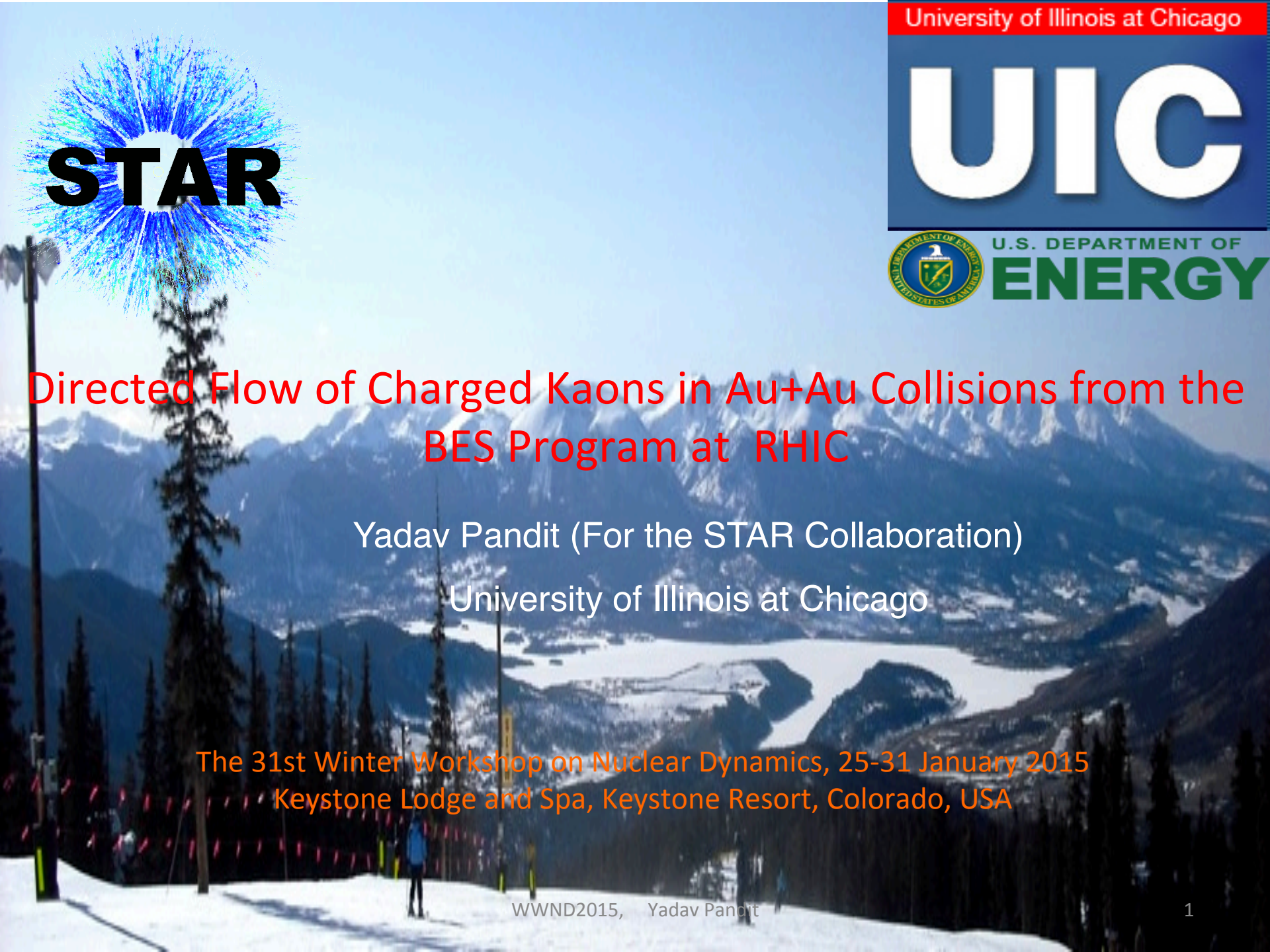


Directed Flow of Charged Kaons in Au+Au Collisions from the BES Program at RHIC

Yadav Pandit (For the STAR Collaboration)

University of Illinois at Chicago

The 31st Winter Workshop on Nuclear Dynamics, 25-31 January 2015
Keystone Lodge and Spa, Keystone Resort, Colorado, USA

Outline

Introduction

- Beam Energy Scan(BES) Program at RHIC
- STAR Detector
- Directed flow
- Top RHIC energy and NA49 results

Results

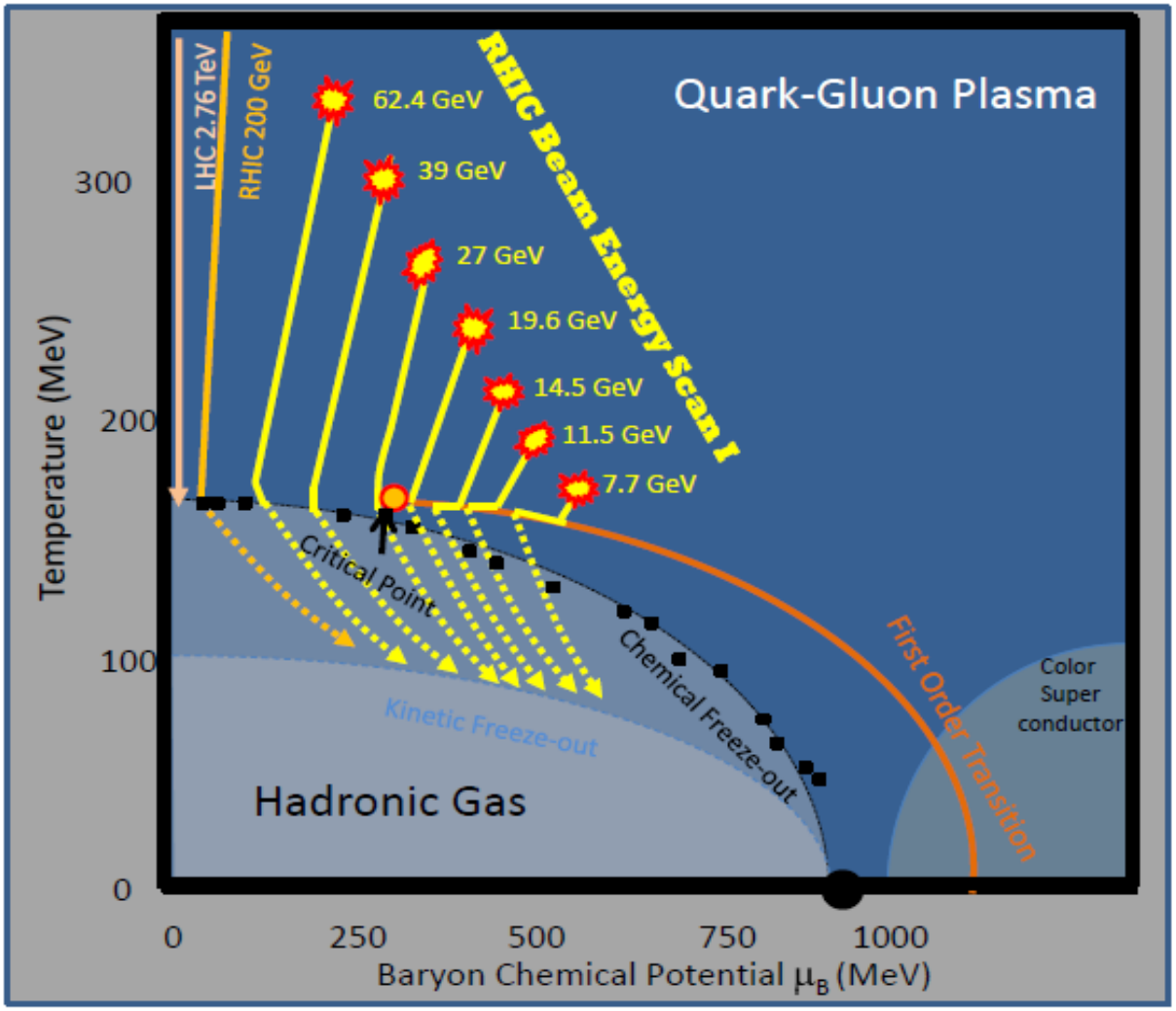
- v_1 of protons and pions from BES
- New: v_1 of Charged Kaons

