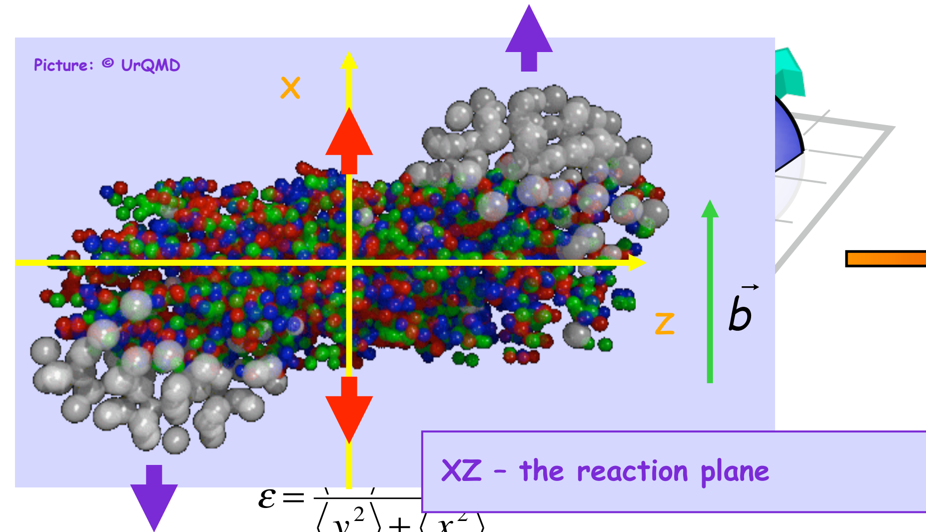
# Directed Flow of Identified Particles

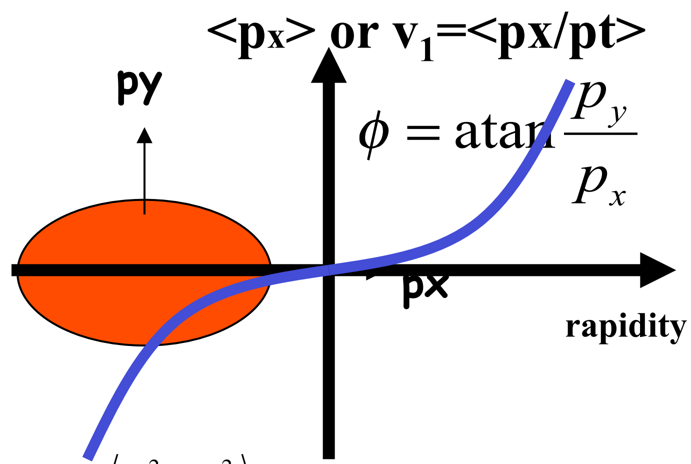
Aihong Tang for the STAR Collaboration

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






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

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

isotropic — directed — elliptic

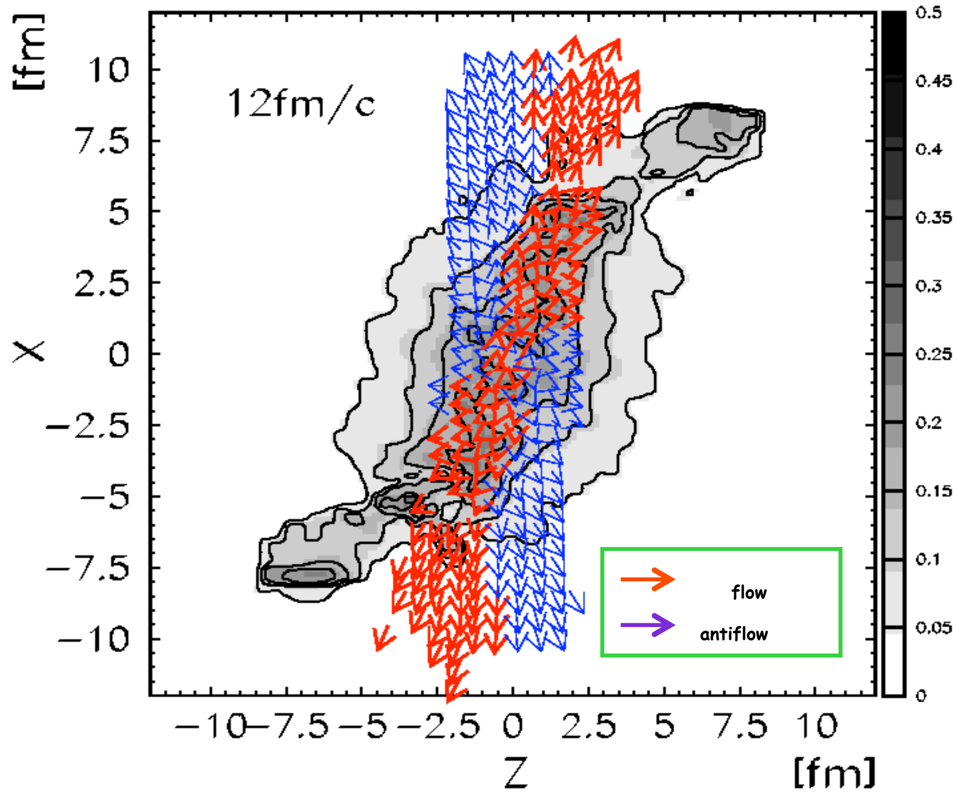
$$v_n = \left\langle \cos\left(n(\phi - \psi_{RP})\right)\right\rangle = \left\langle e^{in(\phi - \psi_{RP})}\right\rangle$$

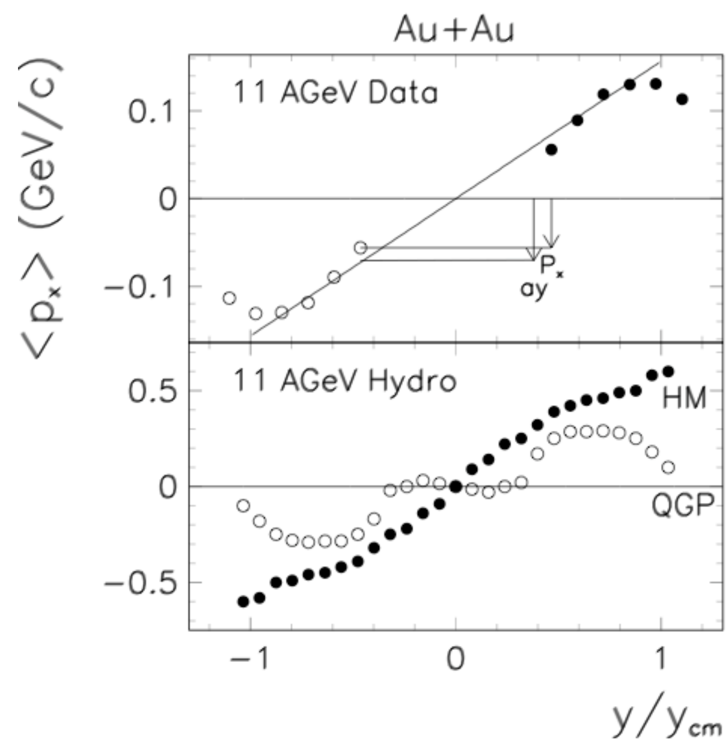
= Correlation to the reaction plane

≡" anisotropic flow "

