Directed Flow of Identified Particles

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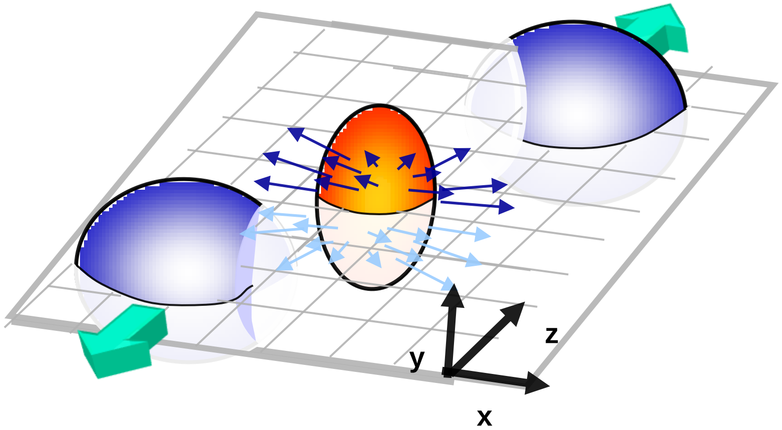
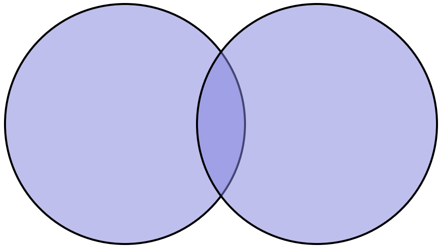
A Few Useful Concepts

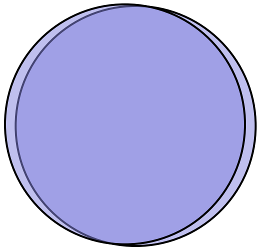


Reaction plane : Defined by the beam and the line connecting two colliding nuclei

Transverse momentum : $p_t = \sqrt{p_x^2 + p_y^2}$



Peripheral collisions : collisions in which two nuclei barely graze each other.



Central collisions : head-on collisions.

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

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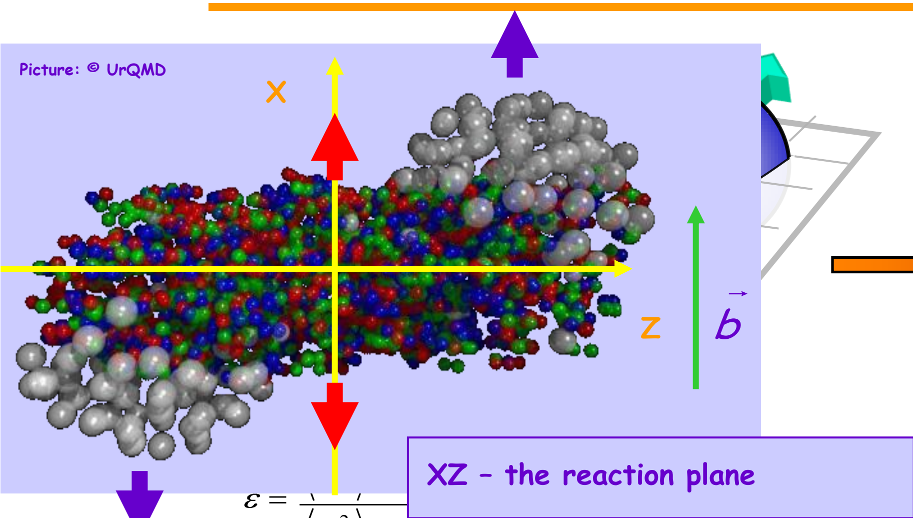
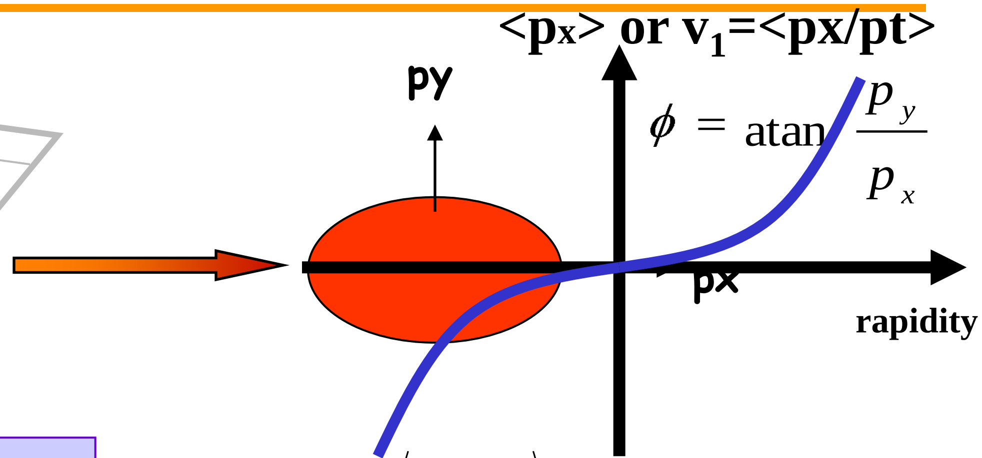


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

initial spatial anisotropy



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

anisotropy in momentum space

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

isotropic　directed　elliptic

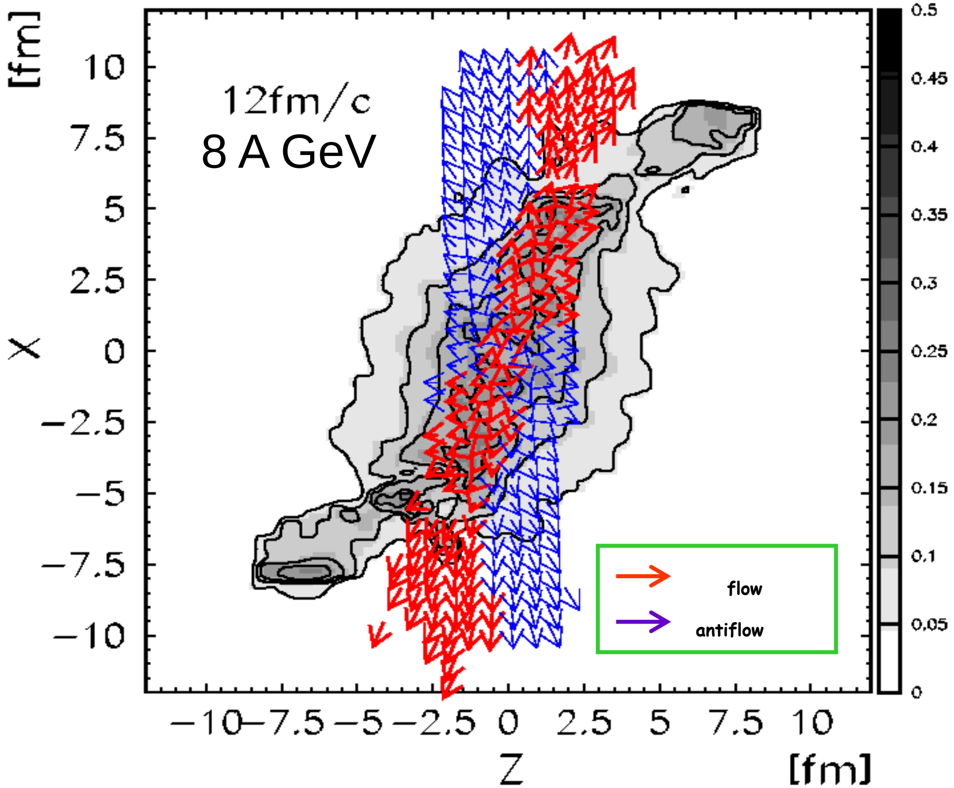
$$v_n = \langle \cos(n(\phi - \psi_{RP})) \rangle = \langle e^{in(\phi - \psi_{RP})} \rangle$$