Summary/Outlook

BES Program at RHIC

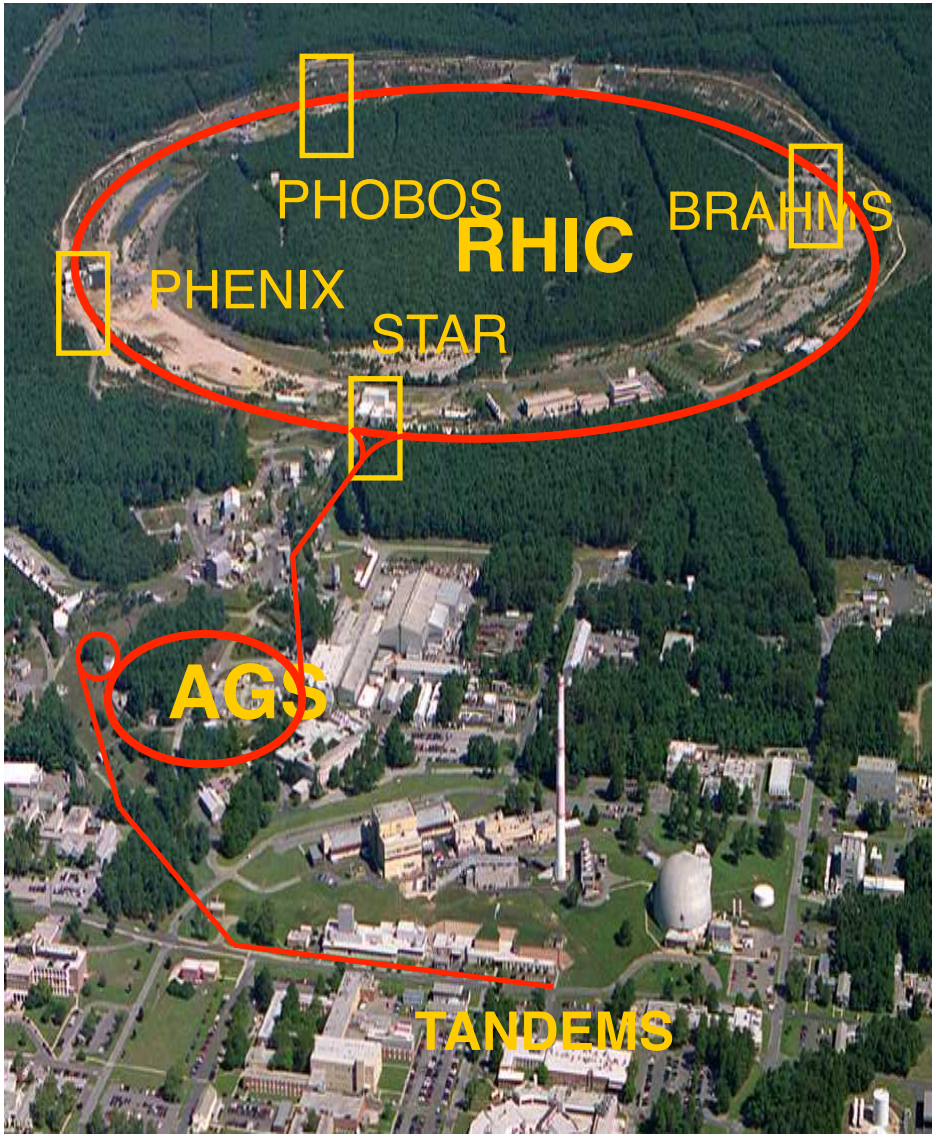
- Exploring QCD phase diagram is one of the main goal of heavy ion physics(Experiment and theory)
- Only a part of this phase diagram is known

  (At μ_B ~ 0 at high μ_B)
- In the intermediate μ_B region, experiment exploration are the best hope
- BES Program at RHIC :
  - Turn-off of sQGP signatures
  - 1st order phase transition signs
  - The QCD critical point



http://arxiv.org/abs/1007.2613

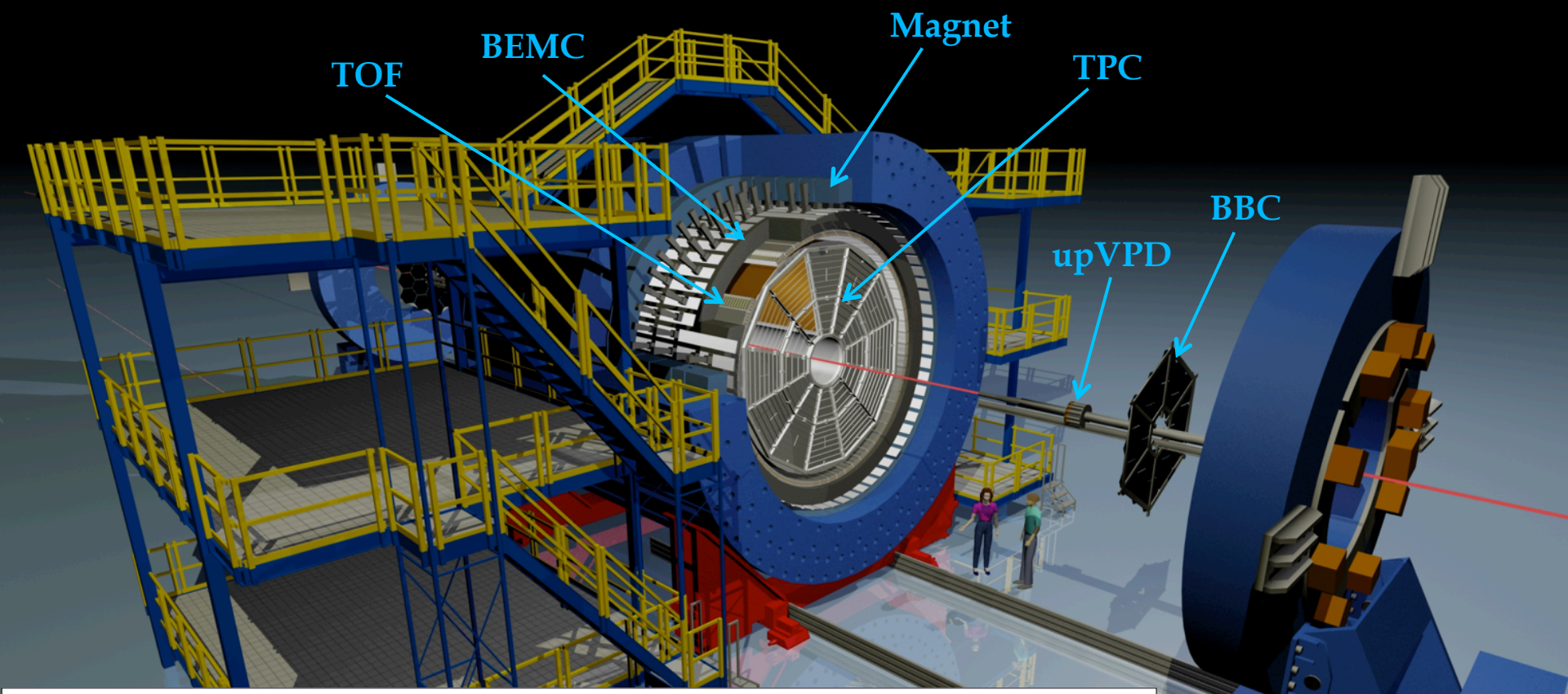
Relativistic Heavy Ion Collider



Study of colliding system as a function of:
1) Center-of-mass energy
2) System size