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

# Anti-flow / 3rd flow component



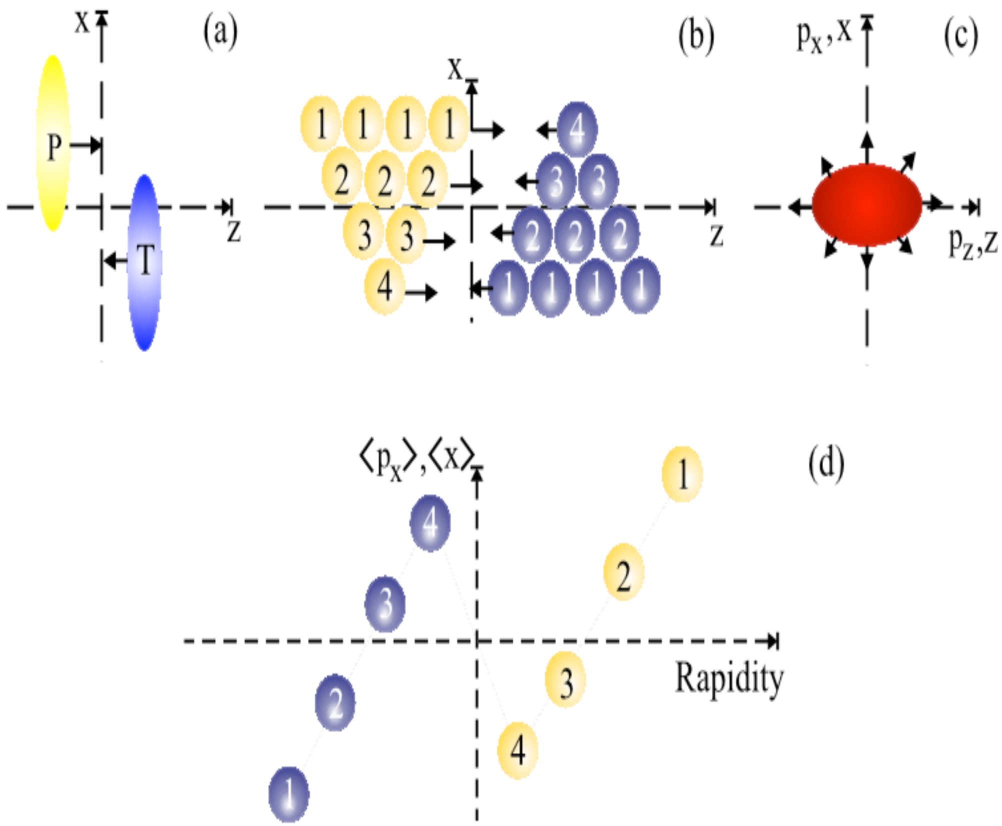



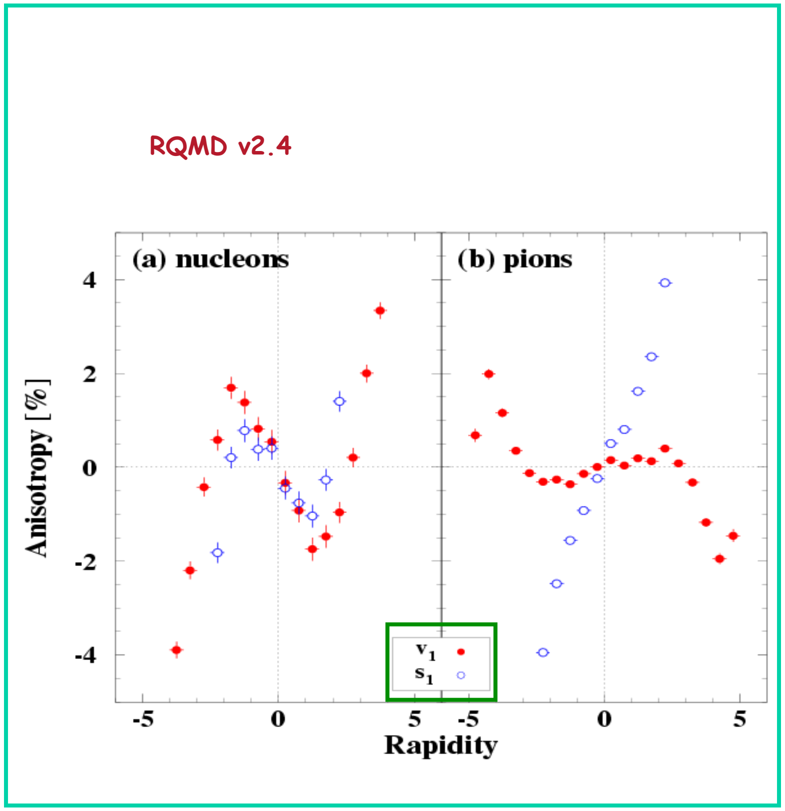

Brachmann, Soff, Dumitru, Stocker, Maruhn, Greiner Bravina, Rischke , PRC 61 (2000) 024909.
L.P. Csernai, D. Roehrich PLB 458, 454 (1999) M.Bleicher and H.Stocker, PLB 526,309(2002)

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



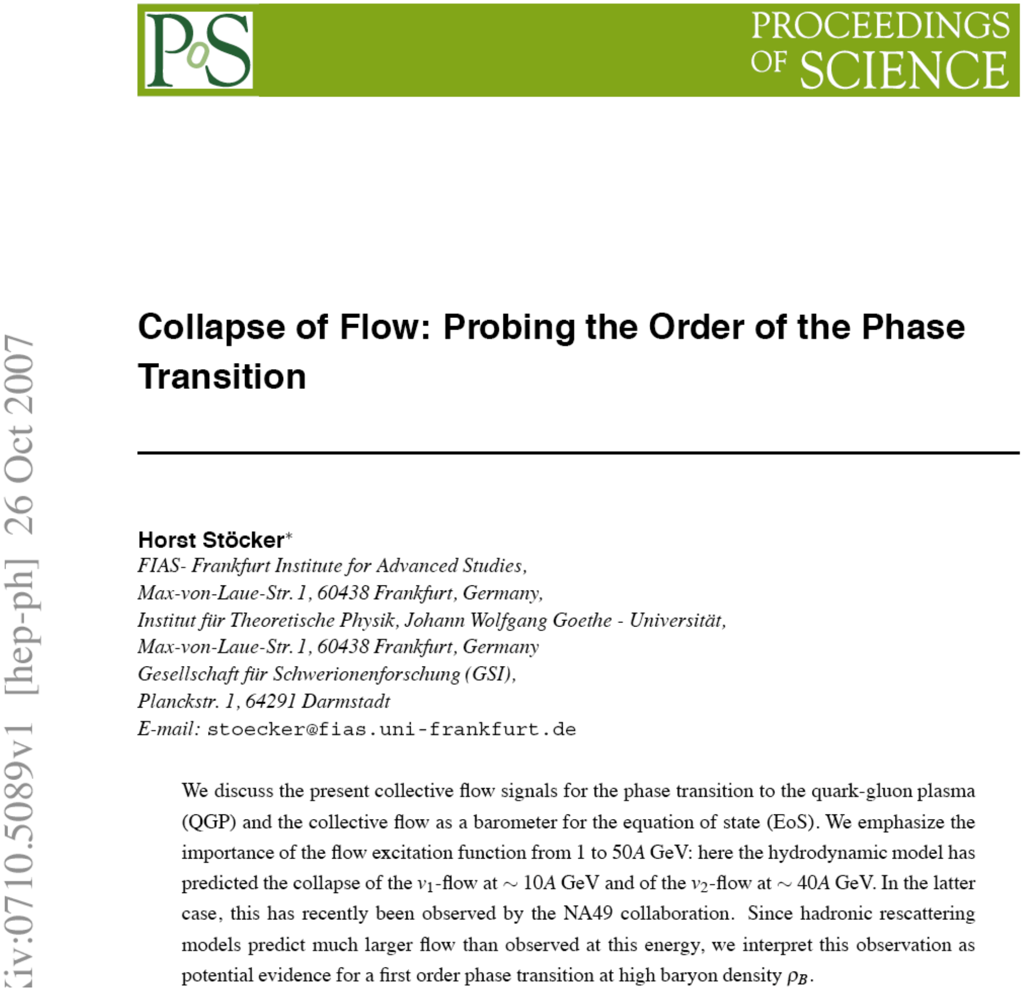




R.Snellings, H.Sorge, S.Voloshin, F.Wang, N. Xu, PRL (84) 2803(2000)

