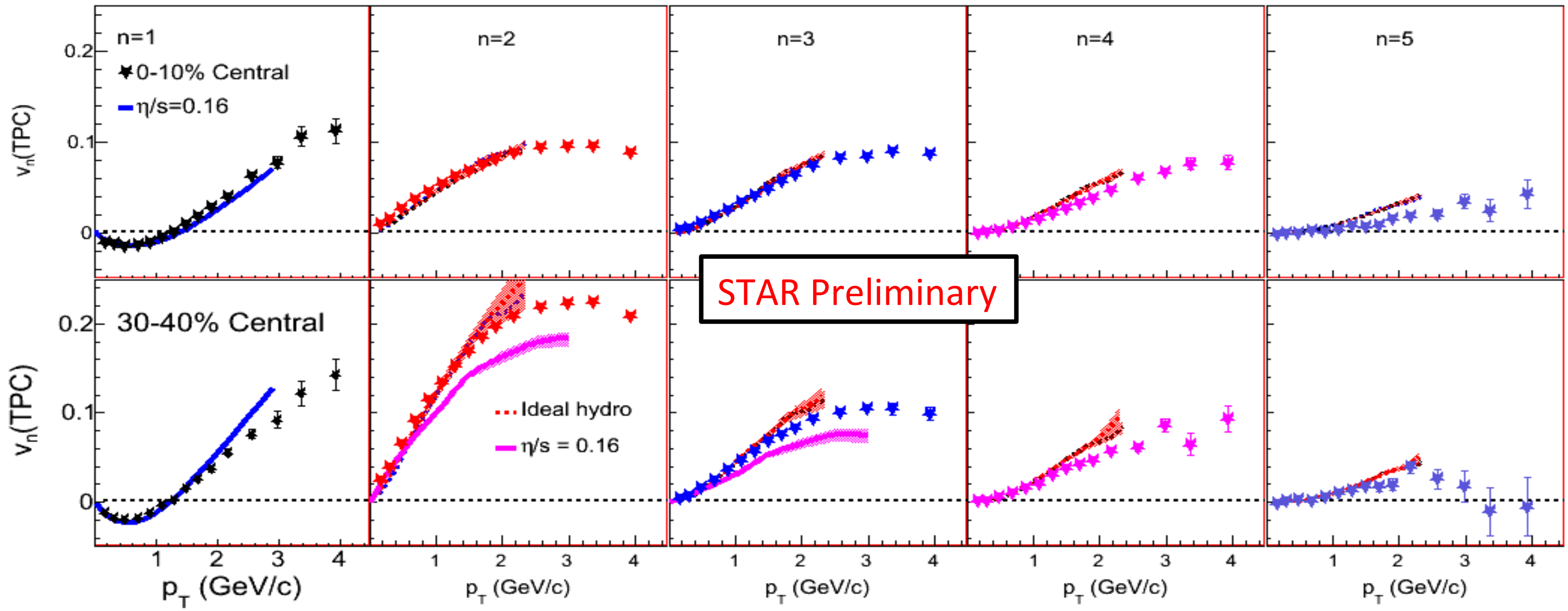
Beam Energy and System Size Dependence





- Triangular flow as a function of centrality within 0-20%, integrated in p_T (0.2 $<p_T<$ 2.0 GeV/c) and η (|η|< 1.0): v_3 appears almost flat up to 27 GeV, with a large increase thereafter.
- v_3 persists all the way down to 7.7 GeV where jets are negligible.
- Triangular flow vs. N_{part} depends on beam energy, but $v_3(N_{part})$ is about the same for Au+Au and Cu+Cu at each energy.

Flow harmonics (n=1-5) at 200 GeV: p_T dependence



- *n*=1 is signal associated with dipole asymmetry, corrected for momentum conservation.
- Model curves for *n*=1 are from Retinskaya, Luzum & Ollitrault, PRL **108**, 252302 (2012) (η/s=0.16); higher *n* curves are from Gardim *et al*., arXiv:1203.2882 (ideal hydro) and for n=2 and n=3 with η/s= 0.16 are from B. Schenke *et al*., PRL **106**, 042301 (2011).
- The models do a good job describing the general features of the data. These comparisons suggest that low or zero viscosity is favored.

Summary

- For mid-central Au+Au collisions, proton directed flow slope (dv_1/dy) changes sign from positive to negative between 7.7 and 11.5 GeV and remains small but negative up to 200 GeV; slope for pions, kaons and antiprotons remains always negative.
- The v_1 slope for net protons shows non-monotonic behavior at low beam energies (is negative at 11.5 and 19.6 GeV & positive at all other energies). UrQMD & AMPT do not qualitatively account for the algebraic signs. More input from theory is necessary to fully understand this behavior.
- Triangular flow as a function of p_T measured for Au+Au at BES energies and compared with 62.4 and 200 GeV Au+Au and Cu+Cu. We also report centrality and N_{part} dependence of v_3.
- All flow harmonics (n=1-5) measured as a function of p_T . These measurements provide significant inputs for understanding both initial fluctuation and transport properties.