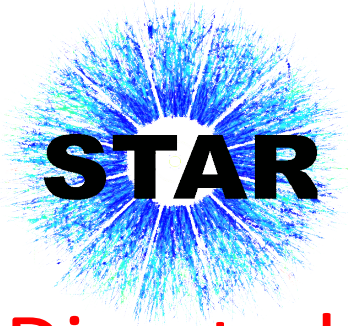


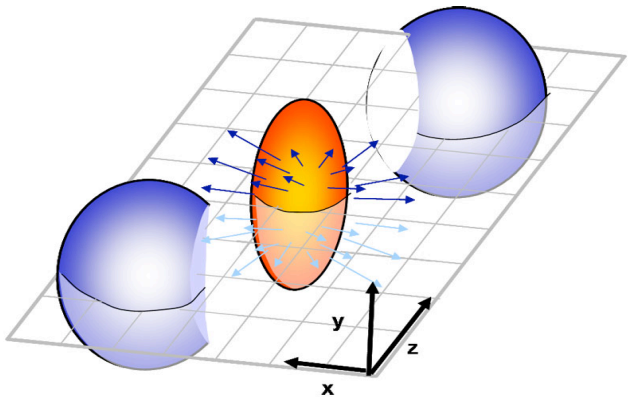
Directed flow of Identified Particles from the RHIC Beam Energy Scan

Yadav Pandit (Kent State University) for the STAR Collaboration

Outline:

- Introduction and Motivation
- The Beam Energy Scan at RHIC
- STAR experiment
- v_1 results @ 7.7, 11.5 and 39 GeV
- Model Comparison
- Summary and Outlook

Introduction: Directed flow



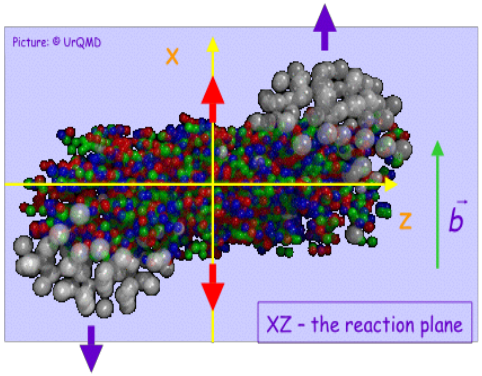
$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \psi_r)\right]\right)$$

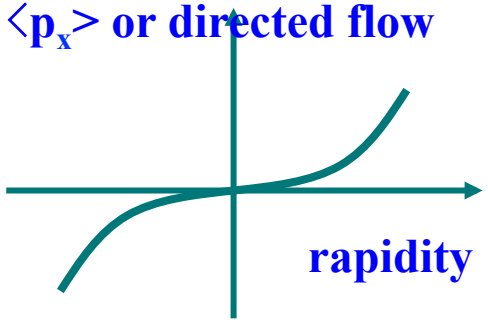
Directed flow is quantified by the first harmonic (v_1)

$$v_1 = \left\langle \cos(\varphi - \Psi_r) \right\rangle$$

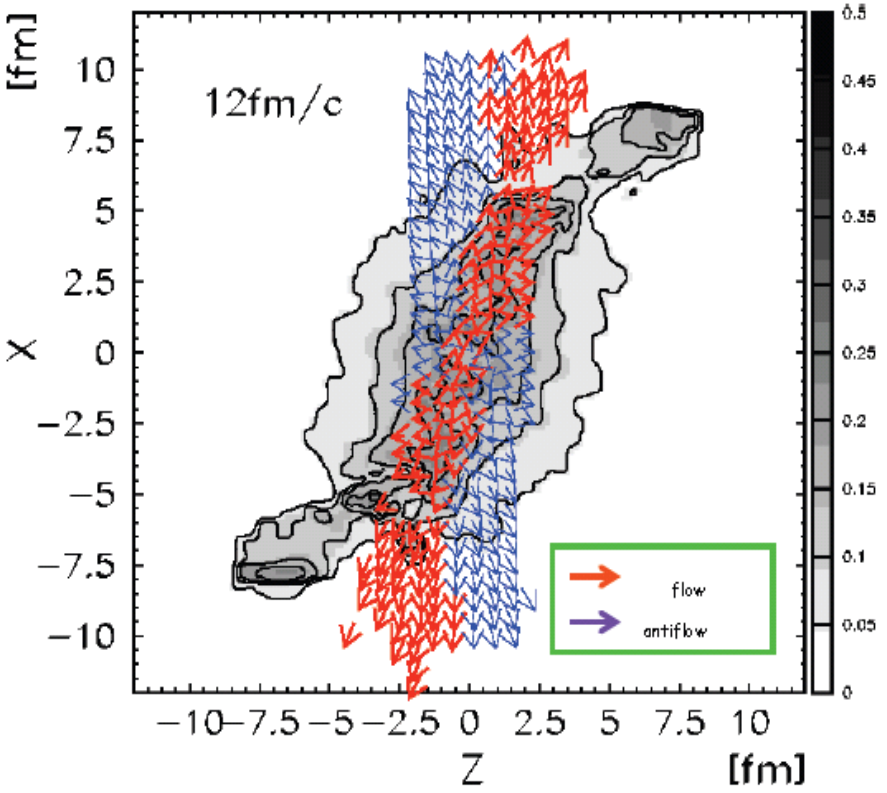
$$\varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

- Directed flow, v_1, describes the sideward motion of the particles within the reaction plane.
- It is generated during the nuclear passage time ($2R/\gamma$ ~ 0.1 fm/c) and therefore it probes the very earliest stage of collision dynamics.