System	Energy
Au+Au	200,130, 62.4, 39,27,19.6, 14.5,11.5,9.2,7.7
Cu+Cu	200,62.4,22
U+U	193
Cu+Au	200
Au+He3	200
d+Au	200
p+p	200,510

The Solenoid Tracker At RHIC (STAR)



Uniform acceptance vs $\sqrt{s_{NN}}$

Main device: Time Projection Chamber

Coverage: $0 < \phi < 2\pi$, $|\eta| < 1.0$

Uniform acceptance: All energies and particles

Excellent particle ID: π, K, p through TPC dE/dx aided by TOF

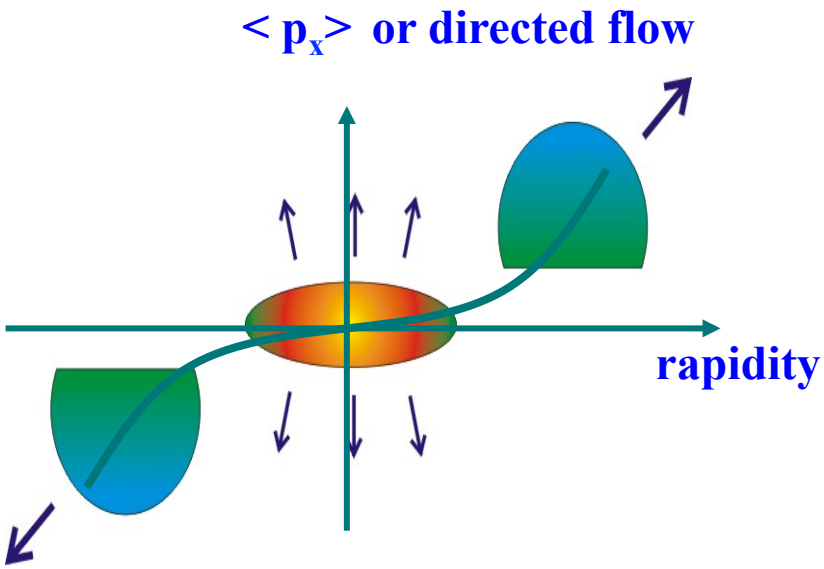
K^0_s, Λ, Ξ, Ω, ϕ through invariant mass

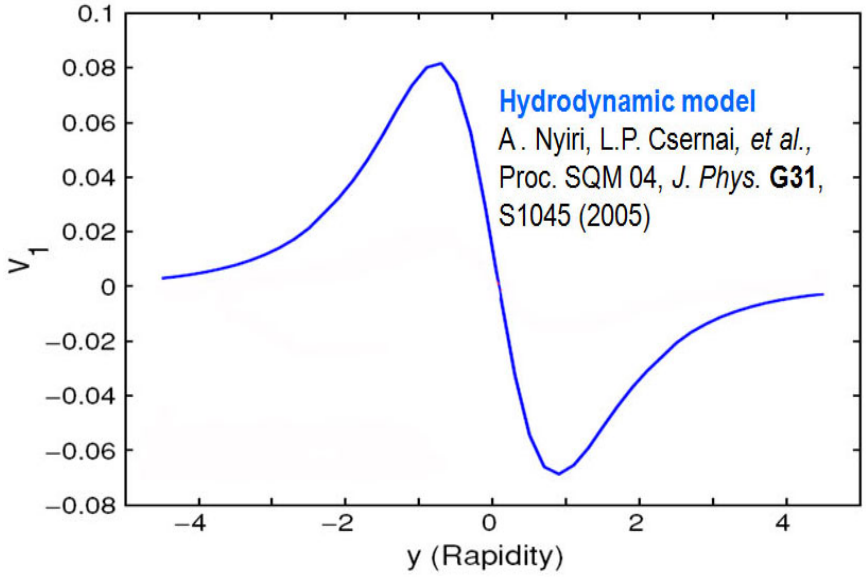
Directed Flow

- Directed flow: first harmonic (v_1)
- First form of flow predicted (one-fluid hydro) and observed (Plastic Ball) in 1980's
- Sensitive to pressure
- Hydro with QGP phase transition shows wiggle
- Less focus on v_1 at higher RHIC energies

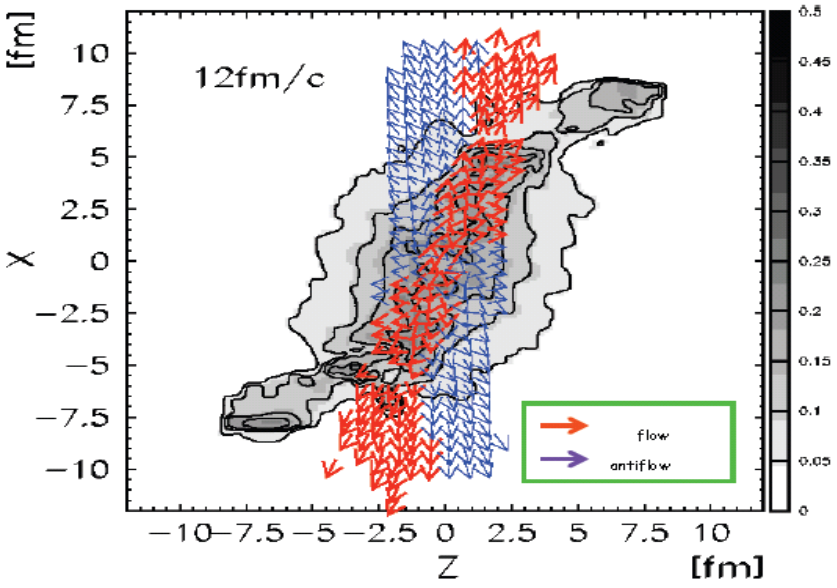
$$\frac{dN}{d\phi} \propto 1 + \sum_n 2 v_n \cos n\left(\phi - \psi_n\right)$$

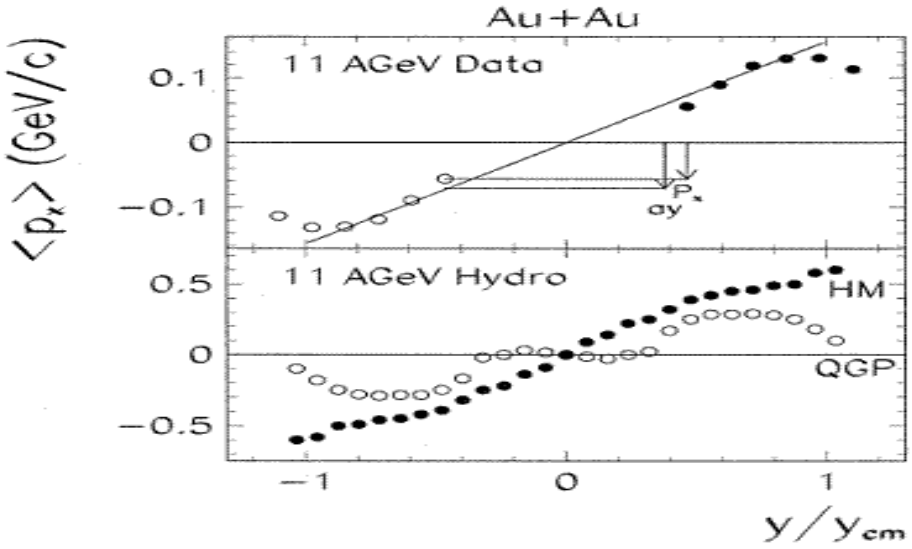
$$v_n = \left\langle \cos\left[n\left(\phi - \psi_n\right)\right]\right\rangle$$