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

# $v_1$ and $1^{st}$ order phase transition





PoS PROCEEDINGS OF SCIENCE

arXiv:0710.5089v1 [hep-ph] 26 Oct 2007

**Collapse of Flow: Probing the Order of the Phase Transition**

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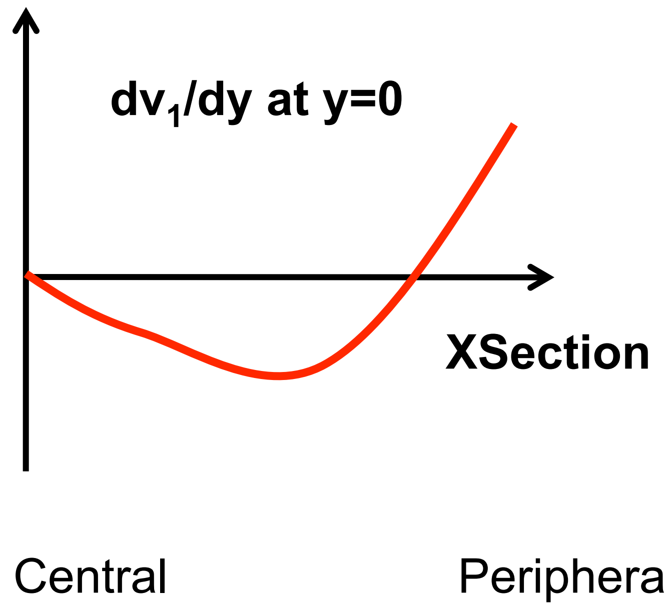
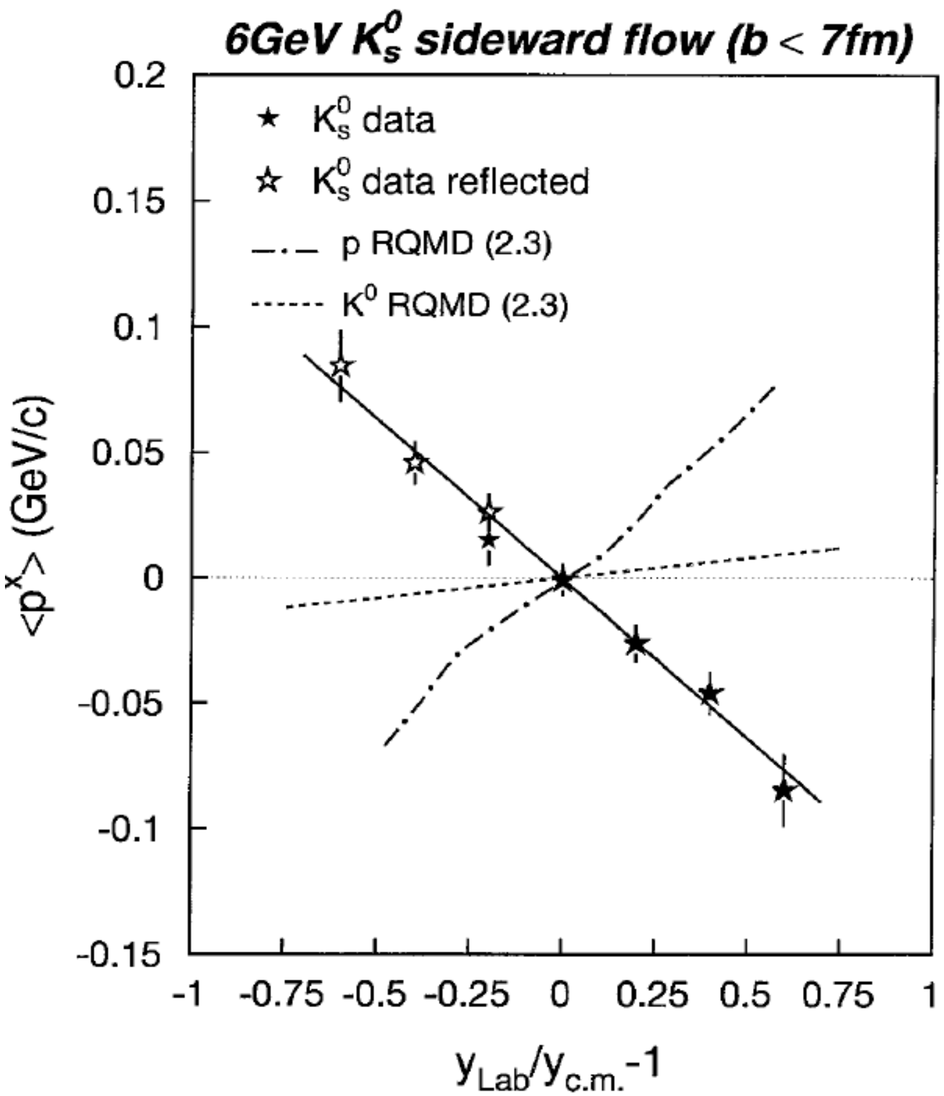
We discuss the present collective flow signals for the phase transition to the quark-gluon plasma (QGP) and the collective flow as a barometer for the equation of state (EoS). We emphasize the importance of the flow excitation function from 1 to 50*A* GeV: here the hydrodynamic model has predicted the 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 $\rho_B$.