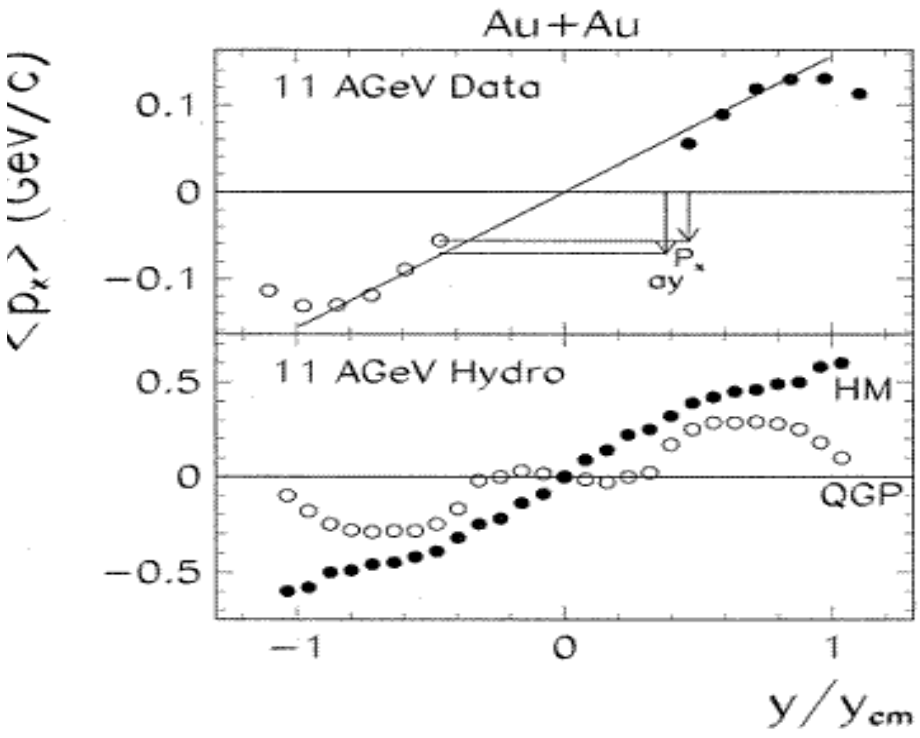




Motivation: $v_1(y)$ Structure



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

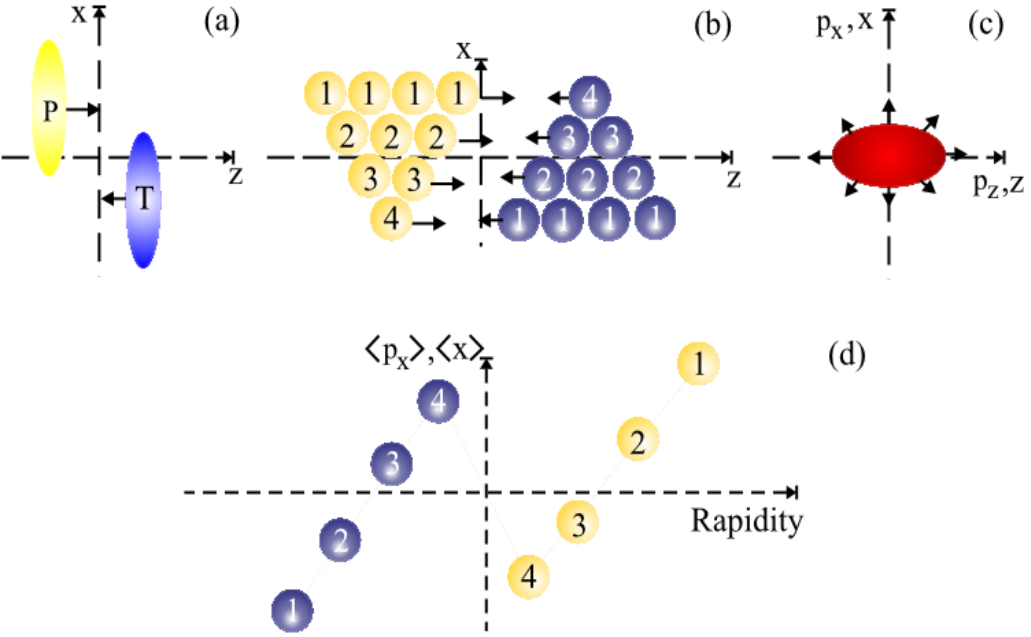


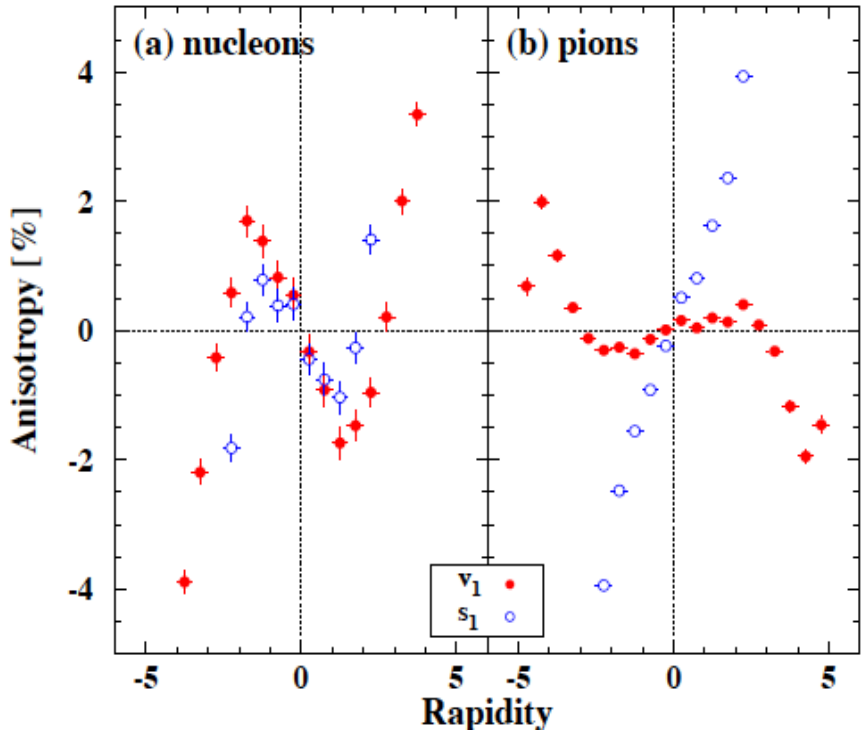
L.P. Csernai, D. Rohrich PLB 458, 454 (1999)

Anti-flow/3rd flow component: $v_1(y)$ crosses zero 3 times (so-called "wiggle") or 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

Motivation: $v_1(y)$ Structure



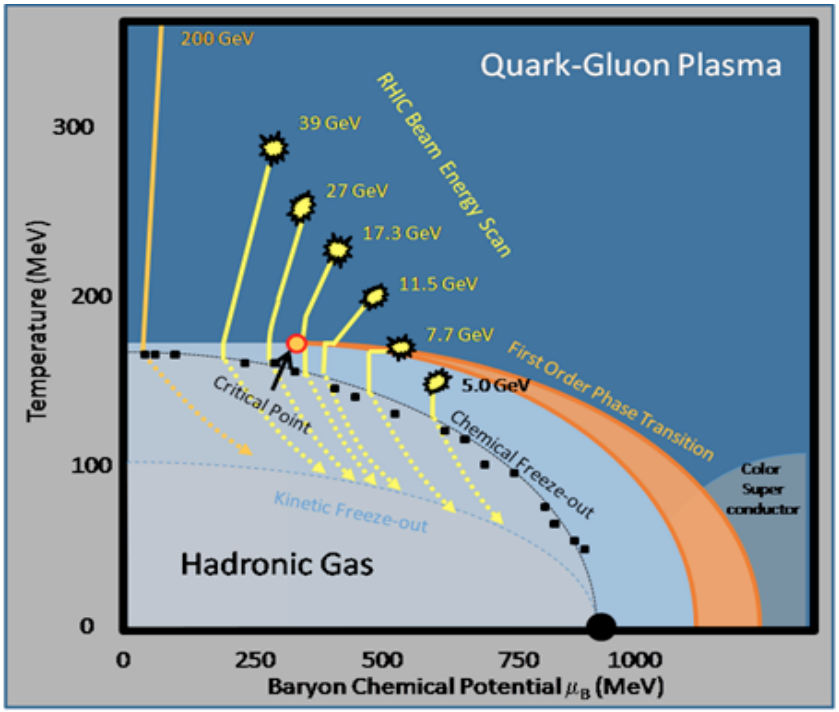


R. Snellings, H. Sorge, S. Voloshin, F. Wang, N. Xu, PRL **84** 2803 (2000)

Baryon stopping +positive space-momentum correlation may also give wiggle structure in v_1: NO QGP necessary

M. Bleicher and H. Stöcker, PLB 526, 309 (2002)

RHIC Beam Energy Scan(BES) Program



Motivation:

Search for signals of phase boundary

Search for signals for critical point

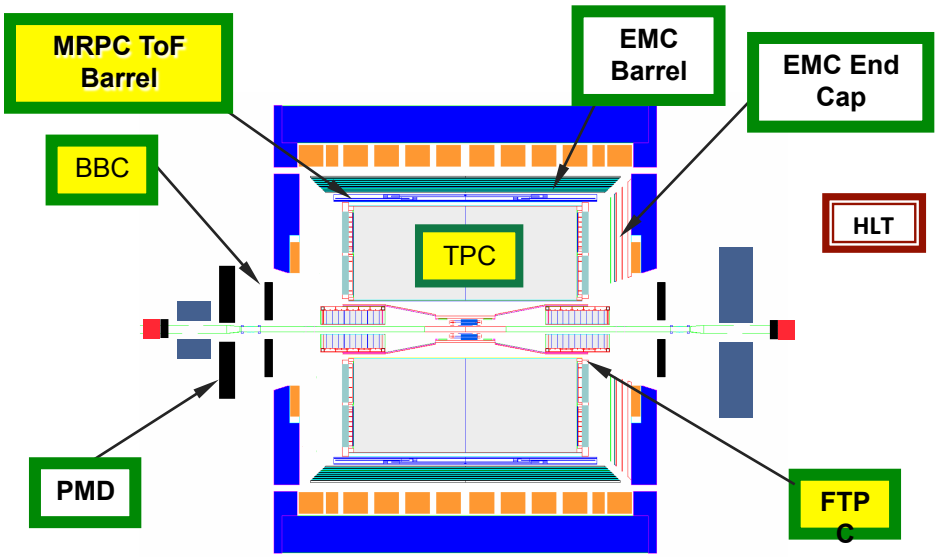
Established observables:

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

$\sqrt{s_{NN}}$ (GeV)	Good Events taken Million MB	
7.7	5	[2010]
11.5	11	[2010]
19.6	17	[2011]
27	130	[2011]
39	170	[2010]

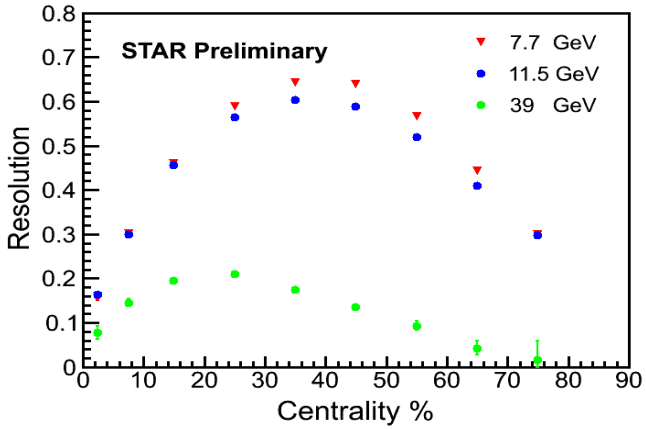
- RHIC successfully completed its First Phase of BES program in 2011.
- Analysis of collected data is going on
- Directed flow results at 7.7, 11.5 and 39 GeV is presented here.
- Results at 19.6 and 27 GeV coming soon.

STAR Experiment

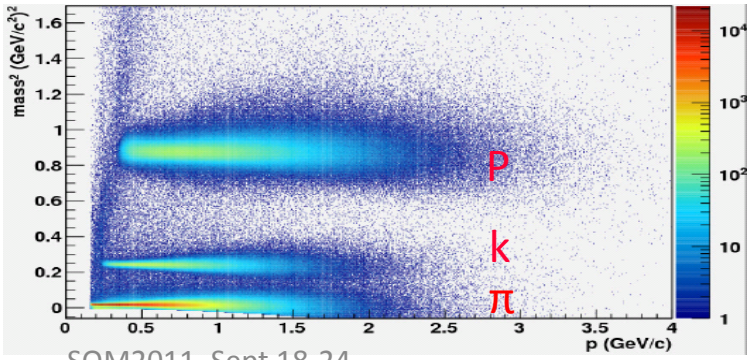


- Time Projection Chamber(TPC) is main tracking detector at STAR.
- Forward TPC(FTPC) (2.5 <|η|< 4.0) also provides tracking at forward rapidity

First order BBC EP Resolution

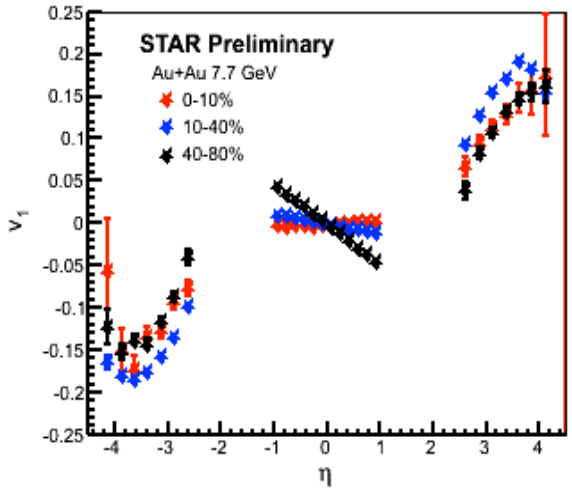


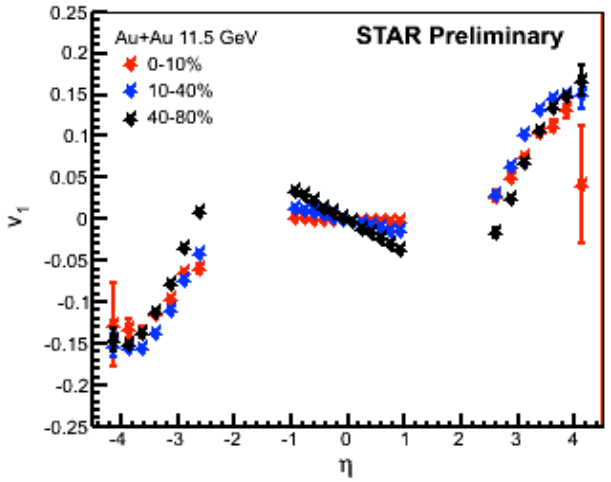
- Time of Flight (TOF) provides excellent particle identification $p_T < 1.6$ GeV/c for pions $(-0.10<m^2<0.10)$ $(GeV/c^2)^2$ and kaons $(0.20<m^2<0.35)$ $(GeV/c^2)^2$ and $p_T<2.8$ GeV/c for protons $(0.8<m^2<1.0)$ $(GeV/c^2)^2$

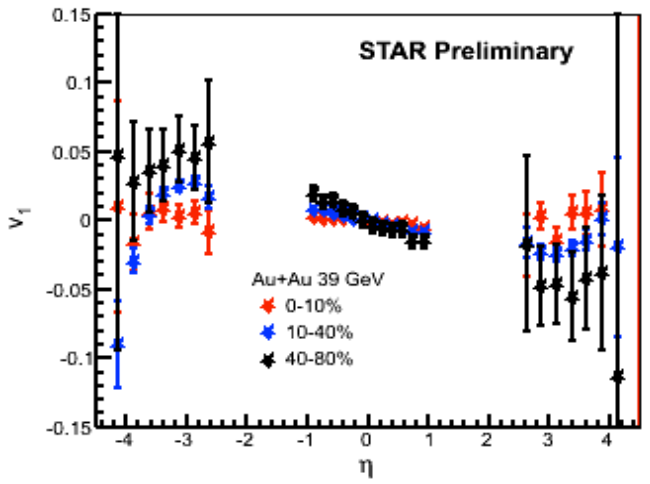


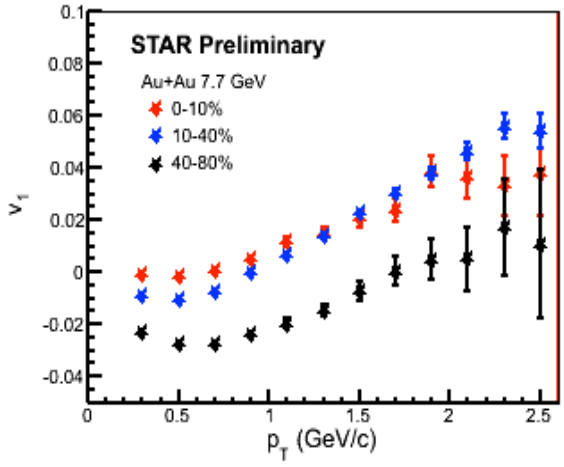
- Beam Beam Counters(BBC) (3.3<|η|<5.0) are used to reconstruct the first-order event plane at 39 GeV and lower beam energies, provides very good event plane resolution
- Reduced non-flow effects in v_1 study because of eta gap between TPC and BBC