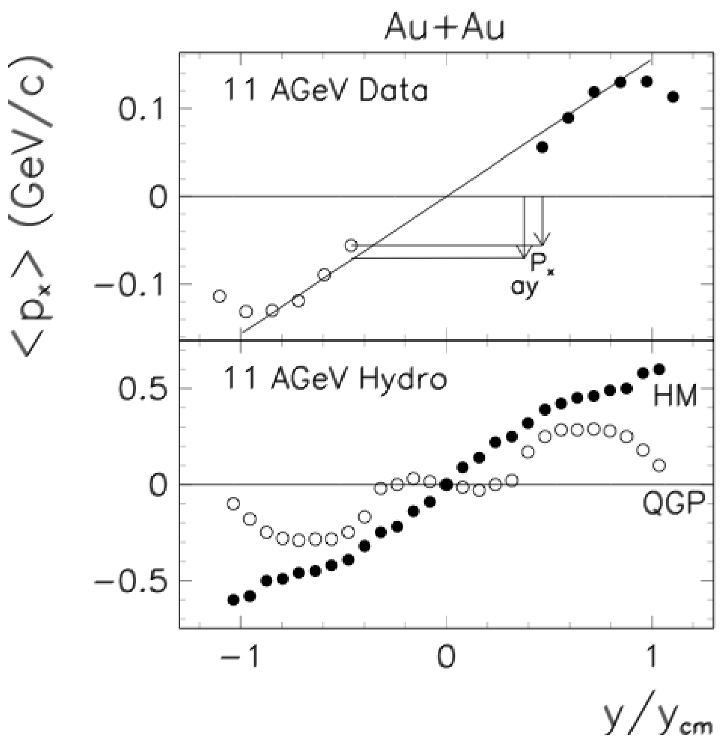
$=$ Correlation to the reaction plane

$\equiv$" anisotropic flow "

It a convention to define the sign of v_1 of spectators at forward rapidity as positive.

Anti-flow / 3rd flow component

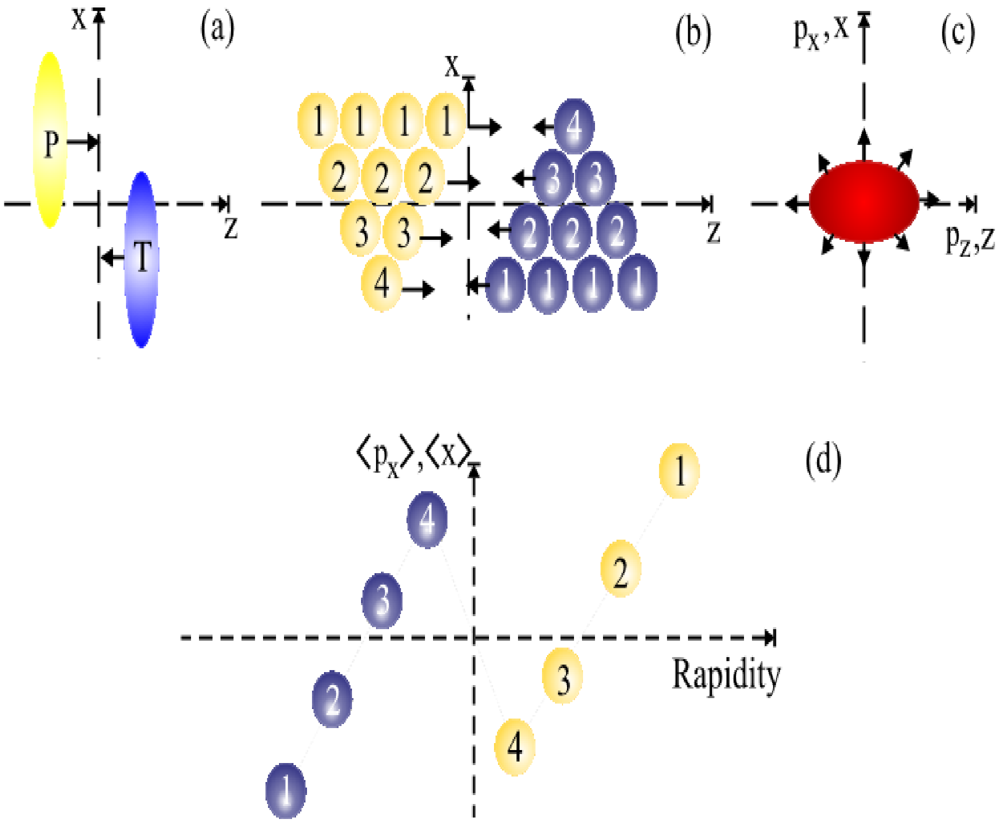


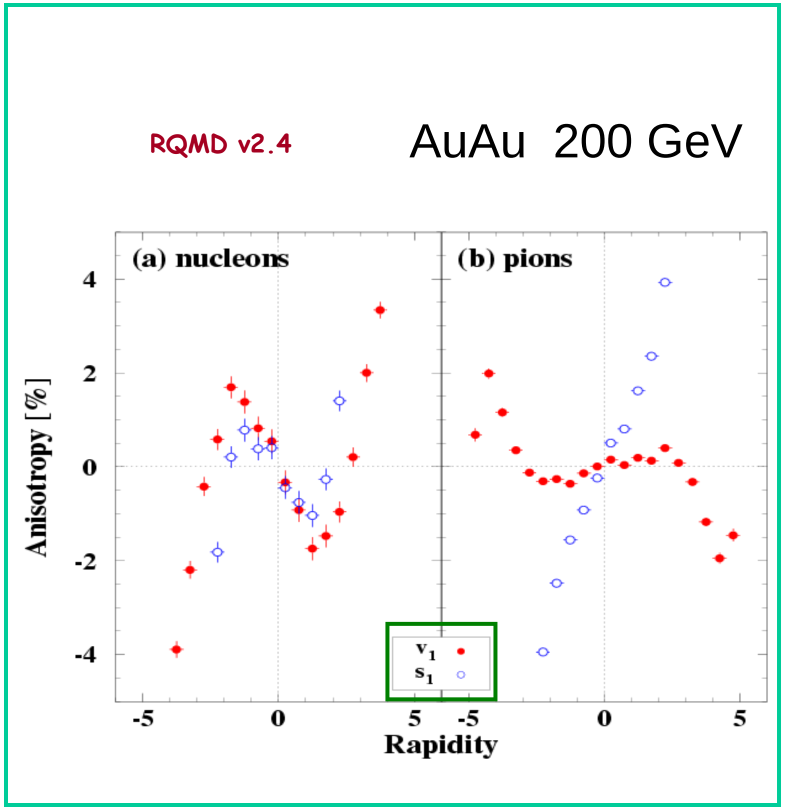


Brachmann, Soff, Dumitru, Stocker, Maruhn, Greiner Bravina, Rischke , PRC 61 (2000) 024909.
L.P. Csernai, D. Roehrich PLB 458, 454 (1999) M.Bleicher and H.Stocker, PLB 526,309(2002)

Anti-flow/3rd flow component : Flat v_1 at midrapidity due to 1st order phase transition
Caution : Seeing anti-flow does not necessarily mean that there is a QGP EoS. (refer to UrQMD). In following slides, anti-flow only means zero or negative slope at midrapidity, due to the fast expansion of a tilted source.