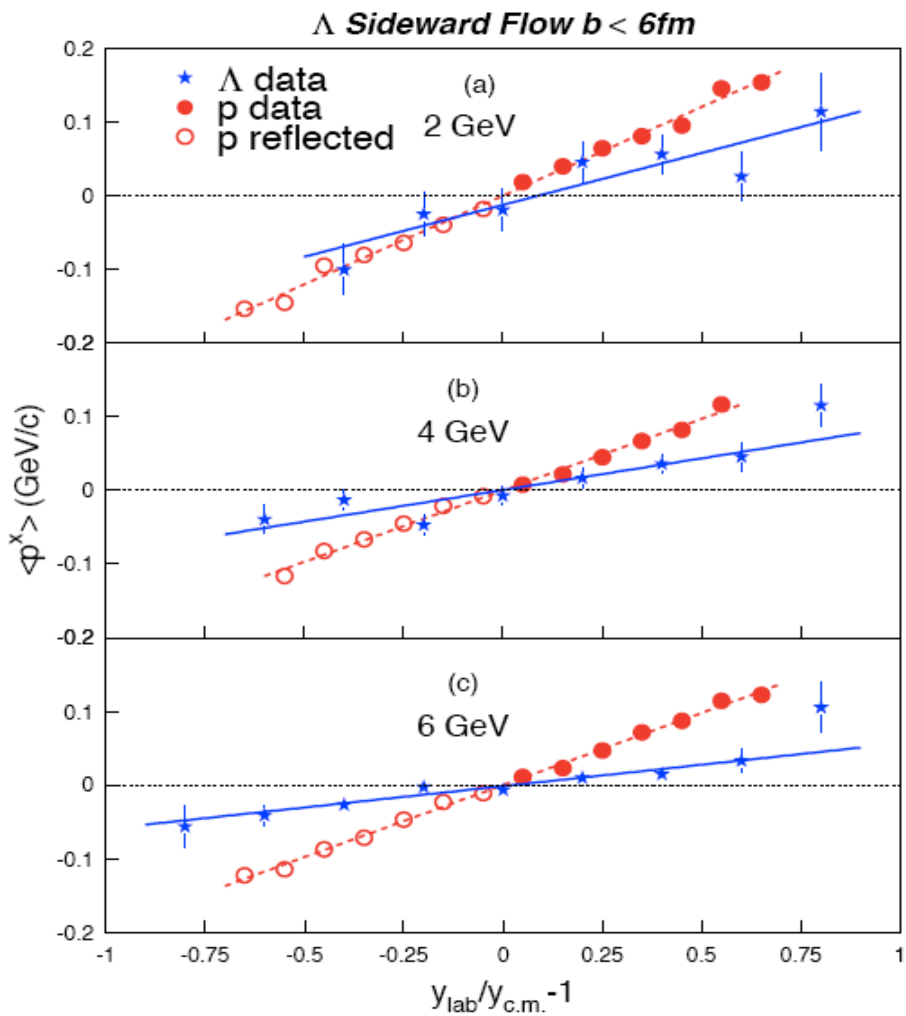


# $v_1$ at low energies



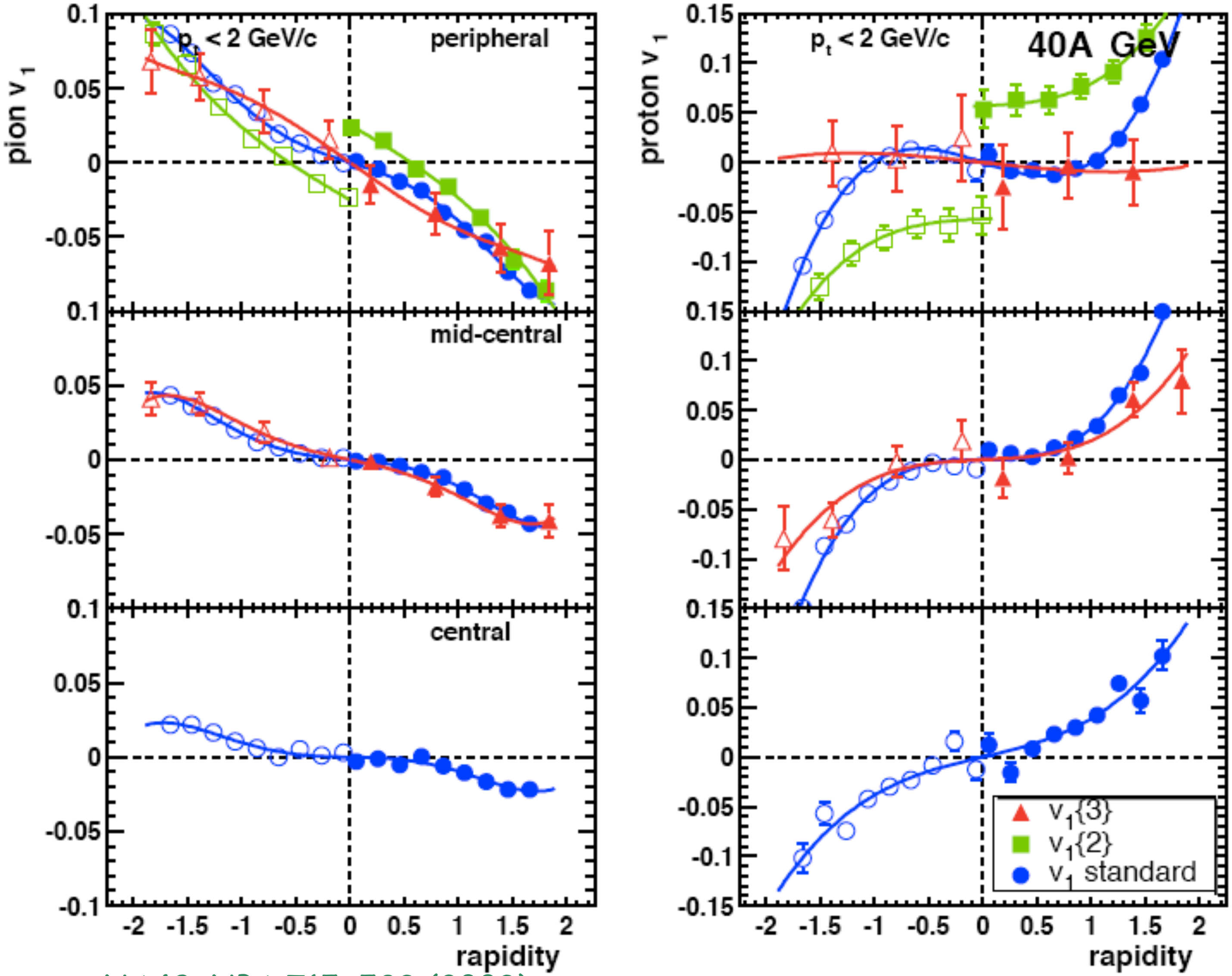



e895, PRL 85 2533 (2000)



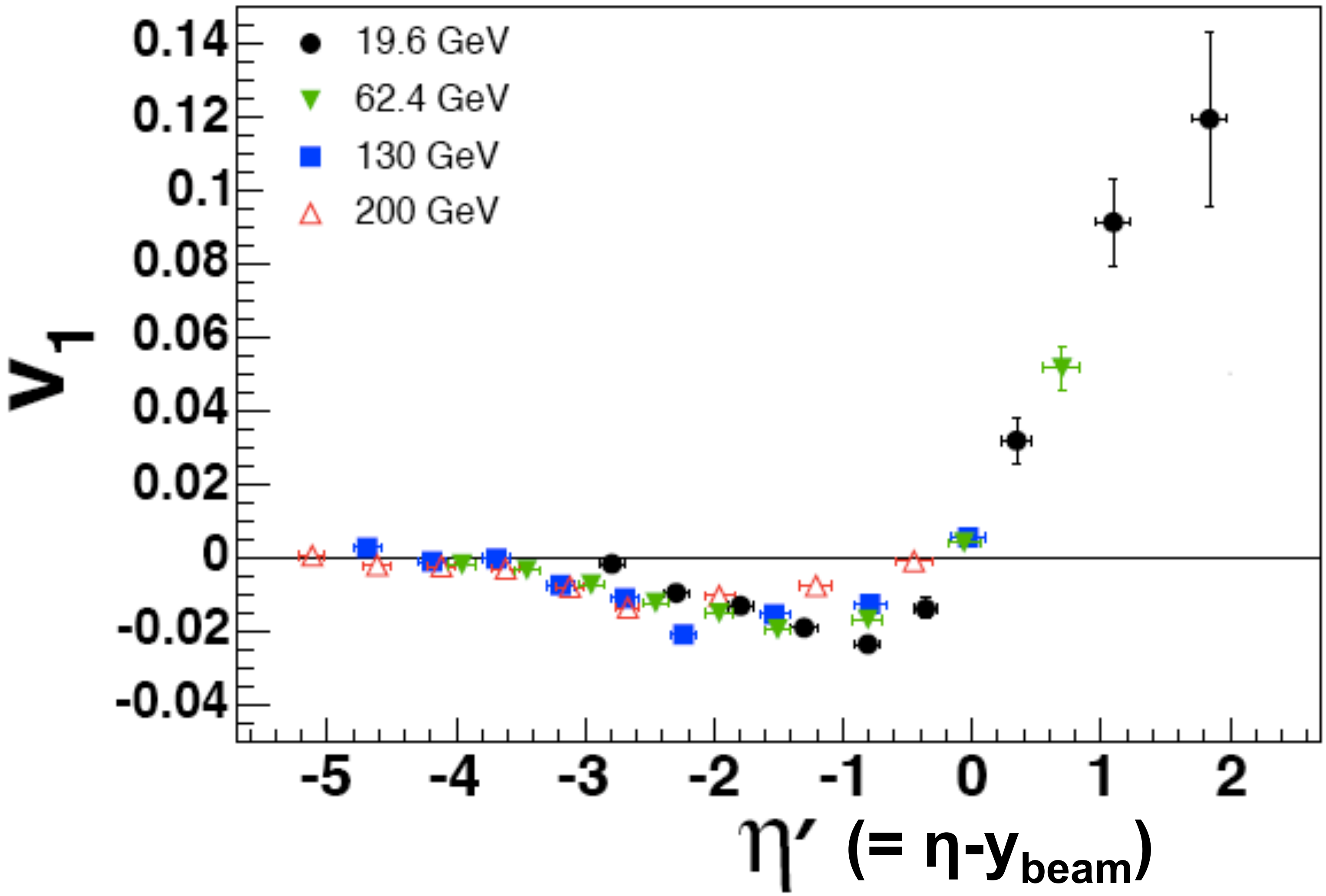

E895, PRL 86 2533 (2001)