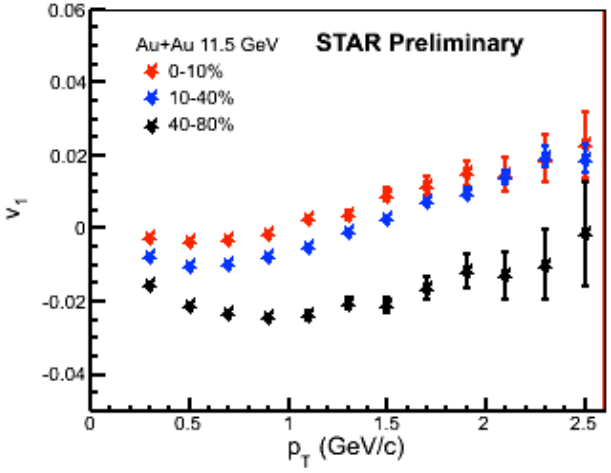
Directed flow of Charged particles

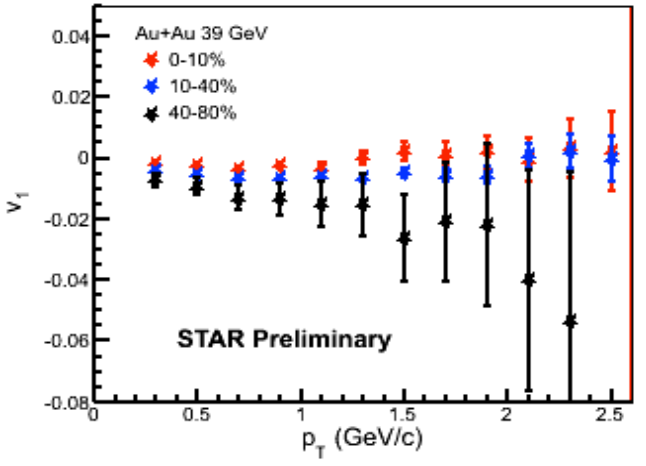






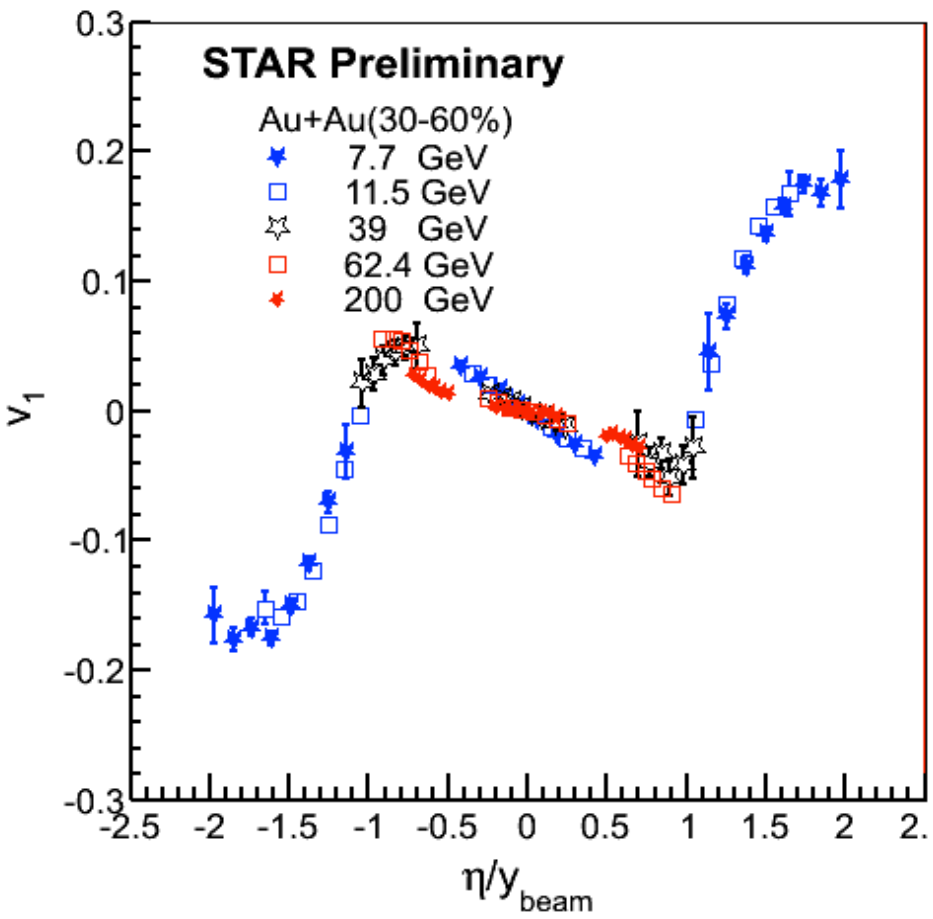


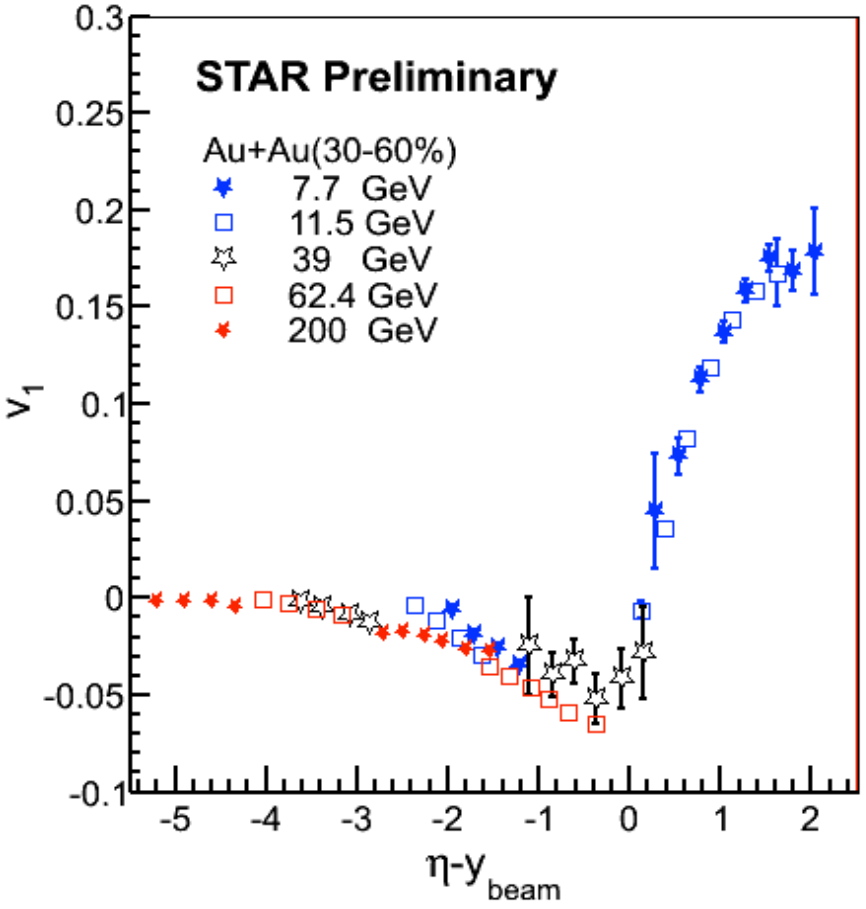




Centrality dependence of $v_1(\eta)$ for [0.2 < pT<2.0 GeV/c] and $v_1(p_T)$ for [-1.0<η <1.0] is observed for BES data