v_1 from baryon stopping

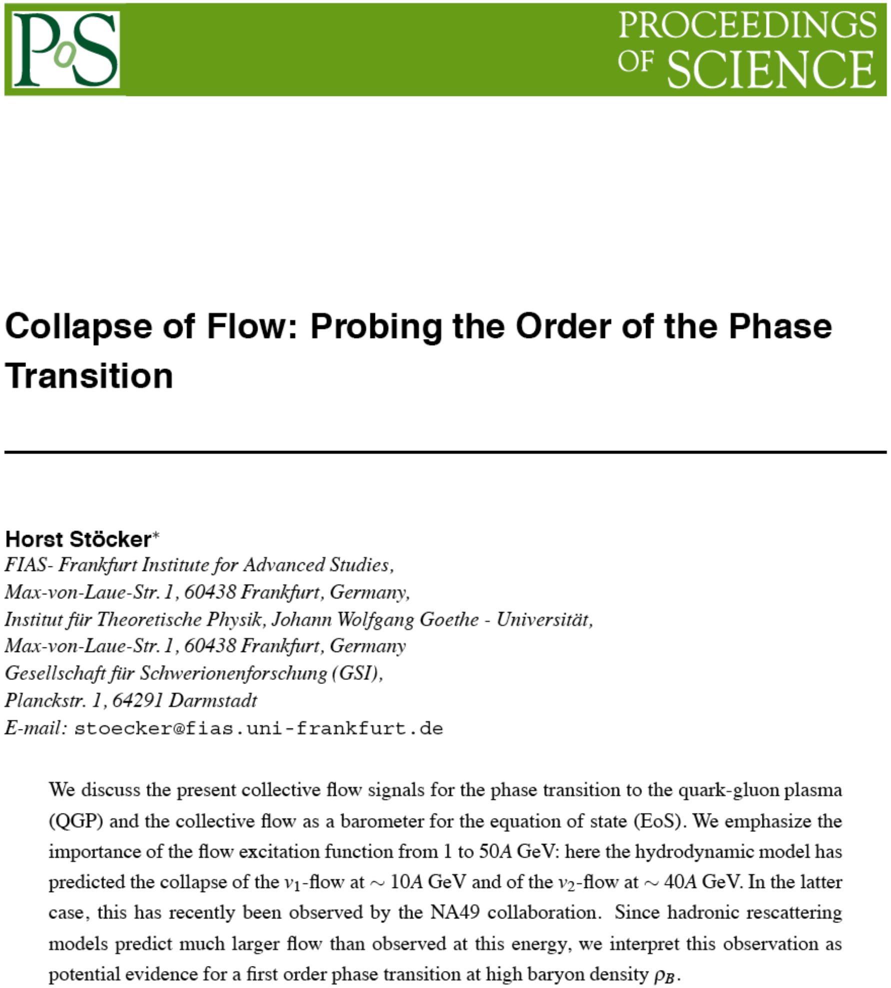




R.Snellings, H.Sorge, S.Voloshin, F.Wang, N. Xu, PRL (84) 2803(2000)

Baryon stopping + positive space-momentum correlation ➔ v_1 wiggle.
No QGP necessary

v_1 and 1st order phase transition



PROCEEDINGS OF SCIENCE

Collapse of Flow: Probing the Order of the Phase Transition

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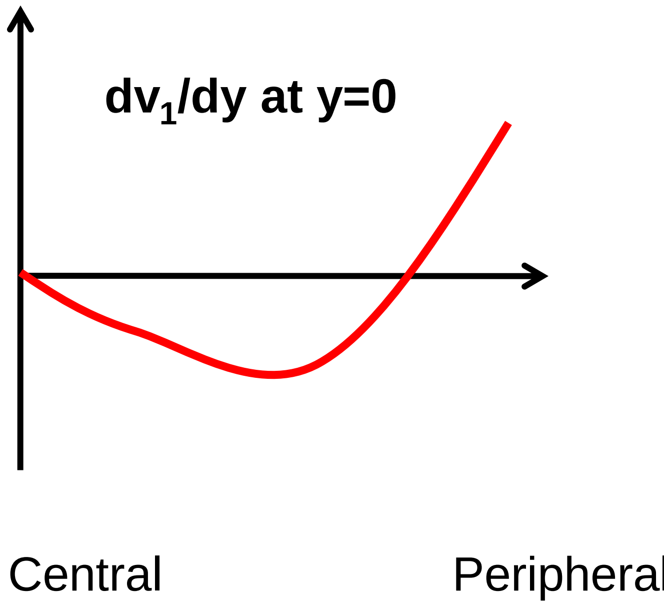
We discuss the present collective flow signals for the phase transition to the quark-gluon plasma (QGP) and the collective flow as a barometer for the equation of state (EoS). We emphasize the importance of the flow excitation function from 1 to 50*A* GeV: here the hydrodynamic model has predicted the collapse of the v_1-flow at $\sim$ 10*A* GeV and of the v_2-flow at $\sim$ 40*A* GeV. In the latter case, this has recently been observed by the NA49 collaboration. Since hadronic rescattering models predict much larger flow than observed at this energy, we interpret this observation as potential evidence for a first order phase transition at high baryon density ρ_B.



v_1 and early thermalization

Directed Flow
The Observable of Early Thermalization

1. Directed flow at RHIC ↔ **HYDRODYNAMICS**
   - explains anti-flow
   - right magnitude
   - system size scaling
2. Qualitatively explains : PID flow (and $p_\perp$ dependence)

Longitudinal pressure appears early!

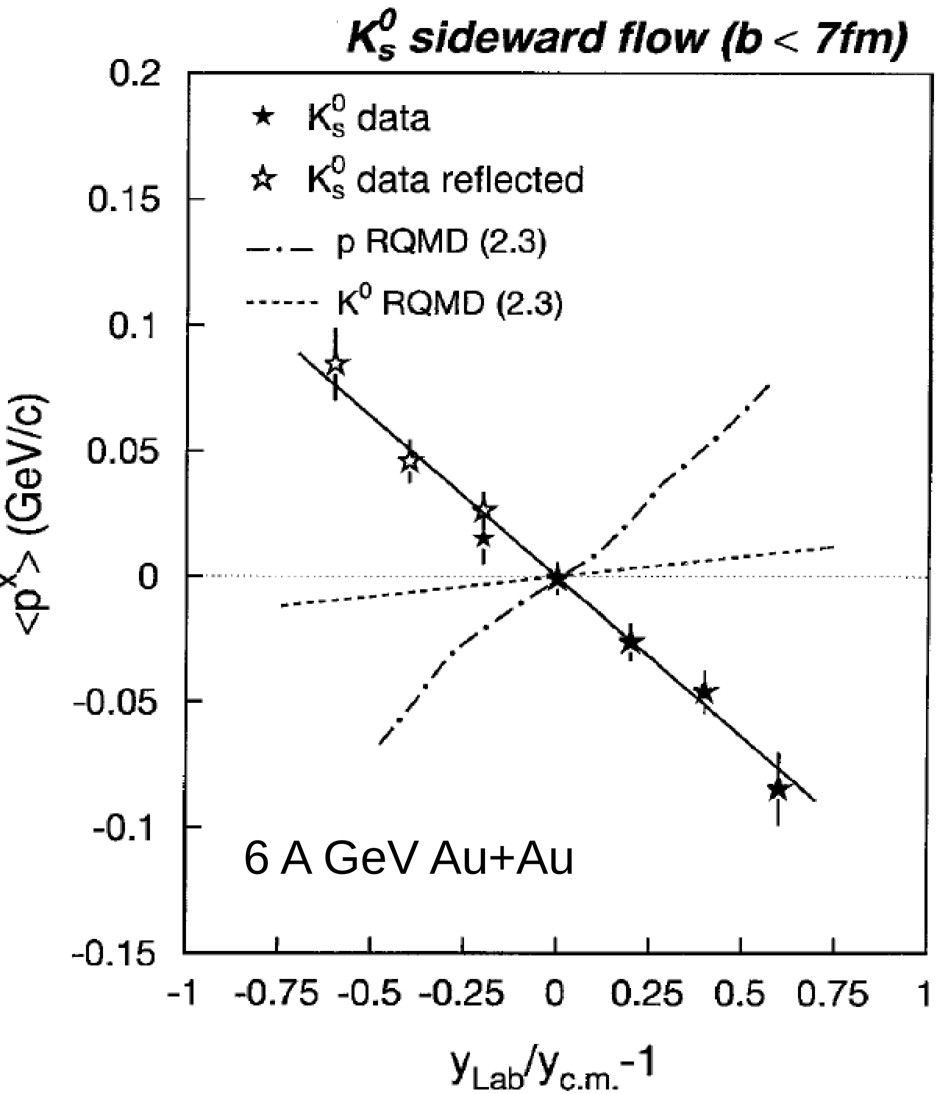
Piotr Bożek | Directed flow

See next talk.