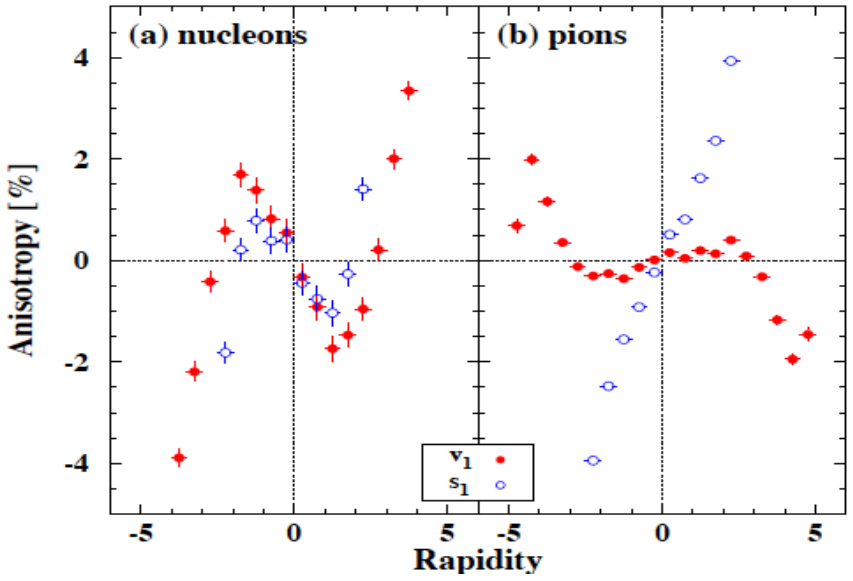




Directed Flow





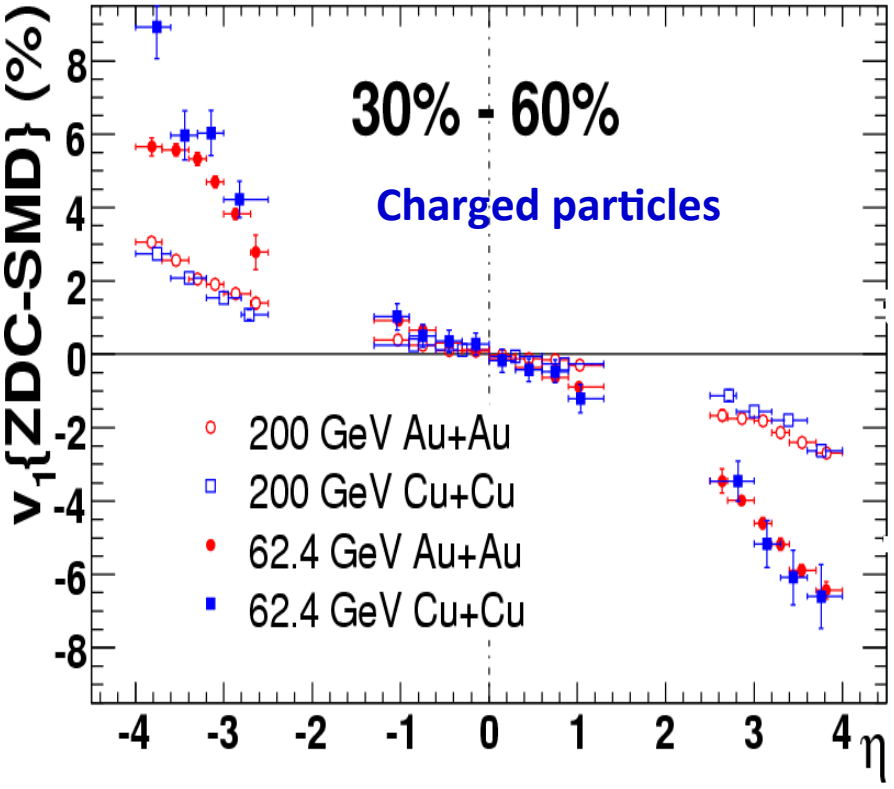


- Anti-flow/3rd flow component: $v_1(y)$ crosses zero 3 times (so-called "wiggle") or flat v_1 at midrapidity due to 1st order phase transition.

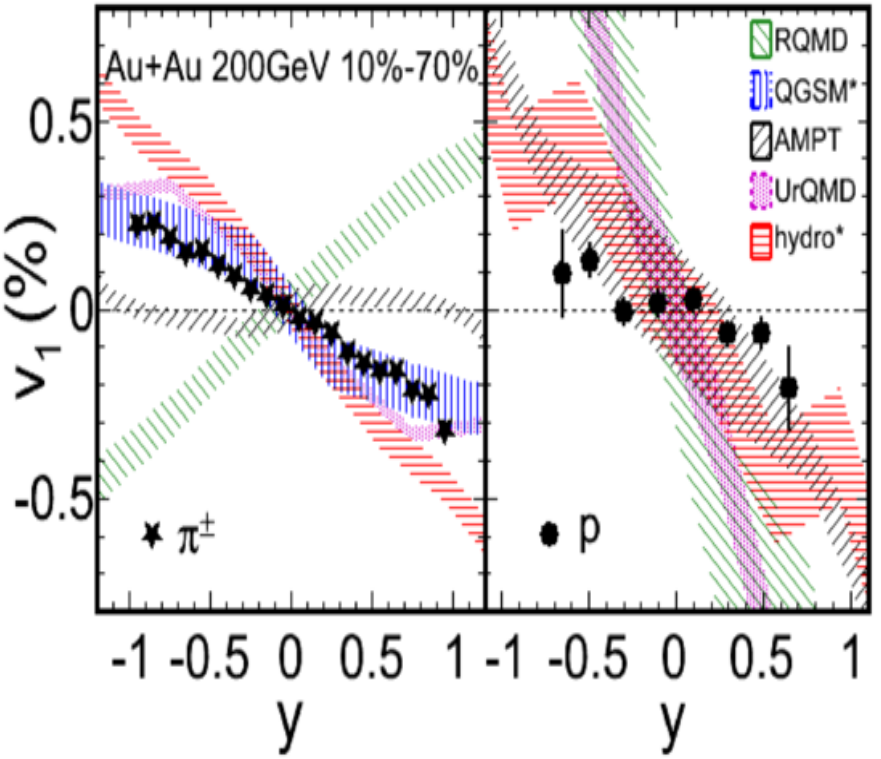
- However, baryon stopping +positive space-momentum correlation may also give wiggle structure in v_1: NO QGP necessary

J. Brachmann et al., PRC 61, 24909 (2000)
L.P. Csernai et. al. , PLB 458, 454 (1999)
R. Snellings et. al. PRL **84** 2803 (2000)

Directed flow at 200 GeV



STAR, PRL 101 252301 (2008) :