# $v_1$ at low energies



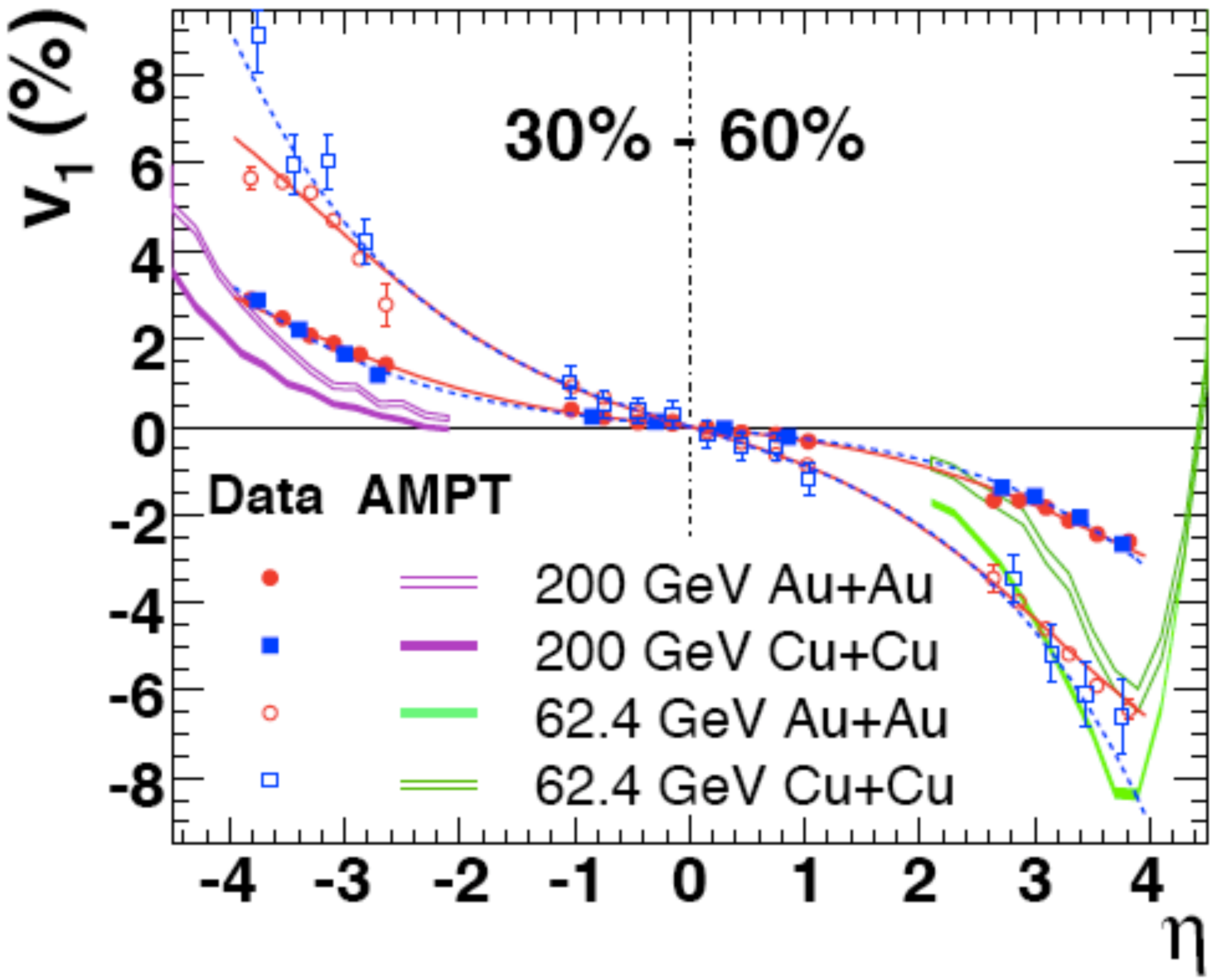

NA49, NPA 715, 583 (2003)

# $v_1$ at RHIC, measured by Phobos



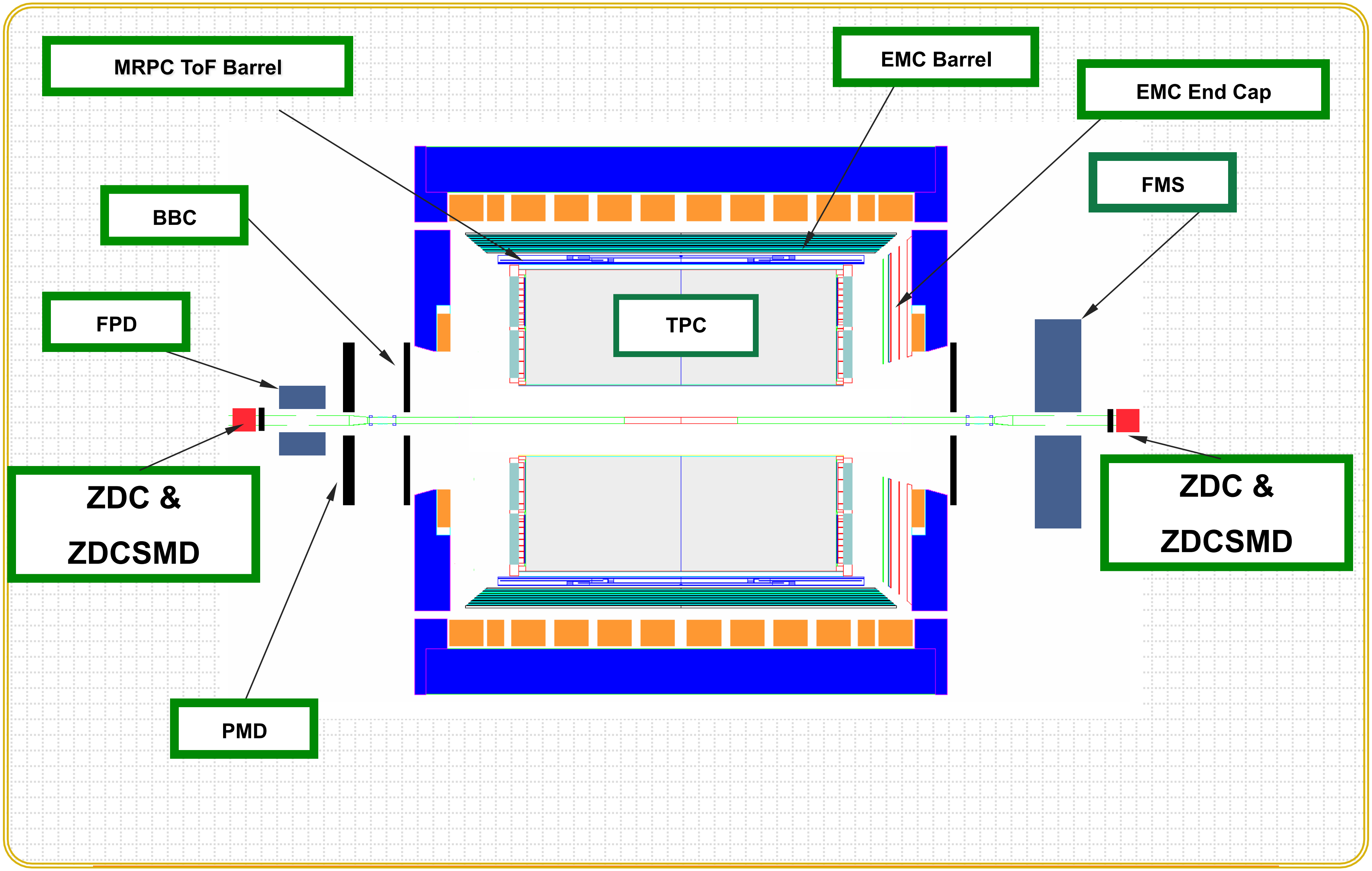

Phobos, NA49, PRL 97 012301 (2006)