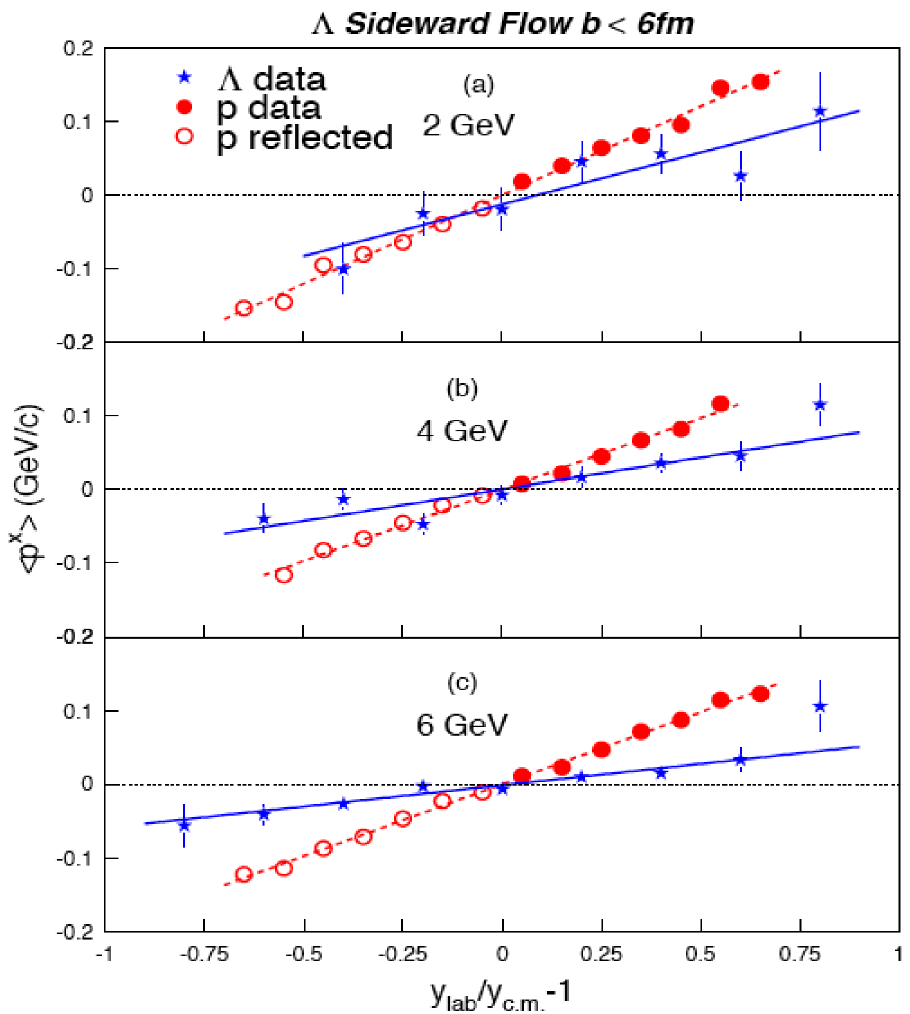
Piotr Bozek, RHIC/AGS workshop 2010

Piotr Bozek and Iwona Wyskiel-Piekarska, Arxive:1009.0701

v_1 at low energies

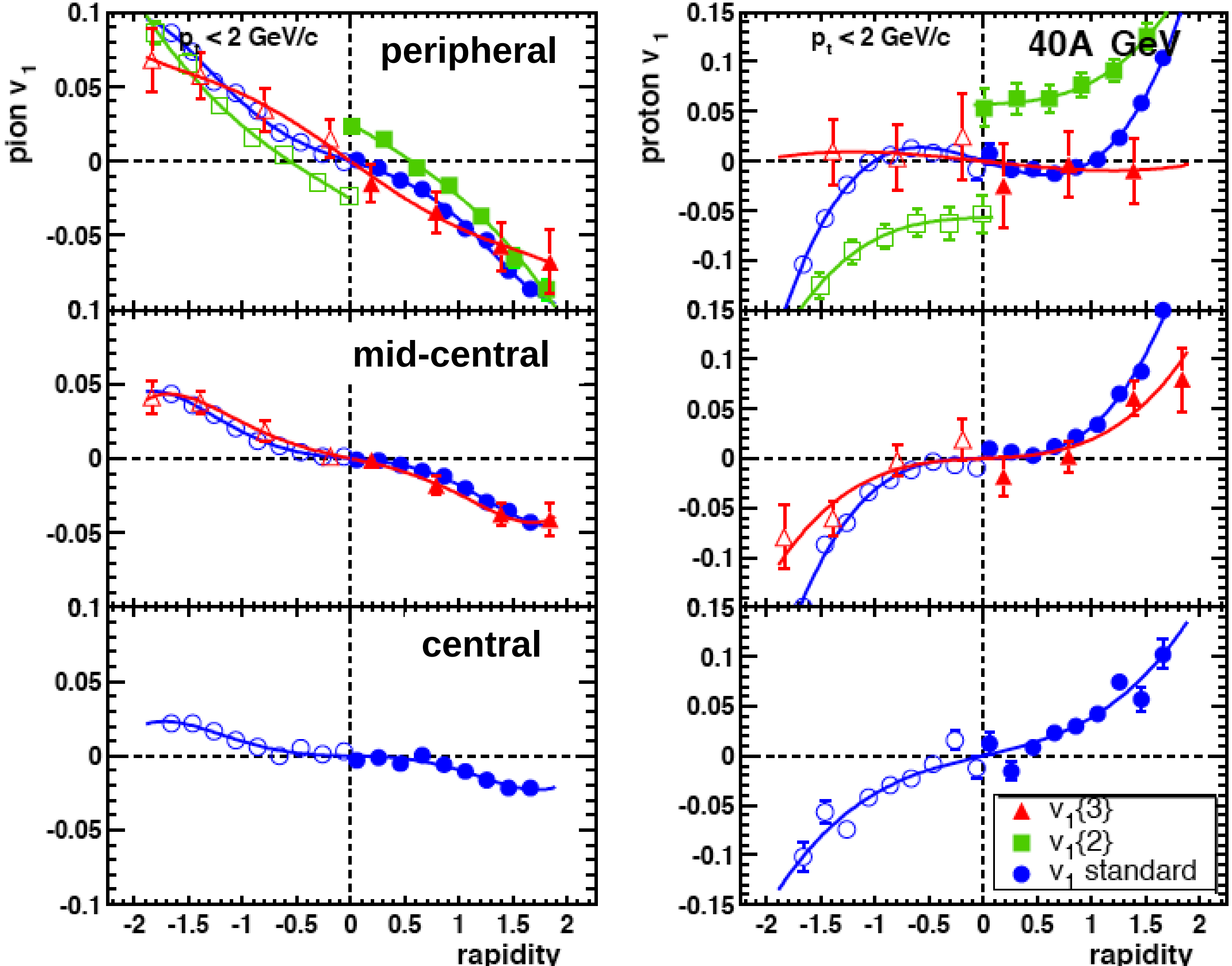


e895, PRL 85 940 (2000)