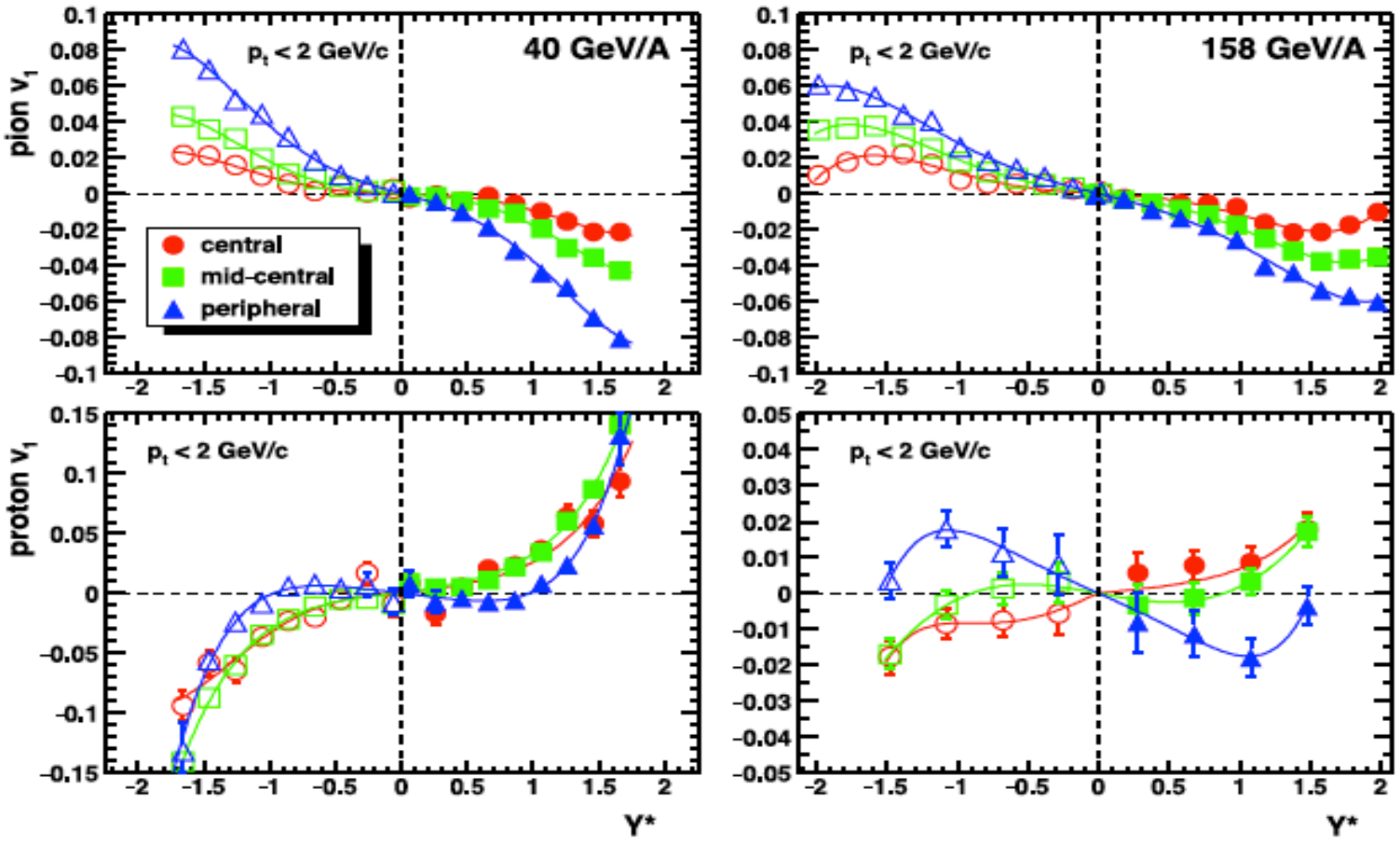
STAR, PRL 108 ,202301(2012)

System-size independence can be explained by Hydro+tilted source: P. Bozek & I. Wyskiel, Phys. Rev. C 81, 054902(2010)

None of models can describe $v_1(y)$ for pions and protons simultaneously.

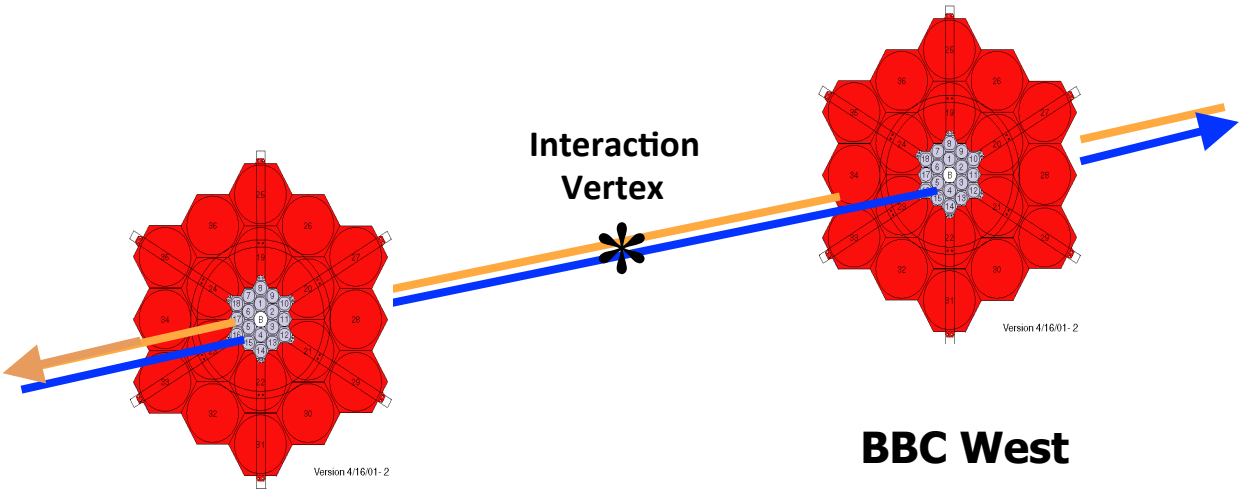
Directed flow at SPS Energies

NA49, Phys.Rev. C68, 034903(2003)