# $v_1$ at RHIC, measured by STAR



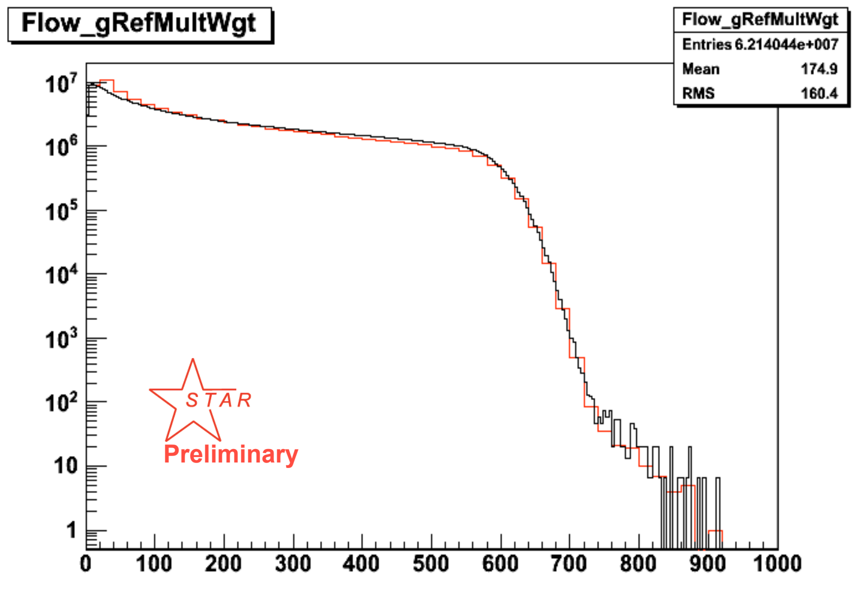

STAR, PRL 101 252301 (2008)

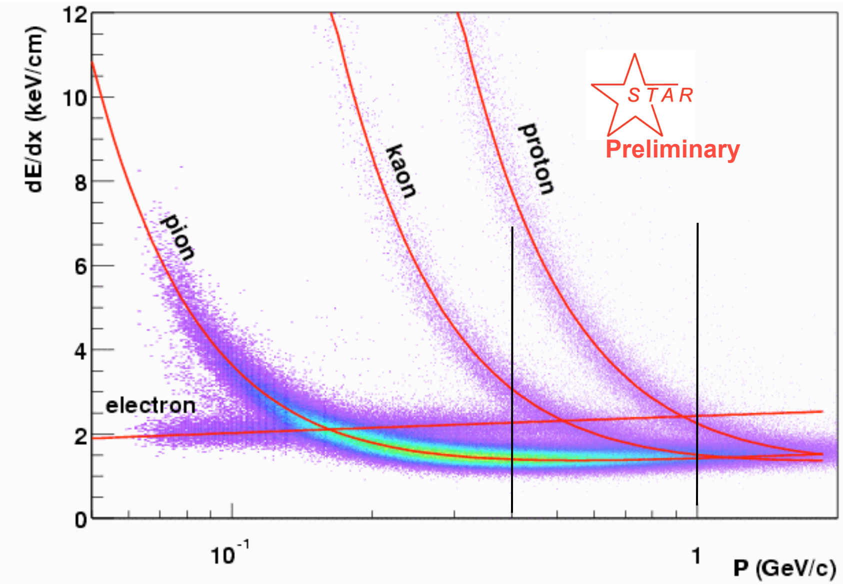
# STAR Experiment



# 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, 2.0]**

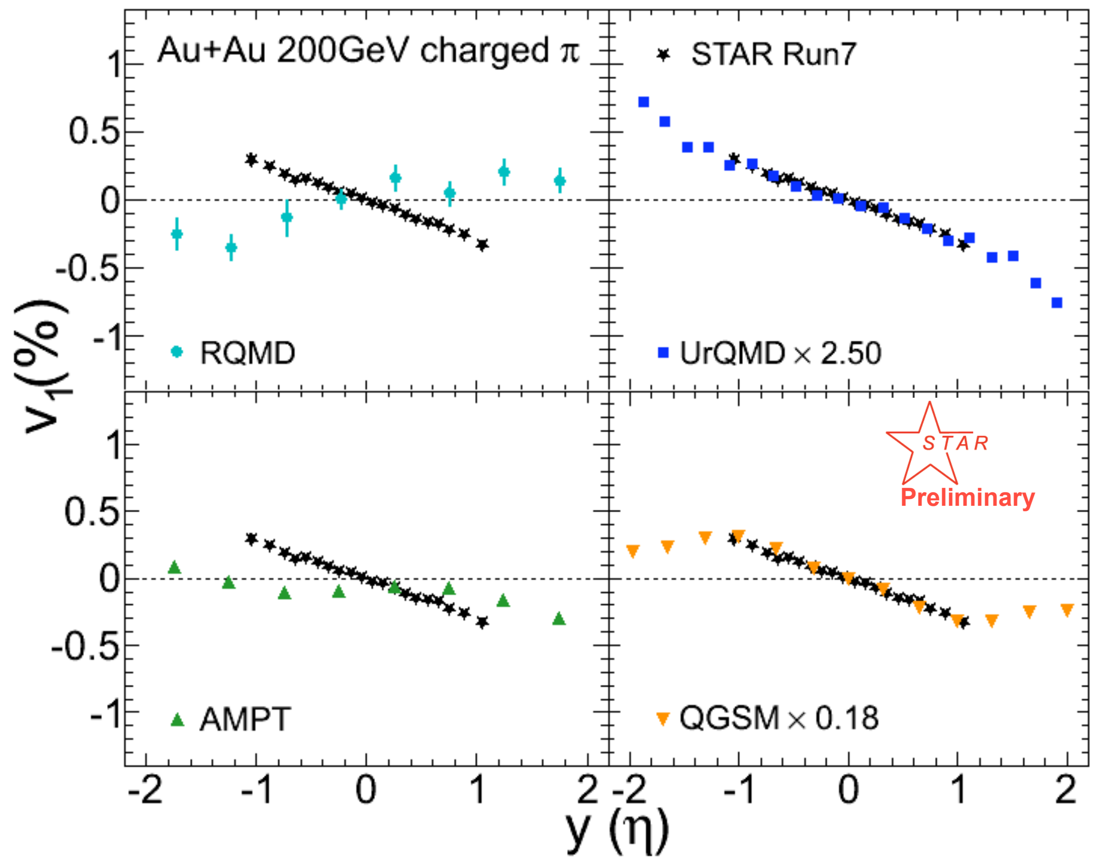
**No. of fit hits/No.of possible hits ∈[0.52, 1.05]**