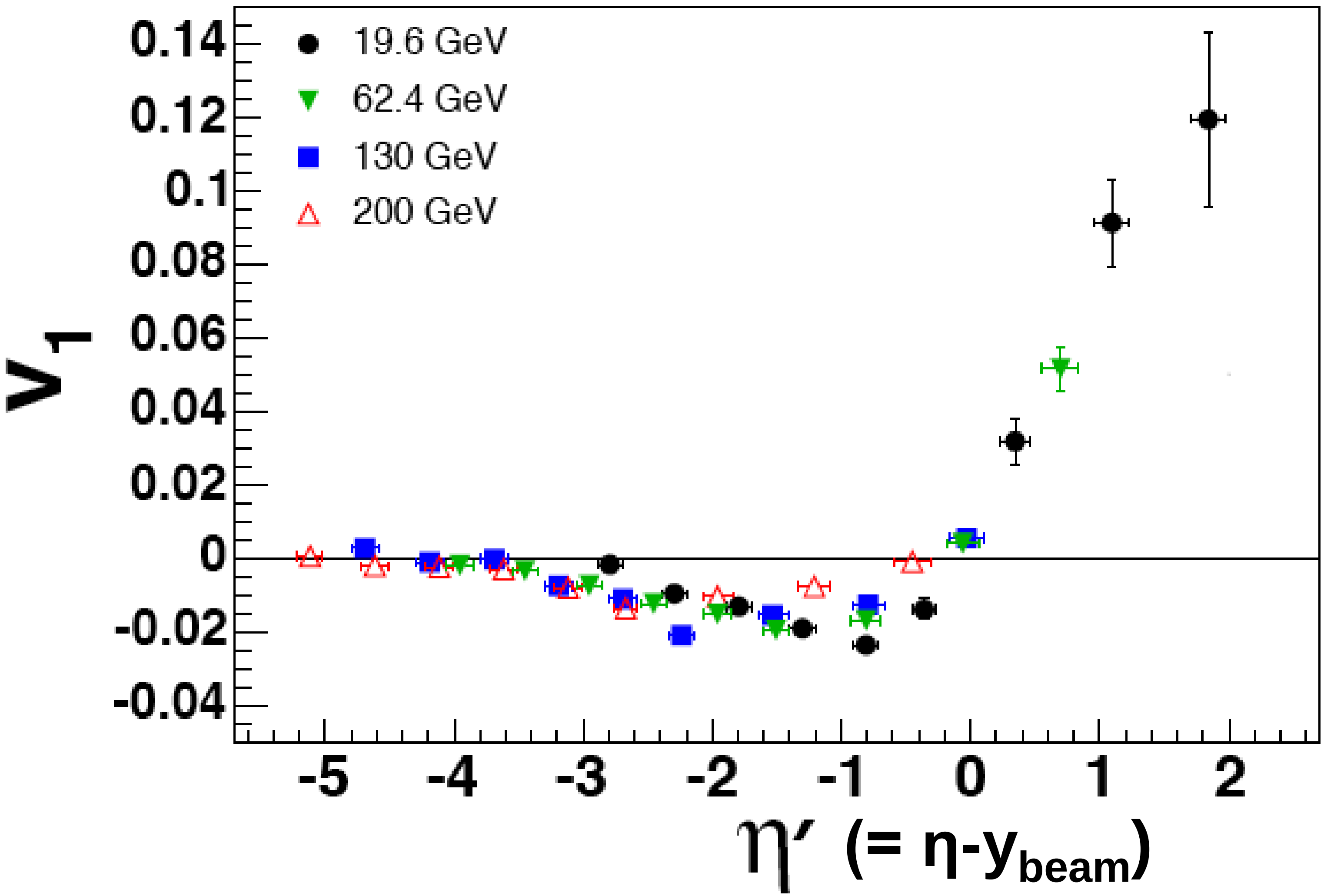
E895, PRL 86 2533 (2001)

v_1 at low energies



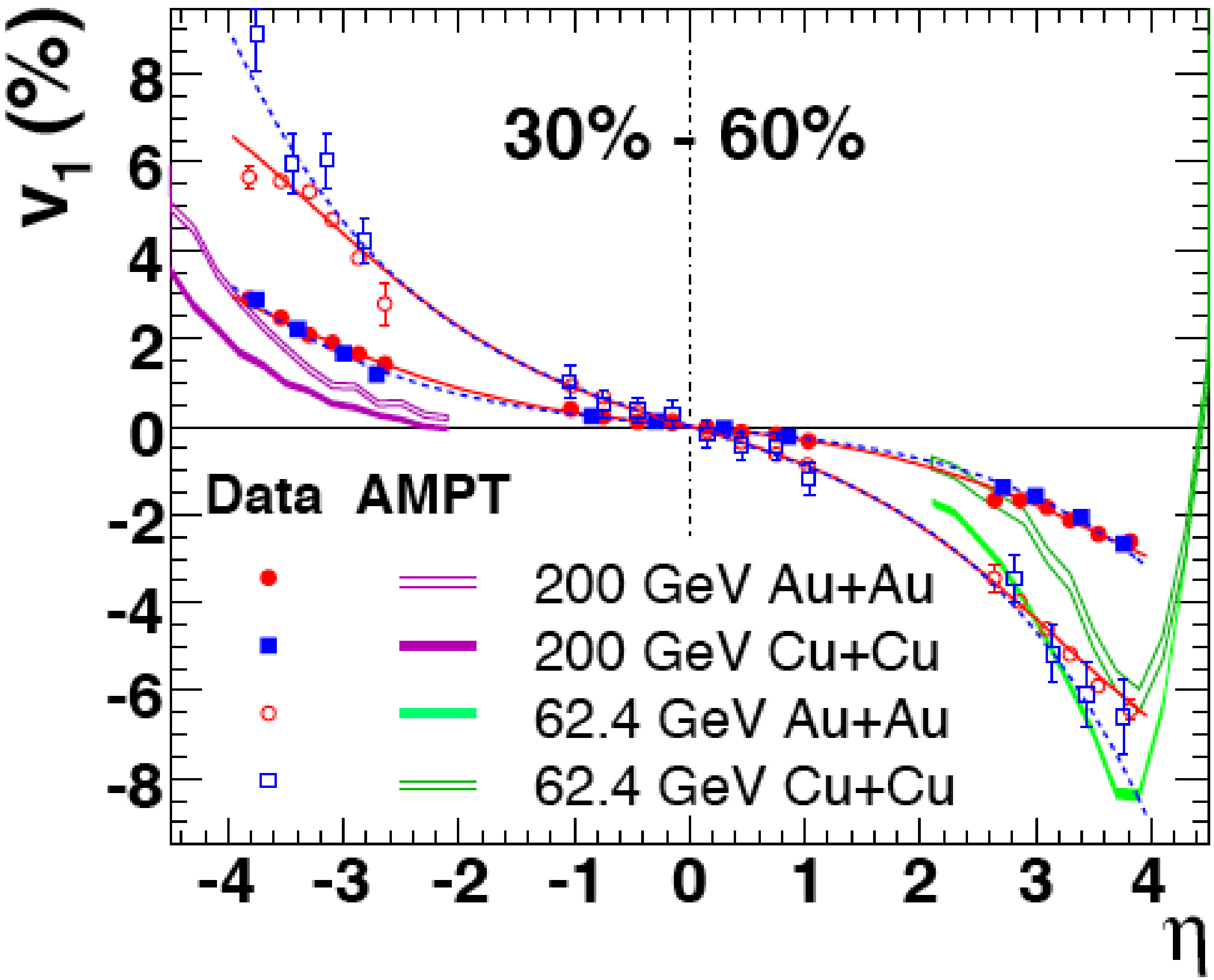
NA49, NPA 715, 583 (2003)