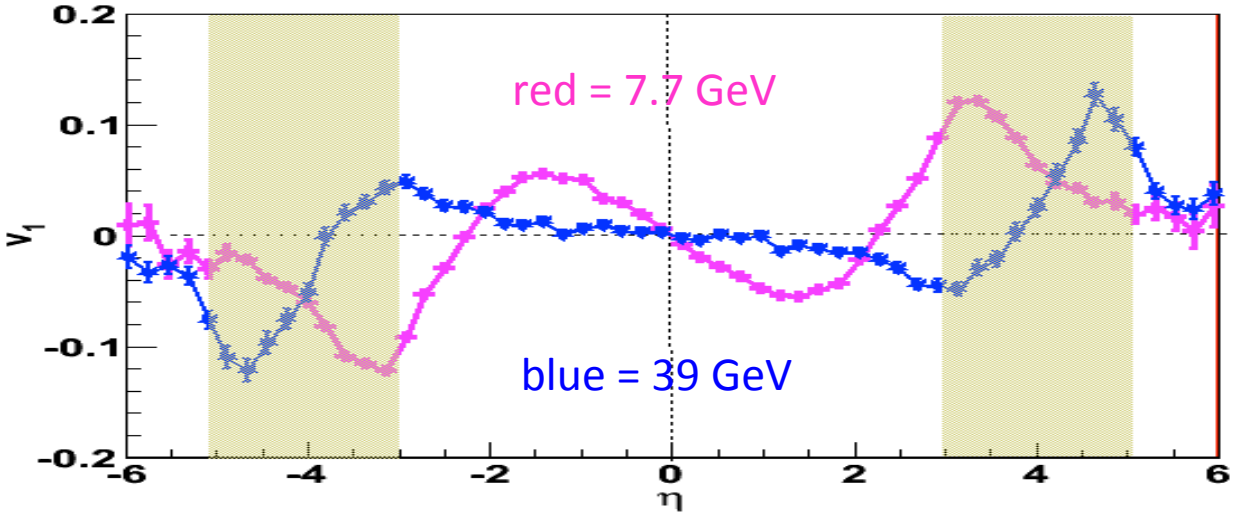


v_1(y) for pions and protons at SPS Energies

BBC Event Plane

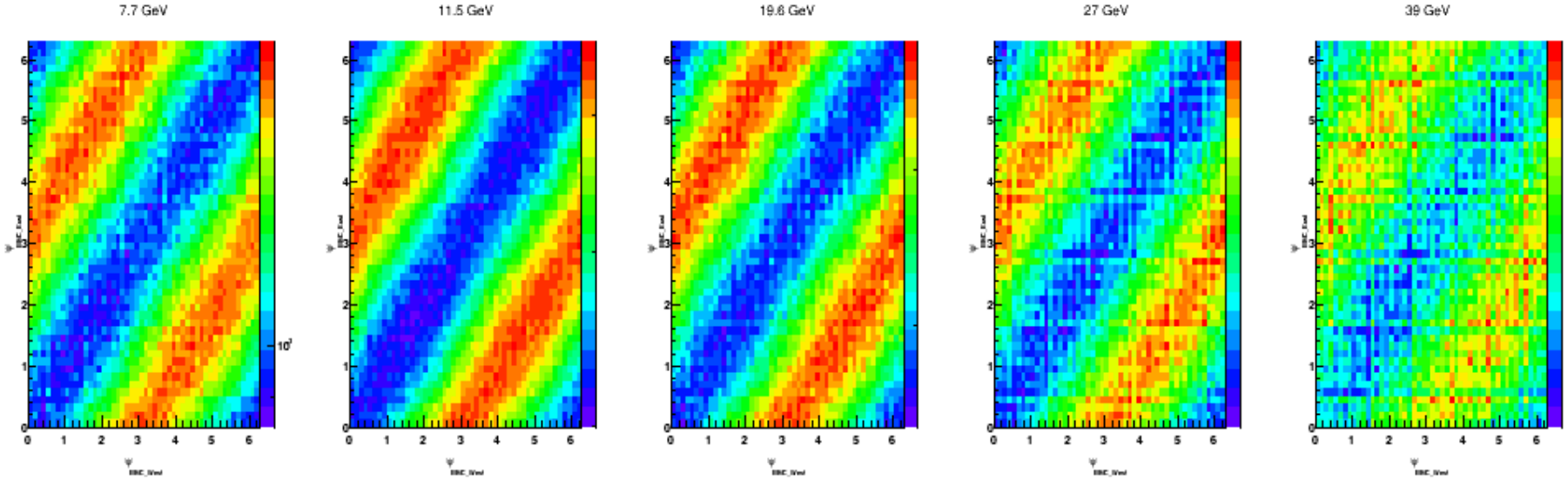


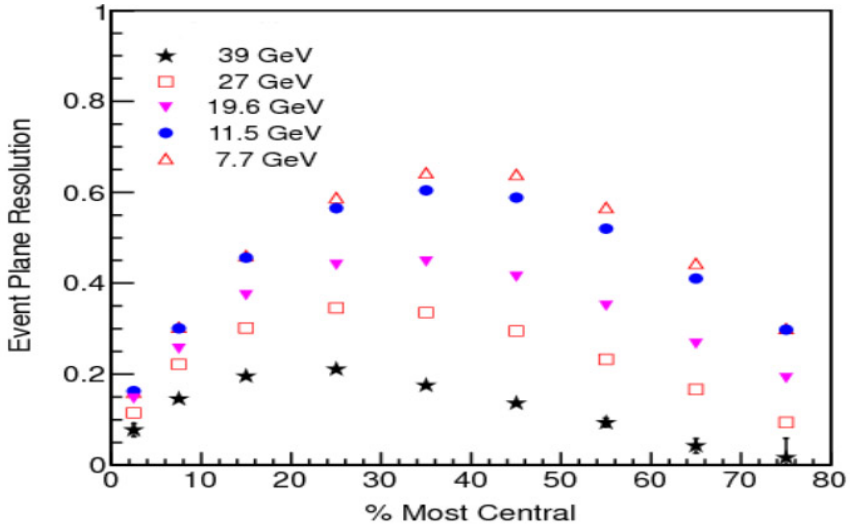
v_1 signal from UrQMD



- At 7.7-39 GeV, peak v_1 signal at BBC coverage ($3.3<|\eta|<5.2$) is observed for intermediate centrality UrQMD events .
- Large pseudorapidity gap between BBC ($3.3<|\eta|<5.2$) and TPC ($1.0<|\eta|$) supresses the non flow correlation
- STAR Beam Beam Counter is used as a reaction plane detector for BES Prgram

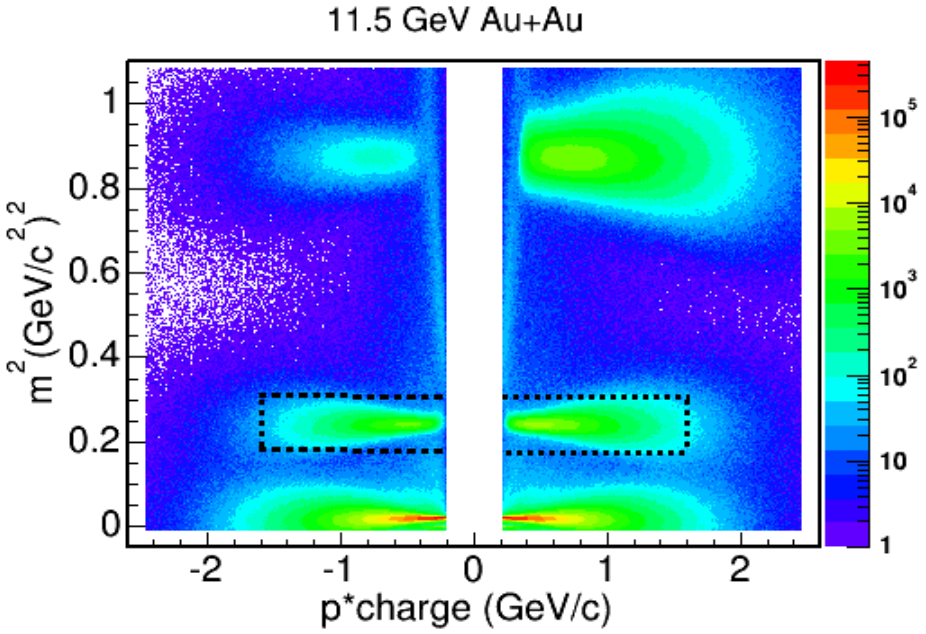
BBC Event Plane





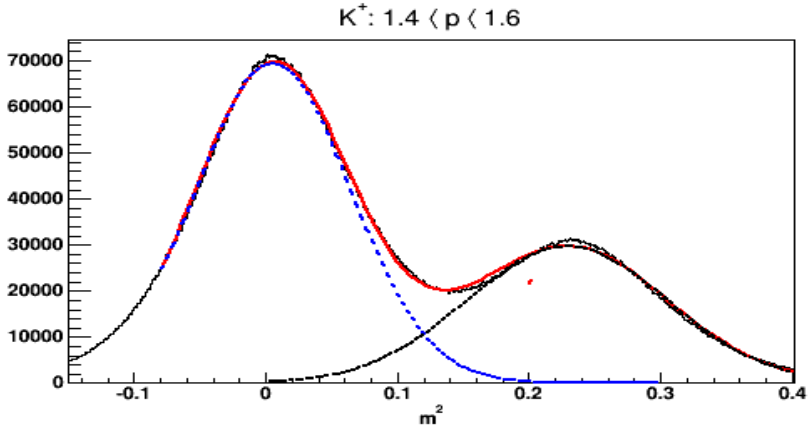
- BBC east and west event plane correlations for 7.7, 11.5, 19.6, 27 and 39 GeV from left to right.
- BBC's 1st-harmonic EP resolution becomes poor at 39 GeV and is unusable at 62.4 & 200 GeV