Charged hadrons: Beam Energy Dependence

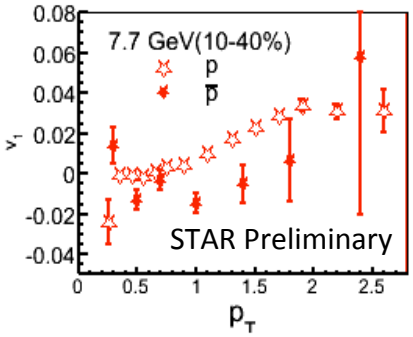


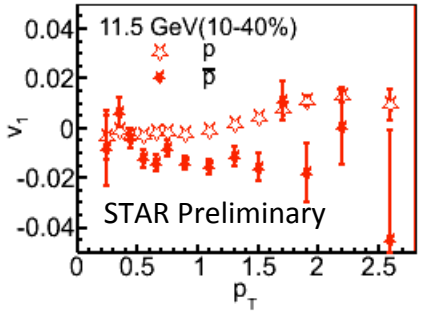


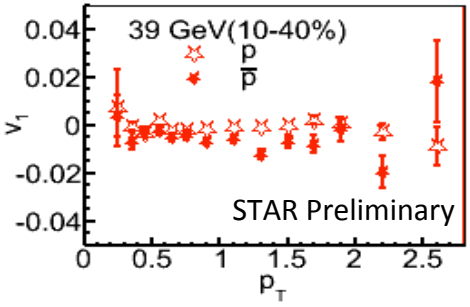
Results at 200 and 62.4 GeV are from STAR, PRL 101 252301 (2008)

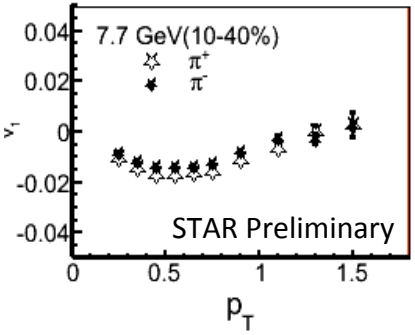
Scaling behavior in v_1 vs. η/y_{beam} and v_1 vs. $\eta'(=\eta-y_{beam})$

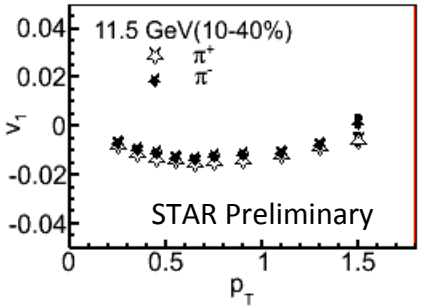
Directed flow of Identified Particles: $v_1(p_T)$