v_1 at RHIC, measured by Phobos



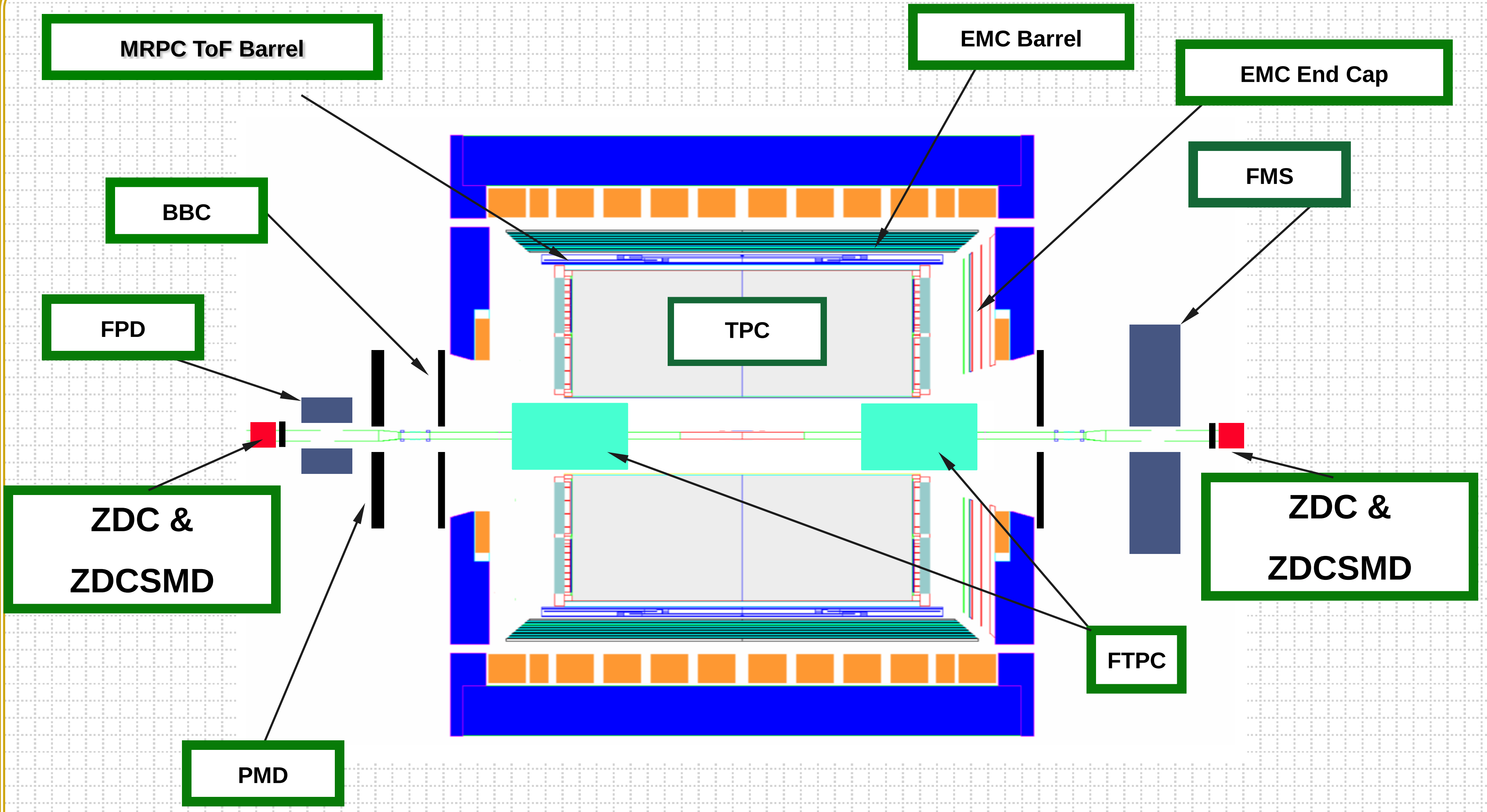
Phobos, PRL 97 012301 (2006)

v_1 at RHIC, measured by STAR



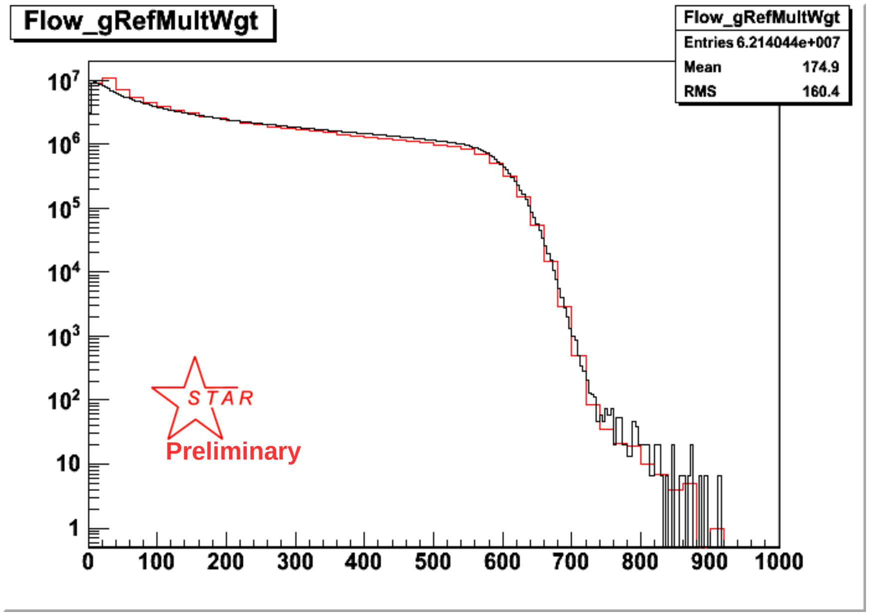
STAR, PRL 101 252301 (2008)

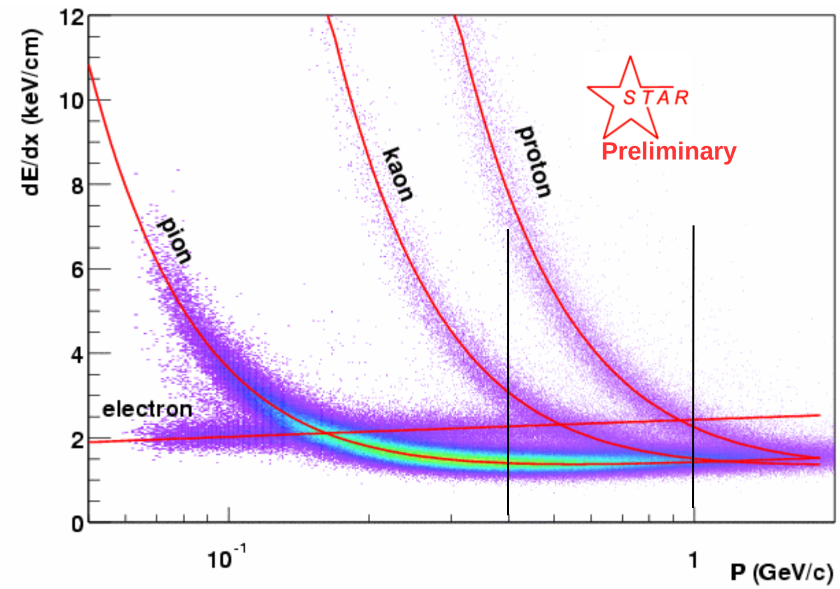
STAR Experiment



Data set for PID v_1 analysis

- **Run7 , 62 M events.**





Tracks used for TPC :

No. of fit hits ∈[15, 50]

Global DCA∈[0.0, 1.0]

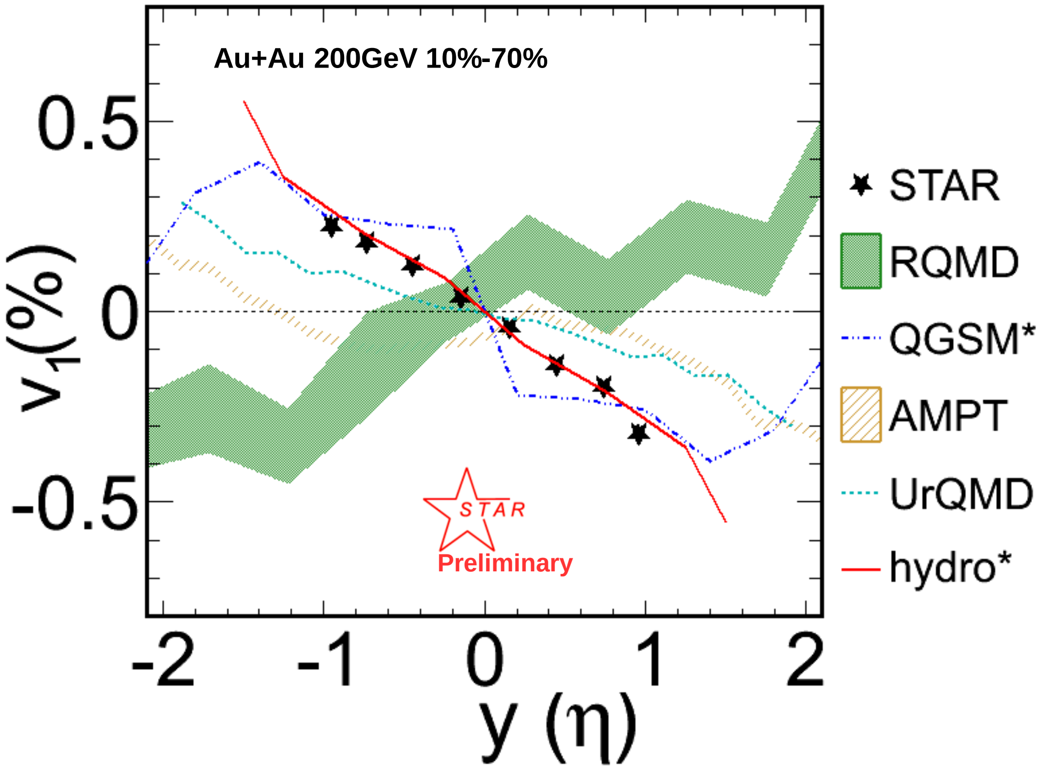
No. of fit hits/No.of possible hits ∈[0.52, 1.05]

0.1 < pT < 12.0 GeV/c | η | < 1.