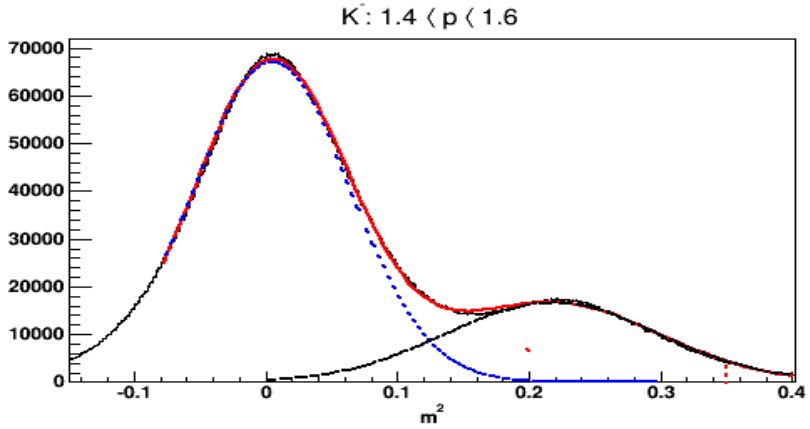
Particle Identification



M^2 on time-of-flight information, versus momentum from TPC curvature, for the case of Au+Au collisions at 11.5 GeV. K^+ and K^- candidates are indicated by dashed-line boxes.

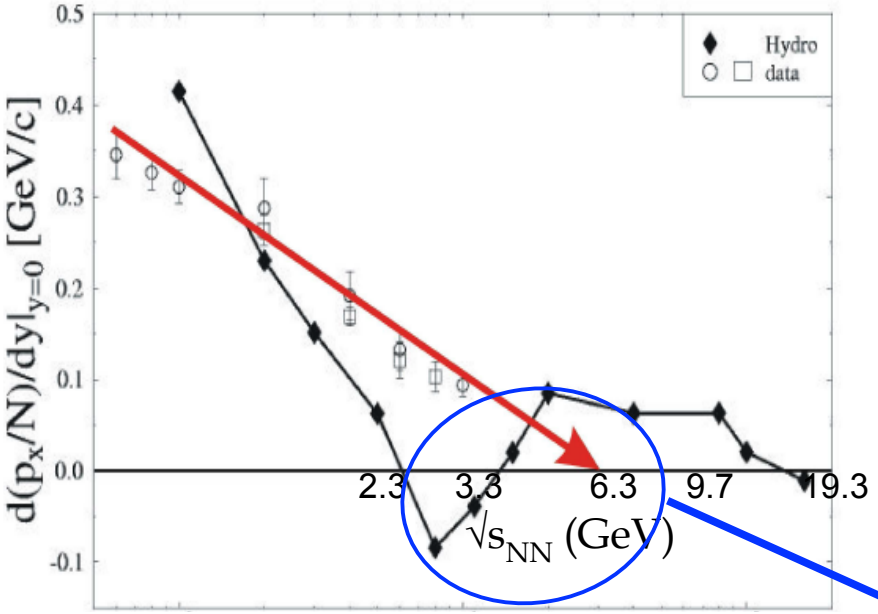
M^2 distribution of kaons and pions at 1.4< p< 1.6 GeV/c. There is negligable pion conribution (less than 1%) in the identified kaons