**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]**

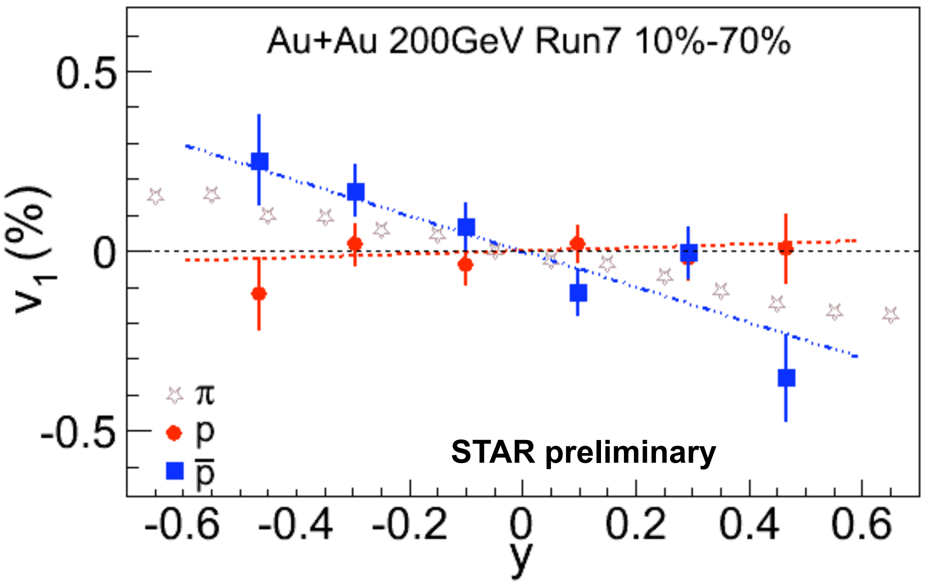
# PID $v_1$ at RHIC

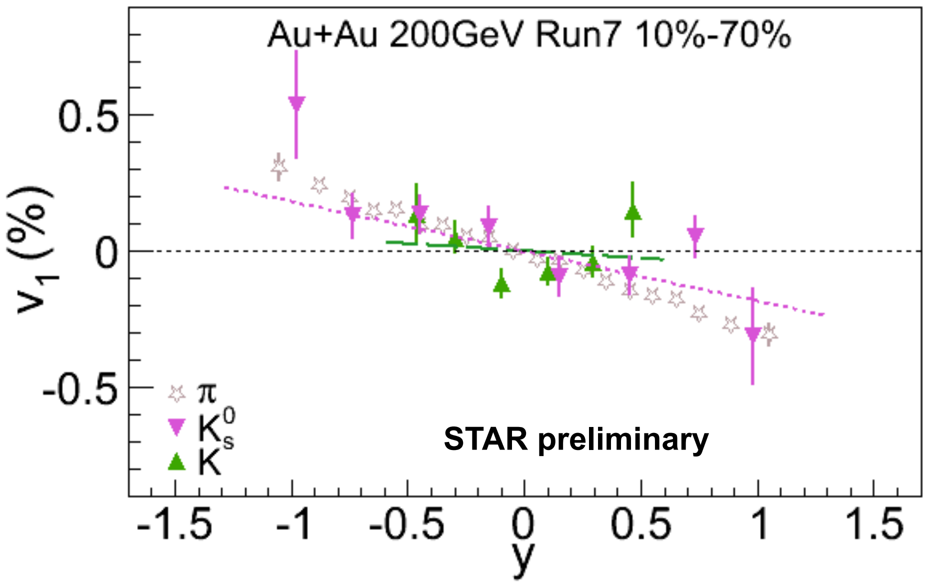



*Phys. Rev. Lett. 84 (2000) 2803;*
*Phys. Lett. B 526 (2002) 309–314;*
*Phys. Rev. C 71, 054905 (2005).*