PID achieved by TPC dE/dx

P_t cut for protons/anti-protons [0.4,1 GeV/c]

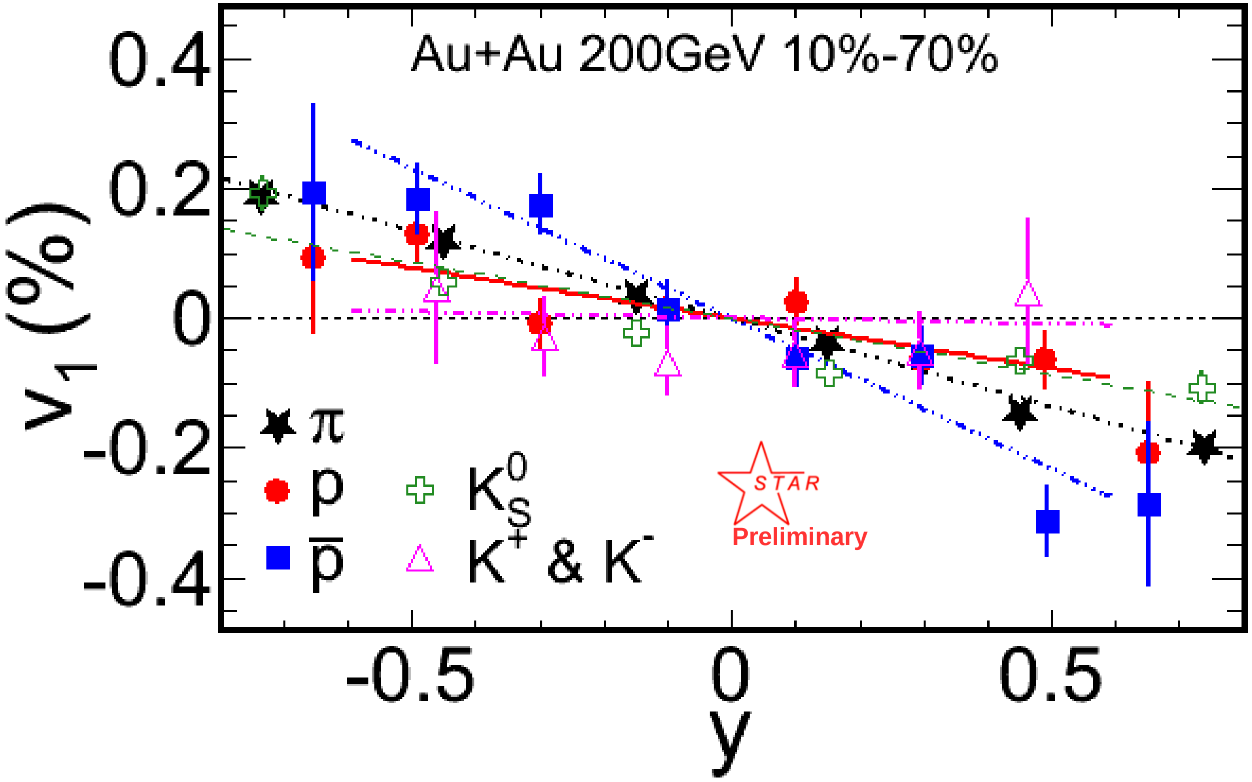
Pion v_1 at RHIC



RQMD: Phys. Rev. Lett. 84 (2000) 2803;
UrQMD: Phys. Lett. B 526 (2002) 309;
AMPT: Phys. Rev. C 81, 014904 (2010);
QGSM+ Partonic recombination: Phys. Rev . C 76 (2007) 024912;
hydro + tilted source: Piotr Bo˙zek and Iwona Wyskiel, arXiv:1002.4999 [nucl-th] (2010).