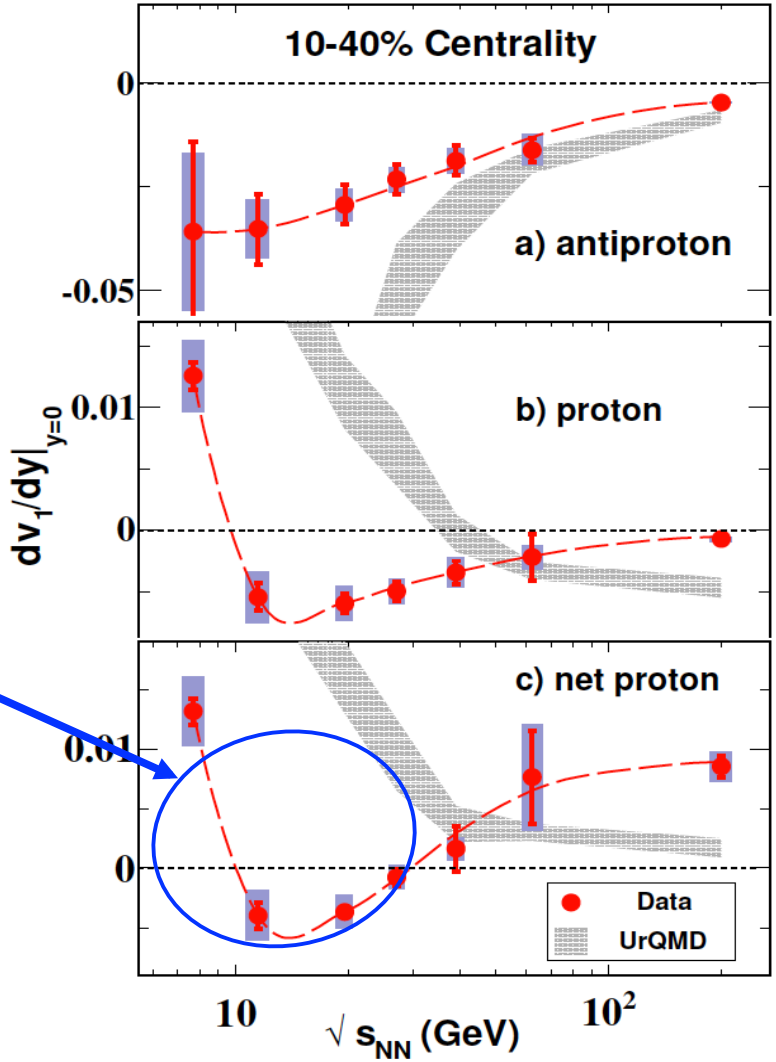


Directed flow: Protons and Net-Protons

H. Stoecker, Nucl. Phys. A 750 (2005)



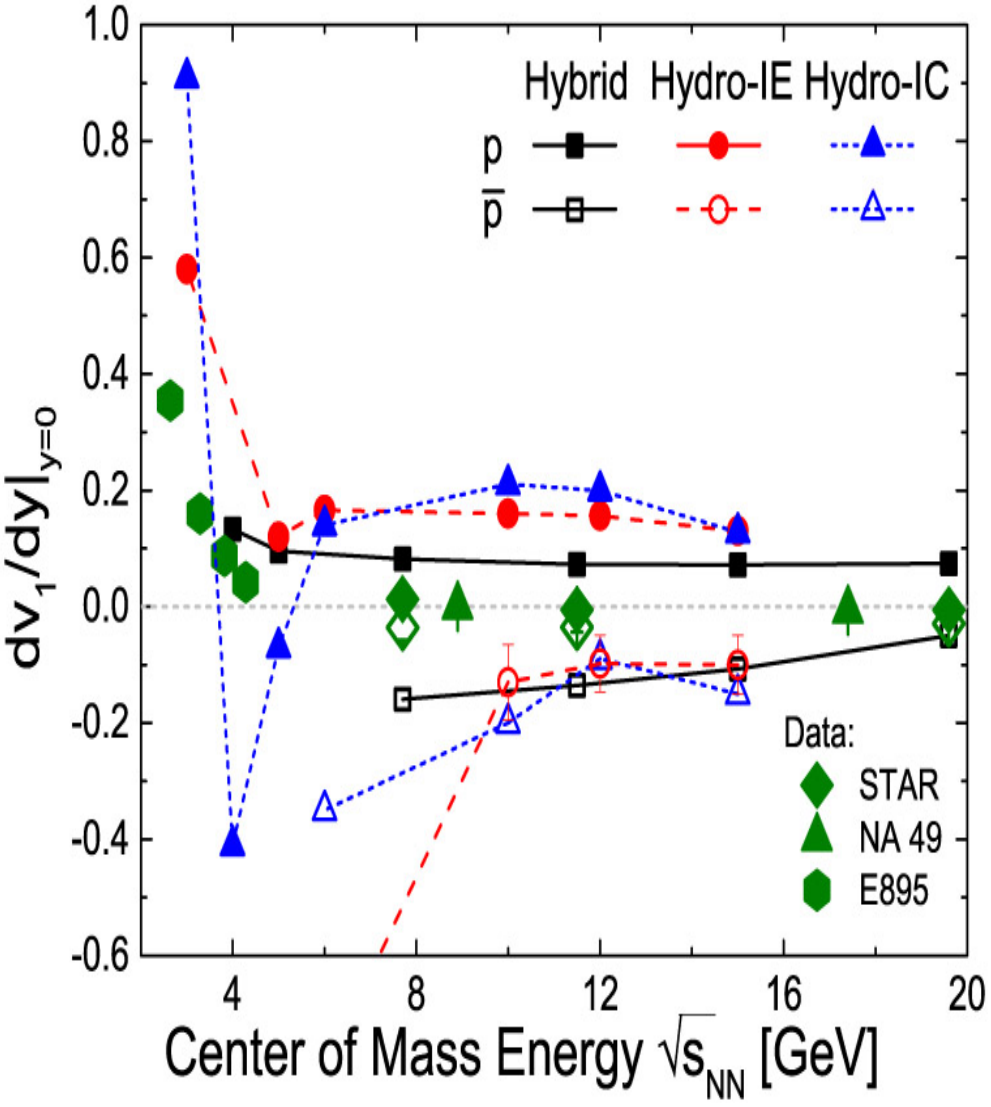
STAR, PRL, 112, 162301(2014)



Dip in net-proton dv_1/dy (but different location) resembles theory prediction with a first order phase transition

→ Softest point of EoS?

Directed flow of Protons



IC =Isochronous freeze-out (sim. to 2005 hydro).

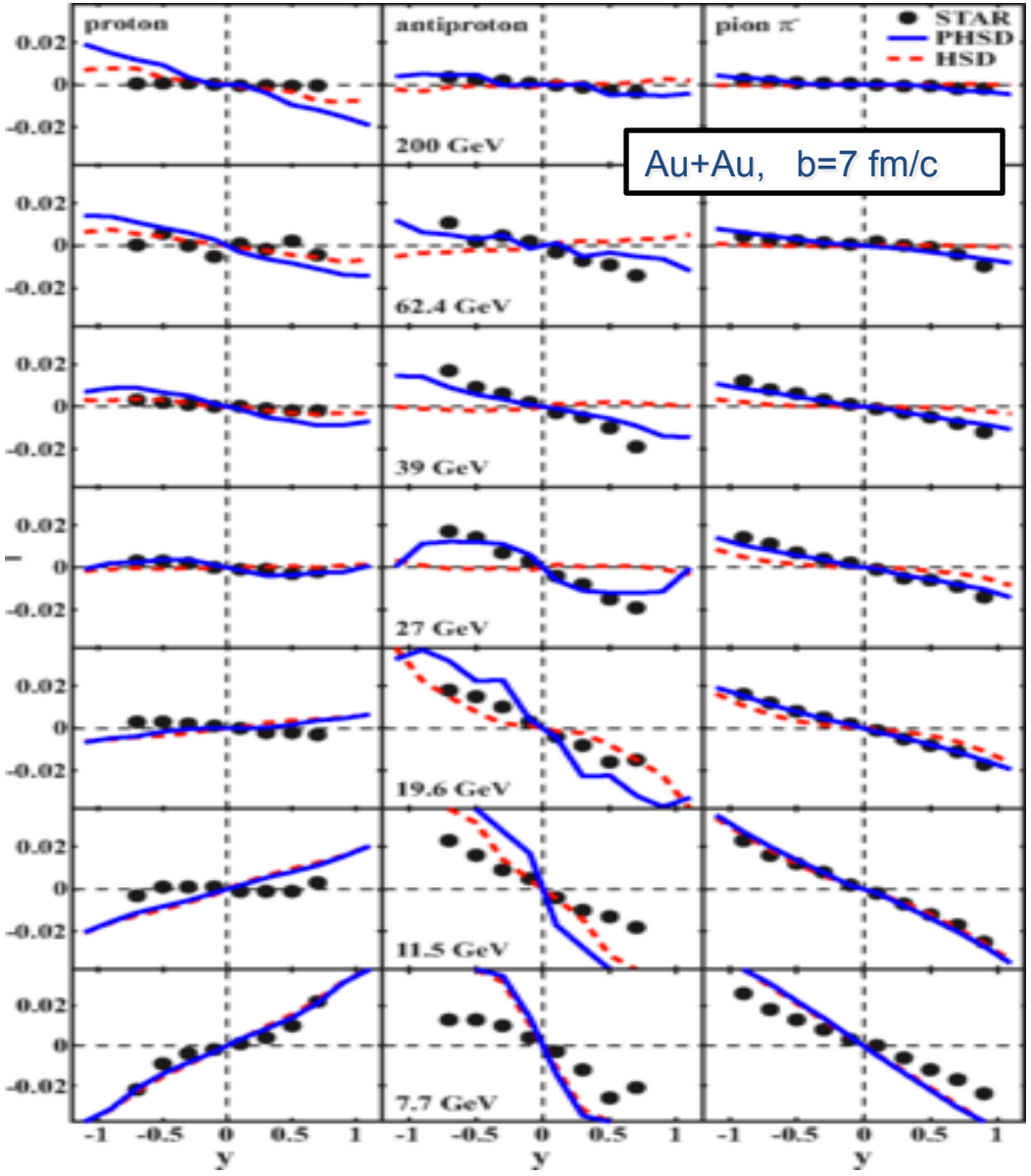
IE =Iso-ρ_E freeze-out (ρ_E is energy density)

Latest Frankfurt Hydro model calculations corroborate earlier double sign-change, but more realistic Hybrid model options don't show it.

No model calculation seems to capture the qualitative experimental trend for all particles at all energies

J. Steinheimer et. al. Phys. Rev. C **89,** 054913(2014)

Directed flow: Protons, Antiprotons and Pions



Models:

* HSD (red) – warning: NO hadronic potentials, cascade mode!
* PHSD (blue) – repulsive parton potential

Discrepancies at low energy – indication on the influence of hadronic potential