So far no models can describe the data

# PID $v_1$ at RHIC



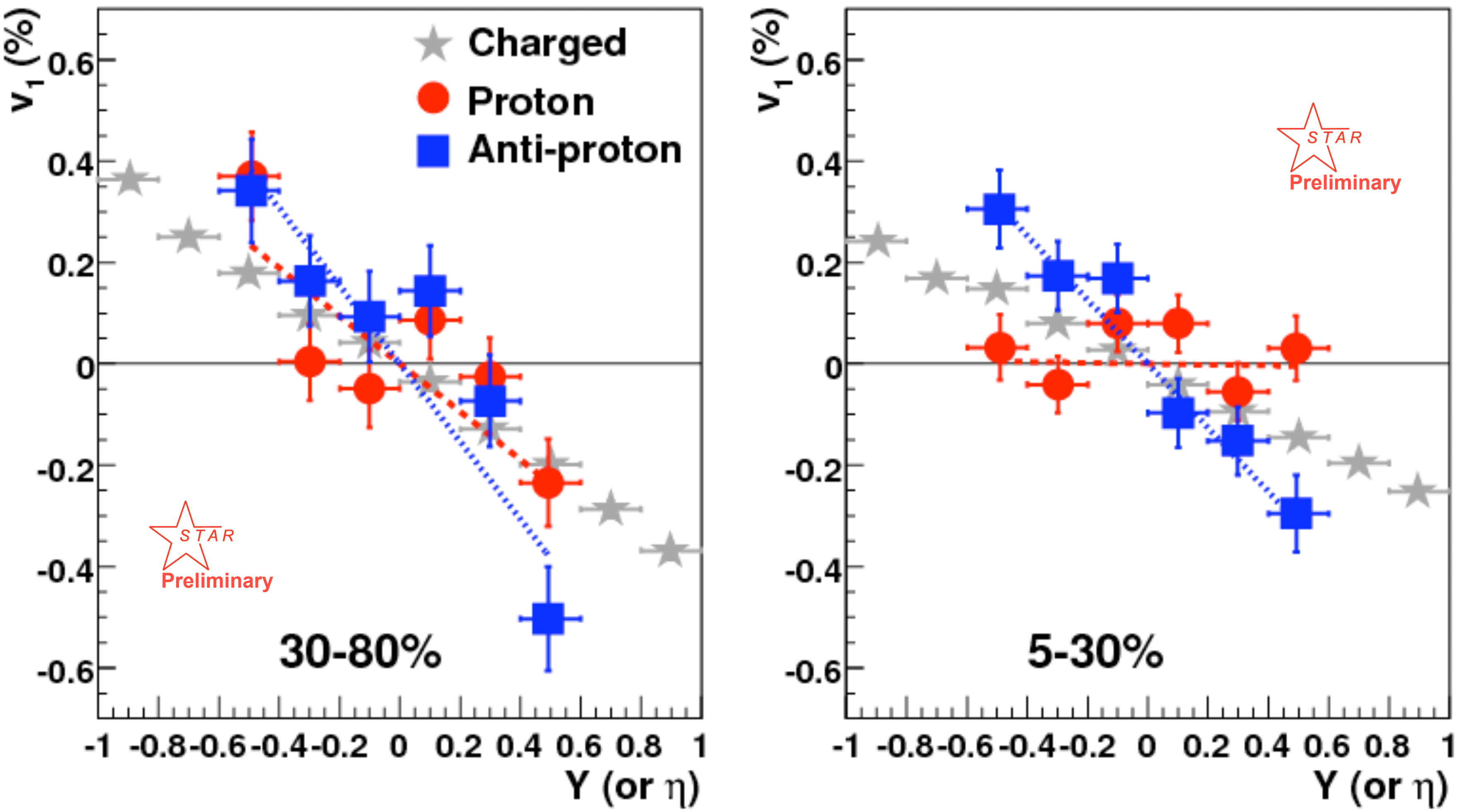

*Proton 0.4<pT<1.0 (GeV/c)*
*Antiproton 0.4<pT<1.0 (GeV/c)*

*Pion 0.15<pT<0.75 (GeV/c)*
*Kaon 0.2<pT<0.6 (GeV/c)*

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

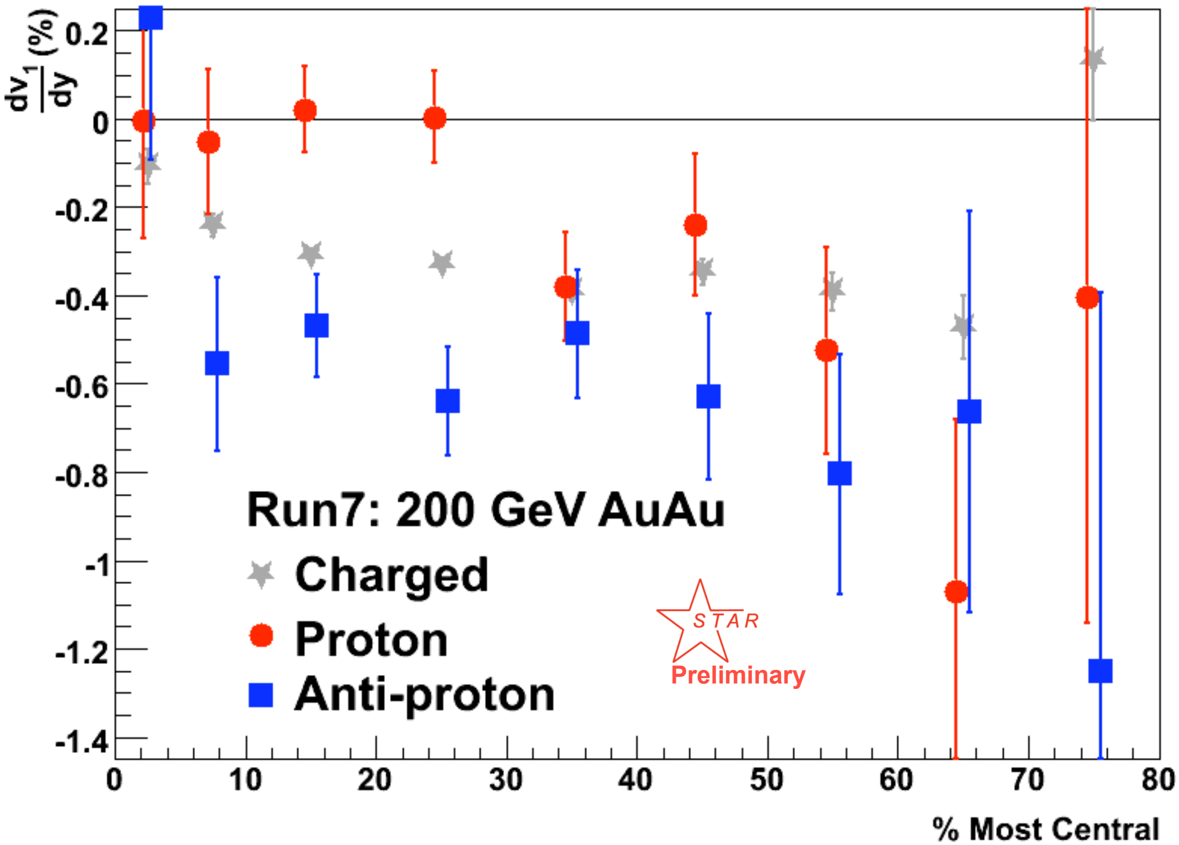
Kaon suffers less shadowing effect due to smaller k/p cross section, yet we found negative $v_1$ slope for both charged kaon and Kshort – consistent with anti-flow

# PID $v_1$ at RHIC



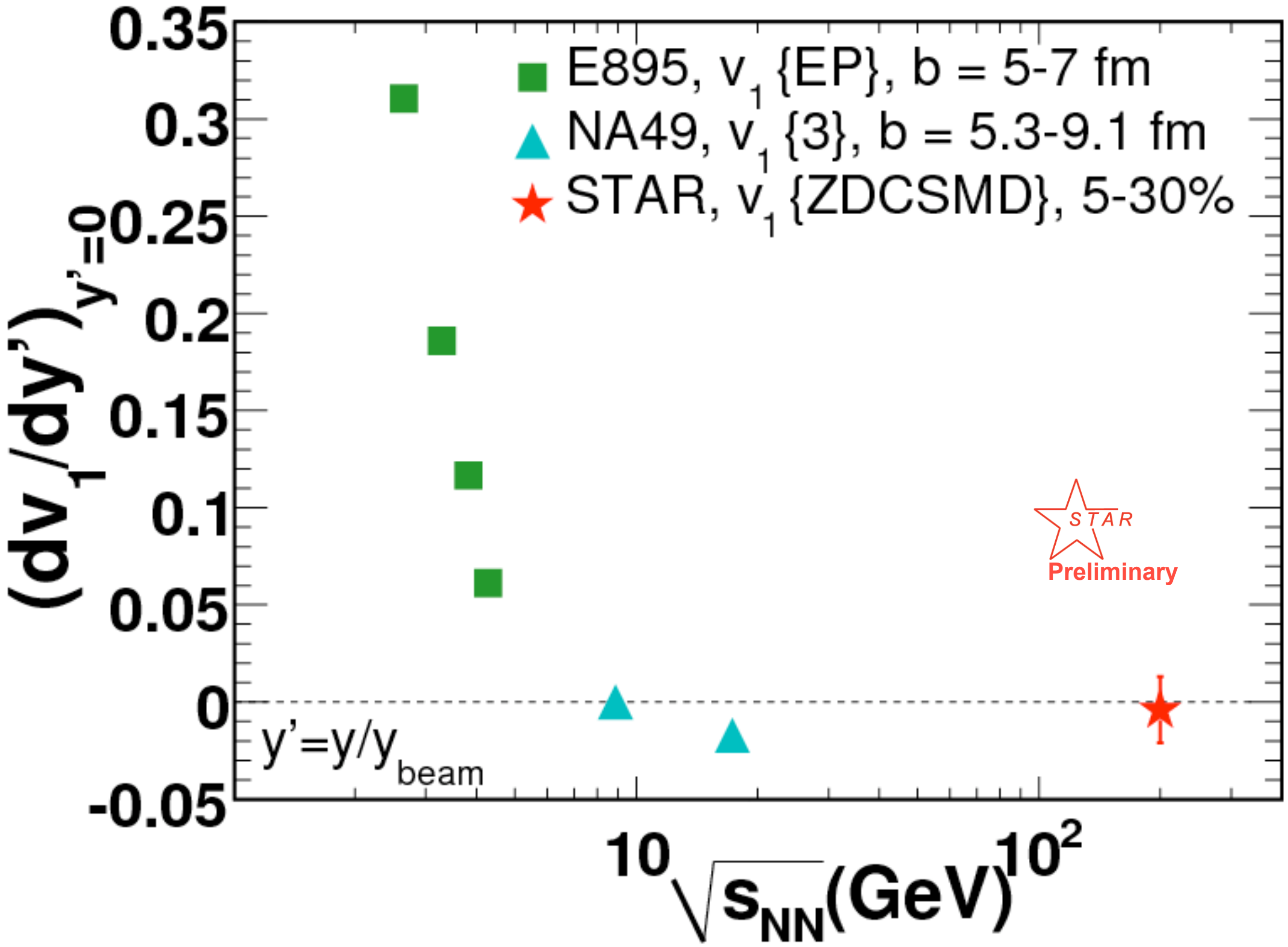

Difference seen between $v_1$ of protons and anti-protons in mid-central collisions.

# 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

STAR ☆

# Summary

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- **Negative slope of pions, antiprotons, protons and kaons $v_1$ is observed – consisten with anti-flow.**

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

- **So far no model can describe data.**