Hydro+tilted source describes the data the best

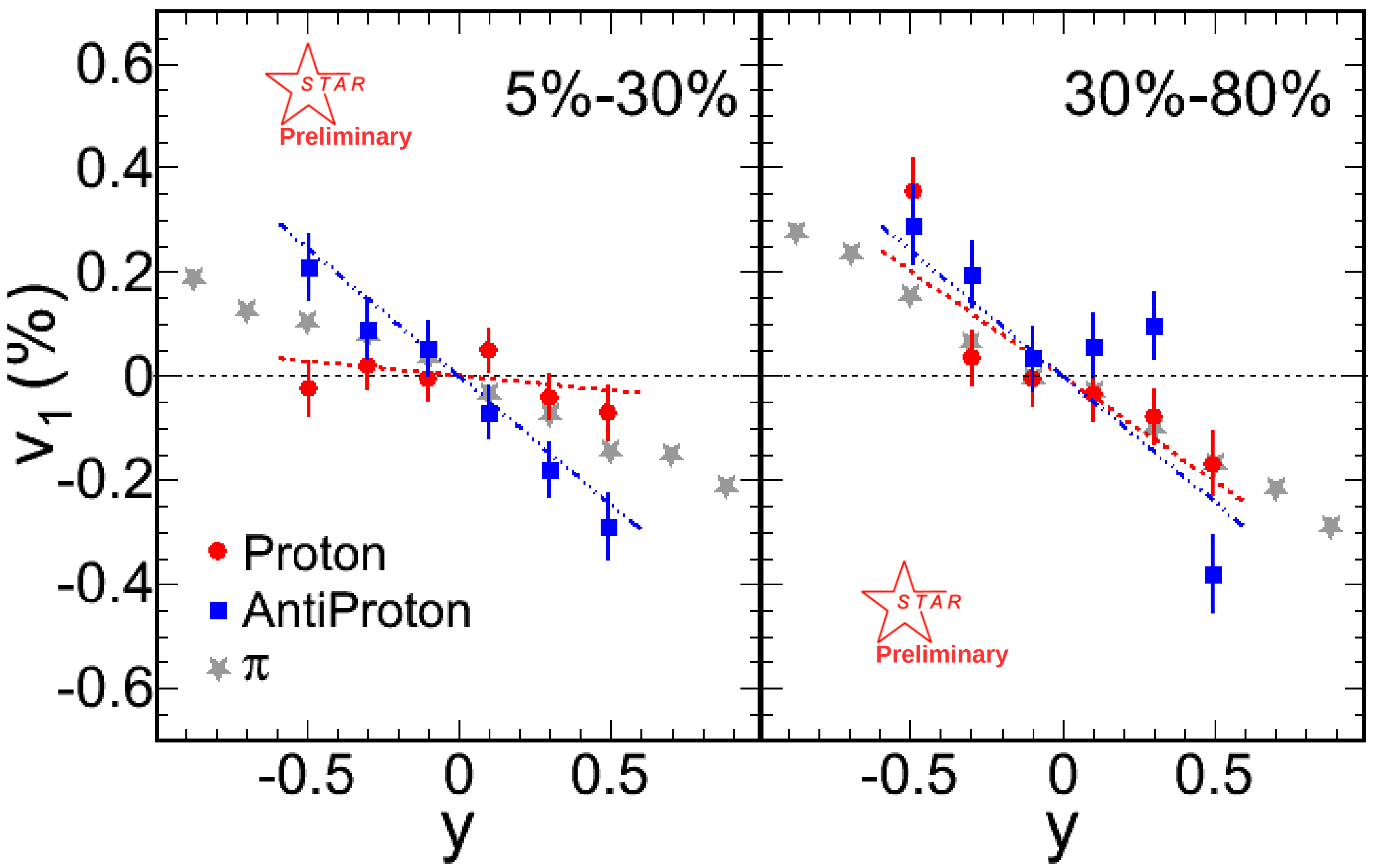
PID v_1 at RHIC



Anti-proton slope has the same sign of pions – consistent with anti-flow

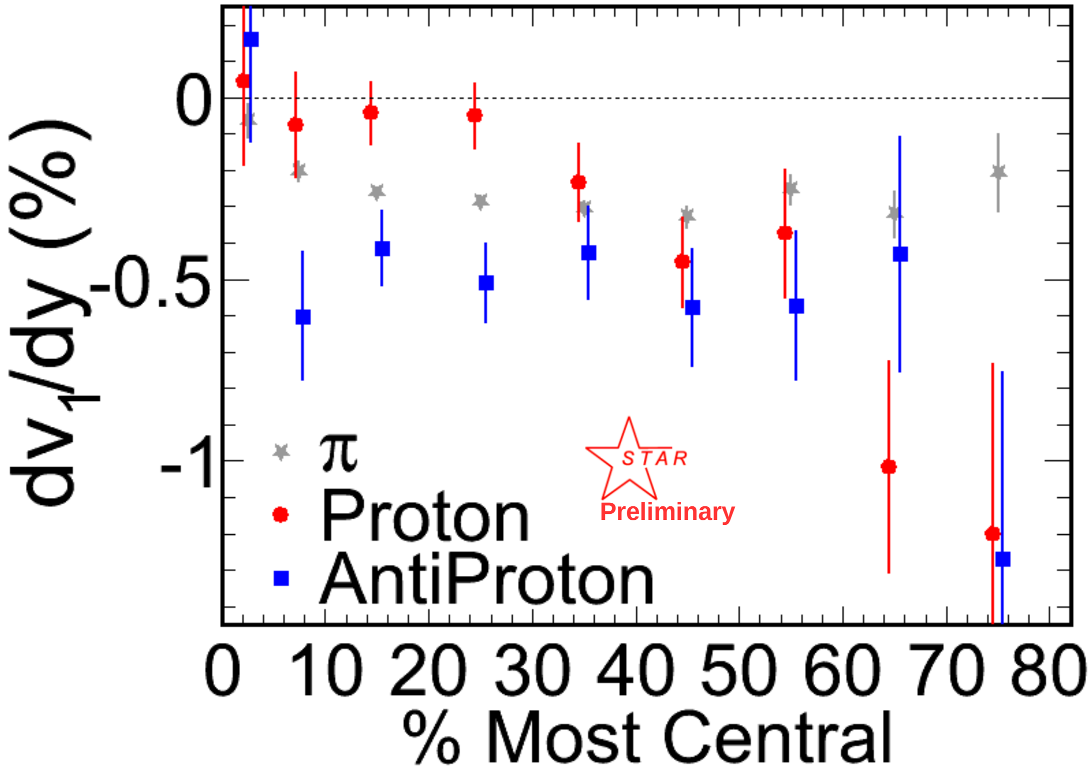
Kaon suffers less shadowing effect due to smaller k/p cross section, yet we found negative v_1 slope for Kshort – consistent with anti-flow

PID v_1 at RHIC



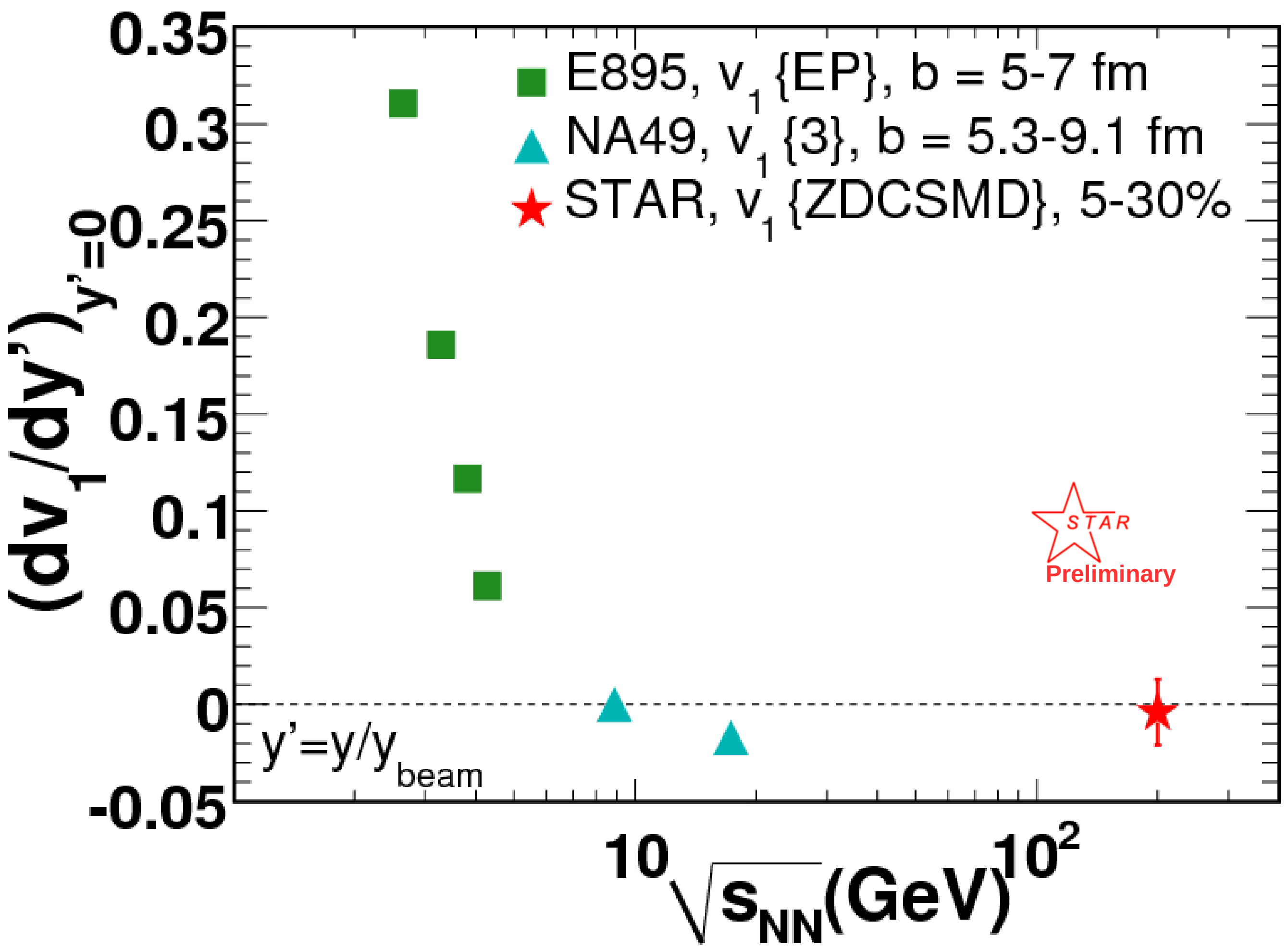
Difference seen between v_1 of protons and anti-protons in 5-30% central collisions.

Centrality dependence of v_1 slope



Negative v_1 slope for protons is observed in 30-80% centralities.
Large difference seen between v_1 of protons and anti-protons in 5-30% centralities.
Considering antiproton/proton ratio is almost flat as a function of centrality, what is observed does not match expectations.

Proton v_1 Excitation Function



Rapidity window used in STAR : [-0.6,0.6]

Proton v_1 in mid-central collisions at RHIC stays small

Summary

- **Negative slope of pions, antiprotons, protons and k_s^0 v_1 is observed**

- **In mid-central collisions (5-30%), proton v_1 slope becomes small (~-0.1%), and sizable difference is seen between v_1 of protons and anti-protons.**

- **Anti-flow can explain the negative $v_1(y)$ slope but it has difficulties in explaining the centrality dependence of the difference between the $v_1(y)$ slope of protons and anti-protons.**