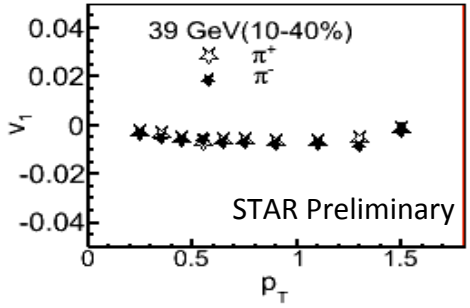


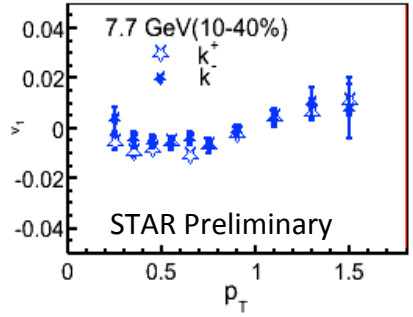


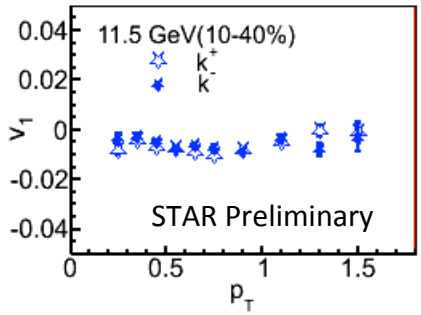


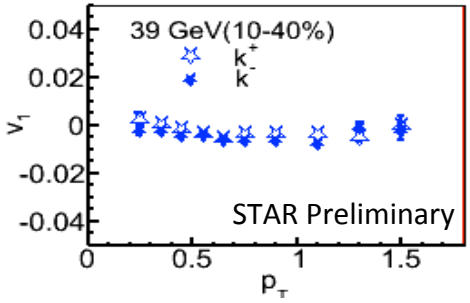






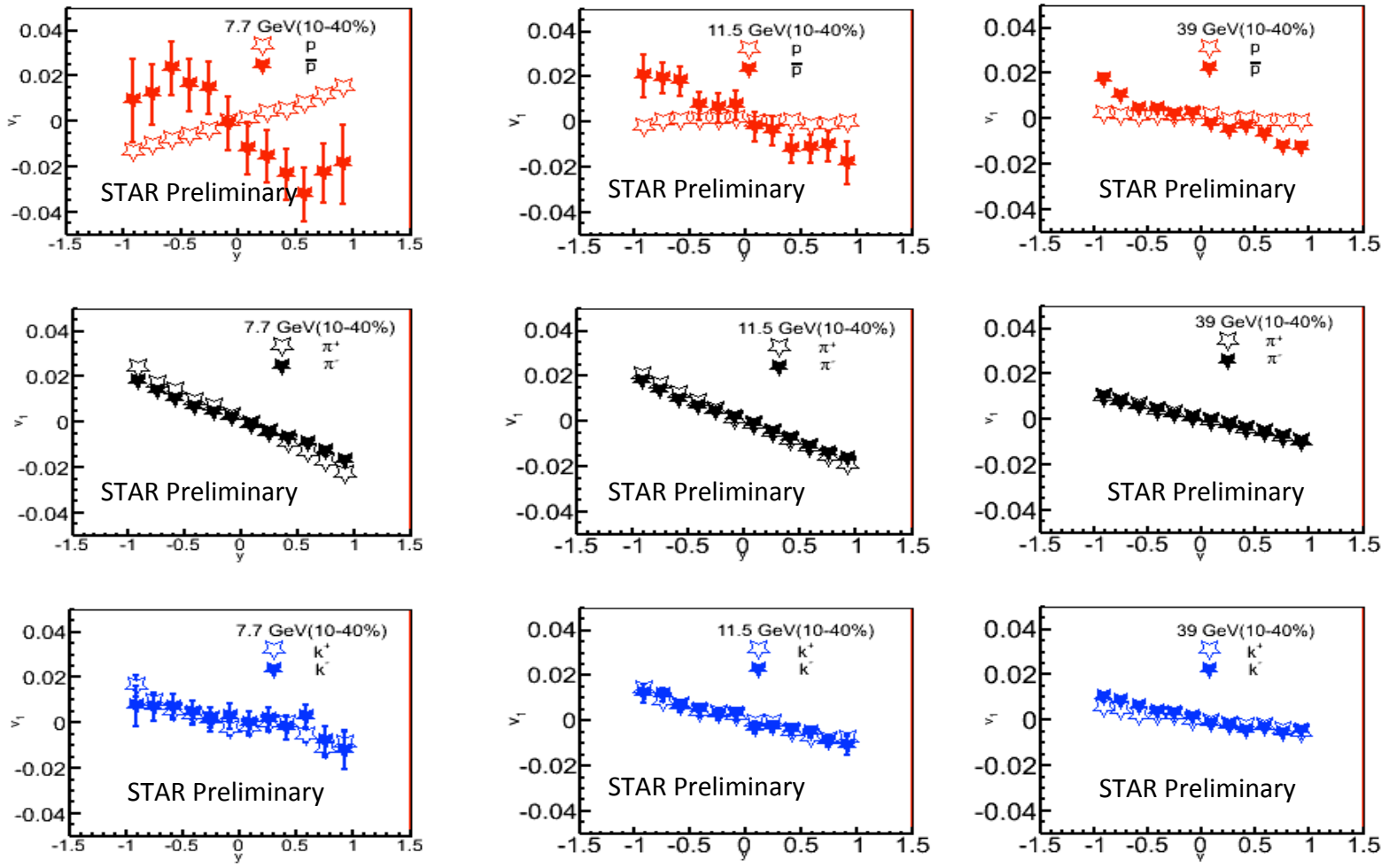






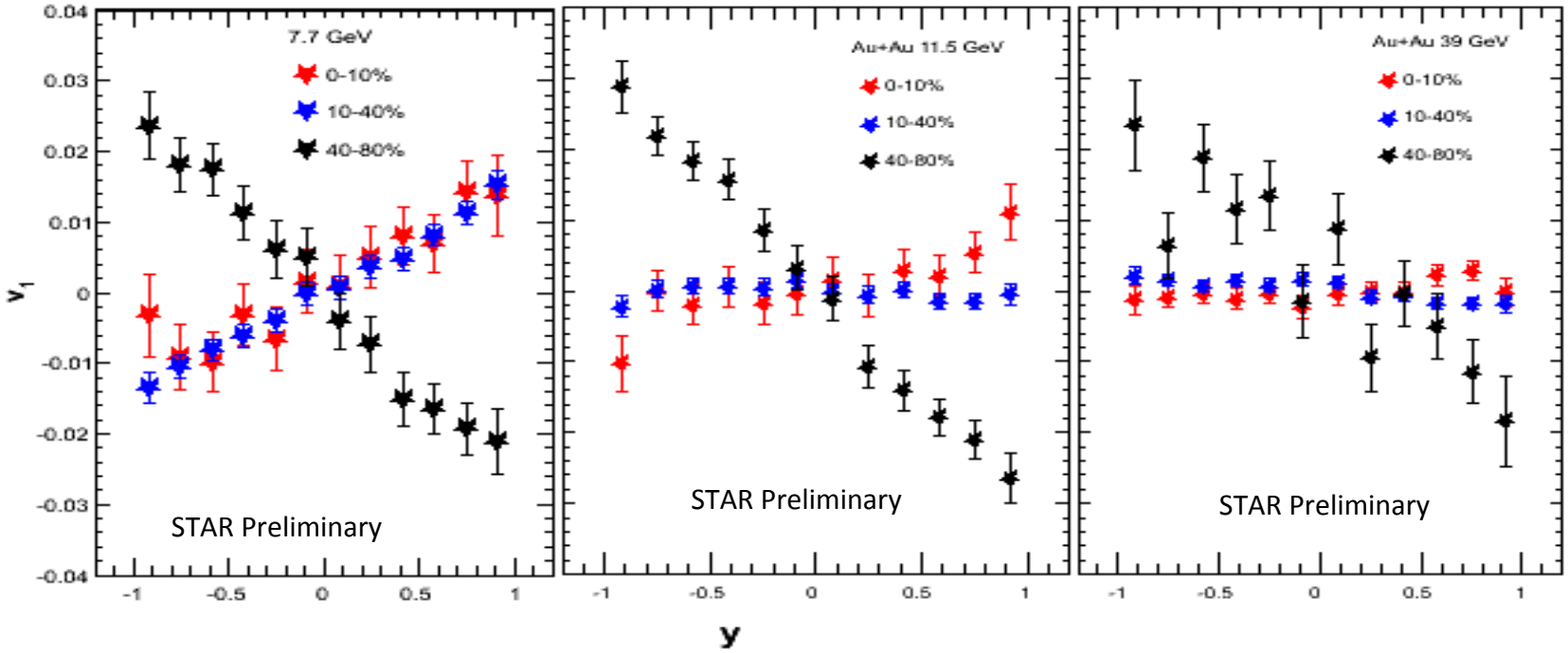
Rapidity range used in this study for proton , pion and kaon is $-1.0 < y < 1.0$ .For mid-central collisions(10-40%) differences in directed flow of h^+ and h^- is observed.

Directed flow of Identified Particles: $v_1(y)$



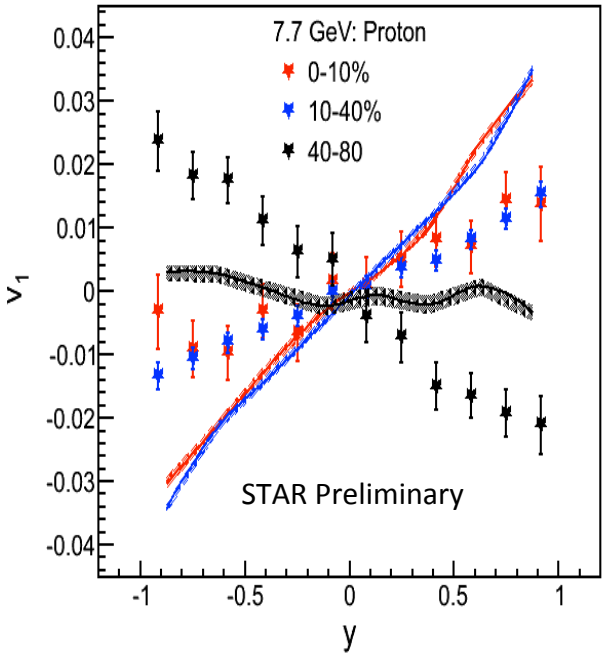
- p_T range used in this study for proton is $0.2<p_T<2.8$ GeV/c, and for pion and kaon it is $0.2<p_T<1.6$ GeV/c.
- For mid-central collisions (10-40%) the $\pi^{\pm}$, $K^{\pm}$ and antiprotons have a negative dv_1/dy at midrapidity but proton dv_1/dy at 7.7 GeV becomes positive.

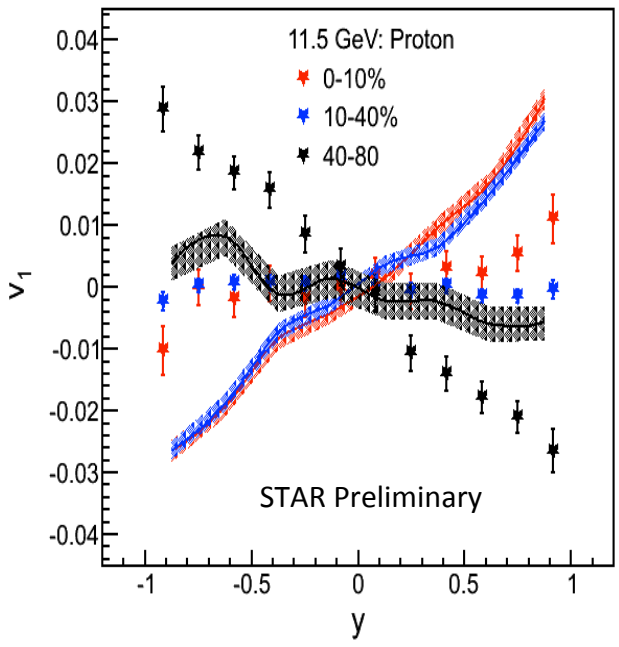
Directed flow of Proton: Centrality Dependence

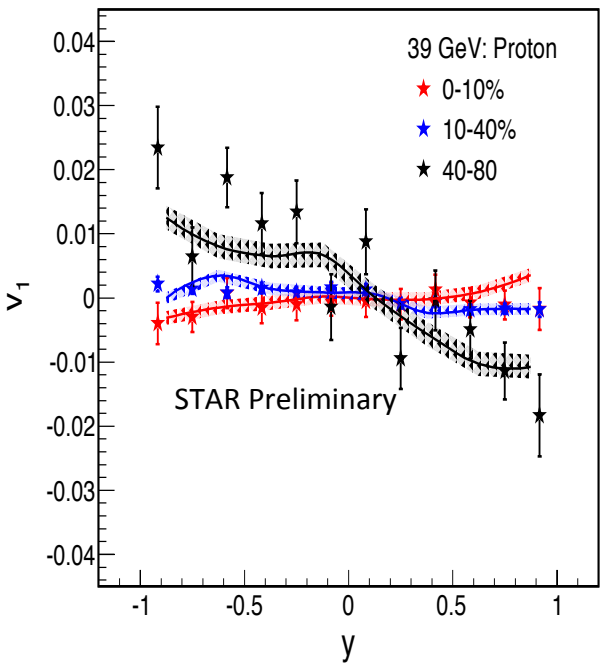


- Proton v_1 slope is positive in mid-central collision at 7.7 GeV. At 11.5 GeV, it is almost flat and at 39 GeV and higher RHIC energies, the proton slope is negative (but small) for mid-central collisions.
- The change in proton slope may be due to the contribution from the transported protons coming to midrapidity at the lower beam energies

Directed flow of Proton: Model Comparisons

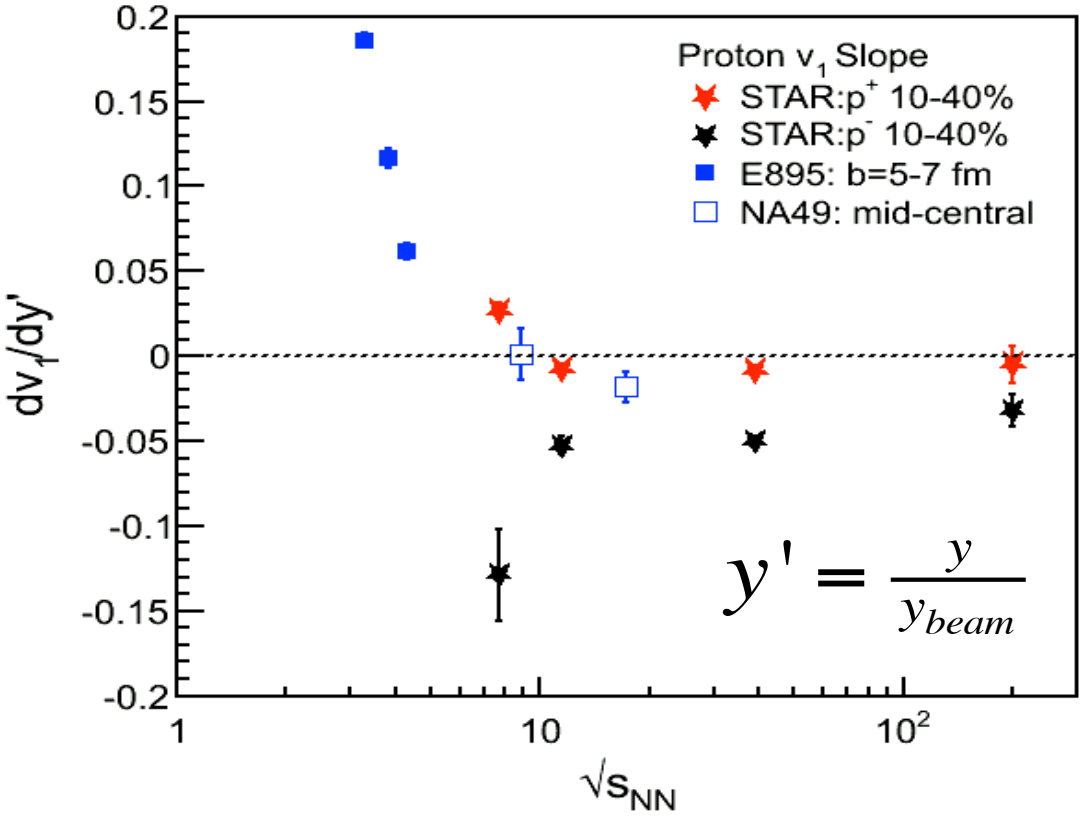






- The bands represent the UrQMD model prediction. The color code(for centrality) is same for data and models
- Tested models do not predict the right magnitude of directed flow but UrQMD and AMPT(default){not shown here} do show sign change of the proton slope going from central to peripheral collision from positive to negative at 7.7 and 11.5 GeV a similar trend shown by the data. However AMPT(String Melting) do not predict the sign change.
- UrQMD and AMPT(default) qualitatively supports the assumption of contribution of transported proton to the sign change of proton slope at 7.7 and 11.5 GeV.

Beam Energy Dependence: Proton flow



Phys. Rev. Lett.(E895 Collaboration) 84, 5488 (2000).

Phys. Rev. C(NA49 Collaboration) 68, 034903 (2003).

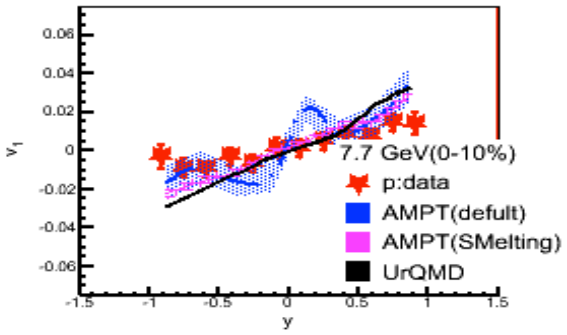
The proton $v_1(y')$ slope decreases rapidly with increasing energy above 7.7 GeV. Its sign changes to negative between 7.7 and 11.5 GeV, and remains close to zero at 11.5, 17, 39 and 200 GeV

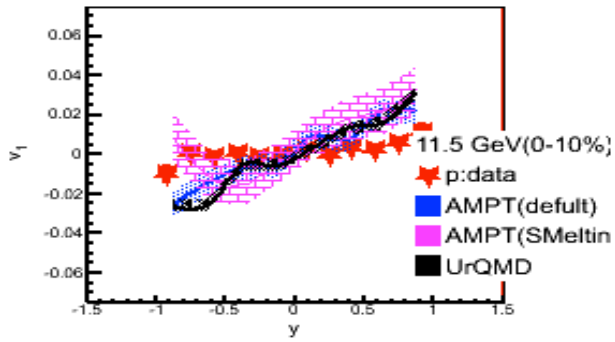
Summary/conclusion

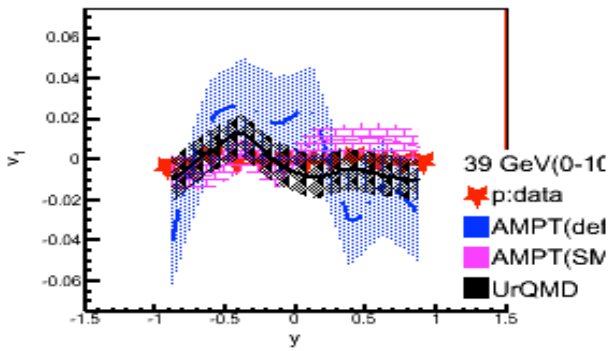
- Scaling behavior in v_1 vs. η/y_{beam} and vs. $\eta-y_{beam}$ is observed for BES data.
- Differences in directed flow of h^+ and h^- is observed.
- For mid central collisions (10-40%) the $\pi^{\pm}$,$K^{\pm}$ and antiprotons have a negative slope (dv_1/dy) at mid rapidity, but proton slope (dv_1/dy) at 7.7 GeV becomes positive .
- Proton v_1 slope changes sign from positive to negative going from central to peripheral collisions at mid central collision at 7.7 and 11.5 GeV.
- The proton $v_1(y')$ slope decreases rapidly with increasing energy above 7.7 GeV. Its sign changes to negative between 7.7 and 11.5 GeV, and remains close to zero at 11.5, 17, 39 and 200 GeV
- Tested models do not predict the right magnitude of directed flow but UrQMD and AMPT(default) do show sign change of the proton slope going from central to peripheral collision from positive to negative at 7.7 and 11.5 GeV a similar trend shown by the data
- UrQMD and AMPT(default) qualitatively supports the assumption of contribution of transported proton to the sign change of proton slope at 7.7 and 11.5 GeV.

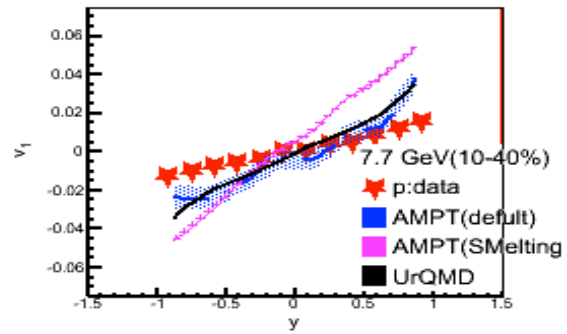
Extra Slides

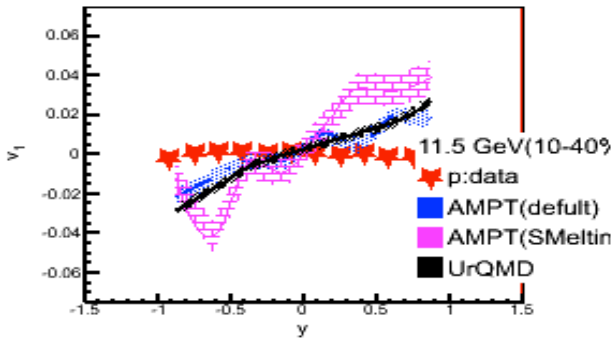
Directed flow of Proton: Model Comparisons

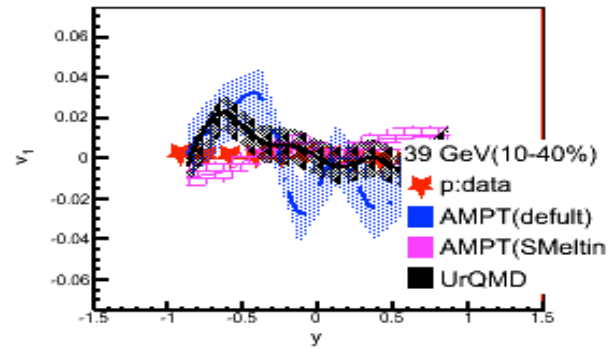


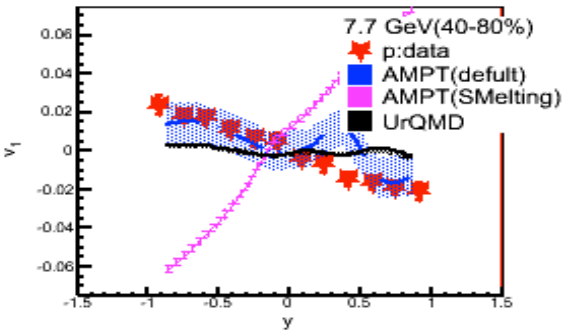


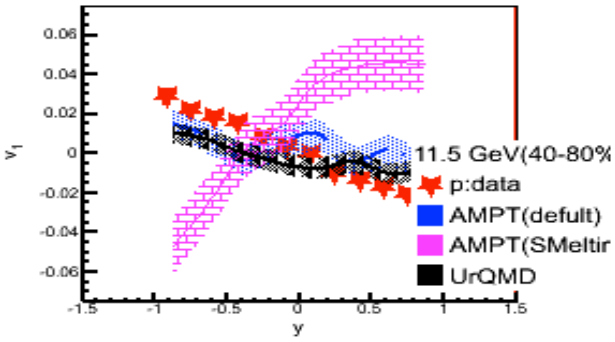


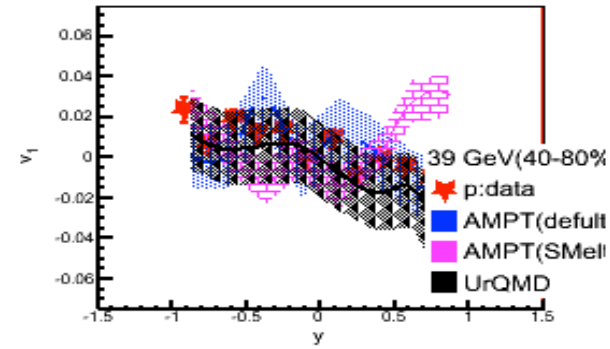




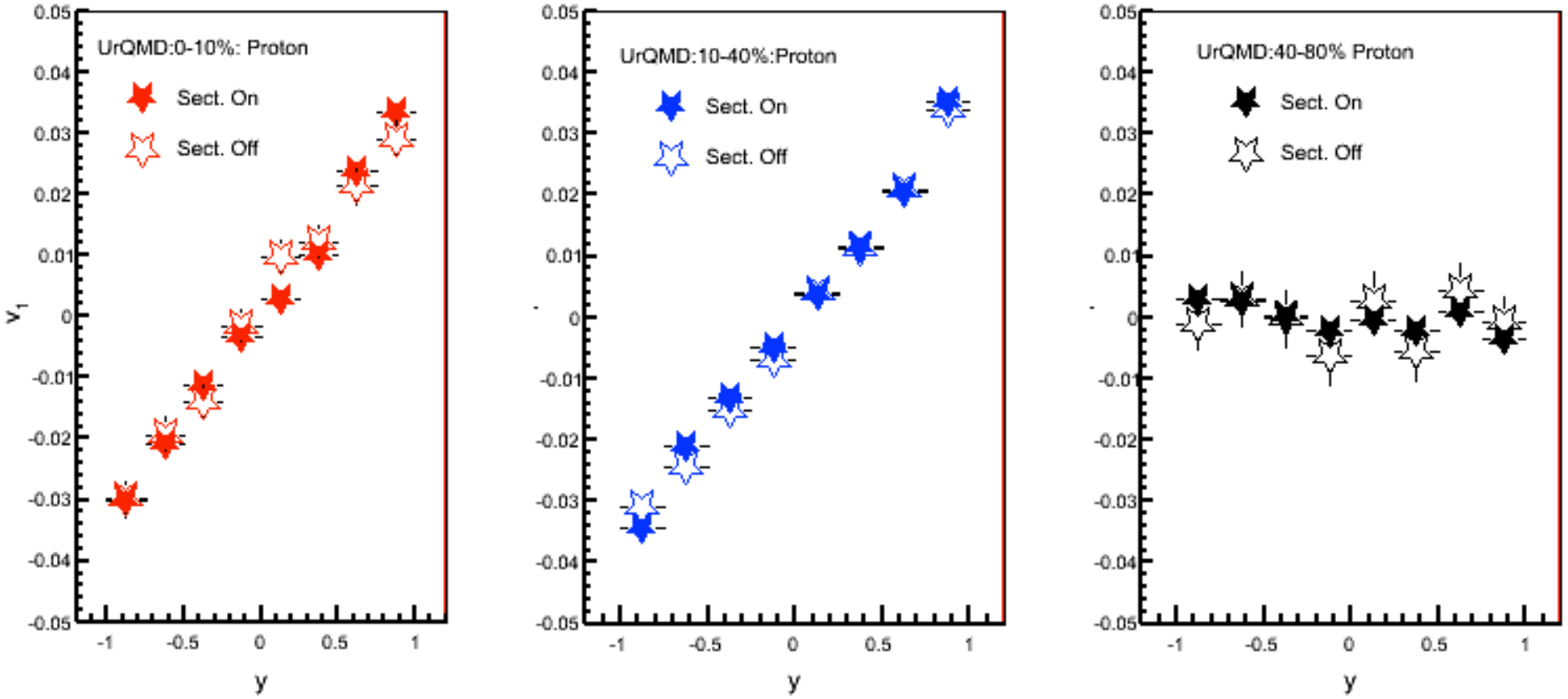








UrQMD: Effect of Spectator protons



We do not observe any significant change in the v1(y) of proton with turning off the spectator in UrQMD data at 7.7GeV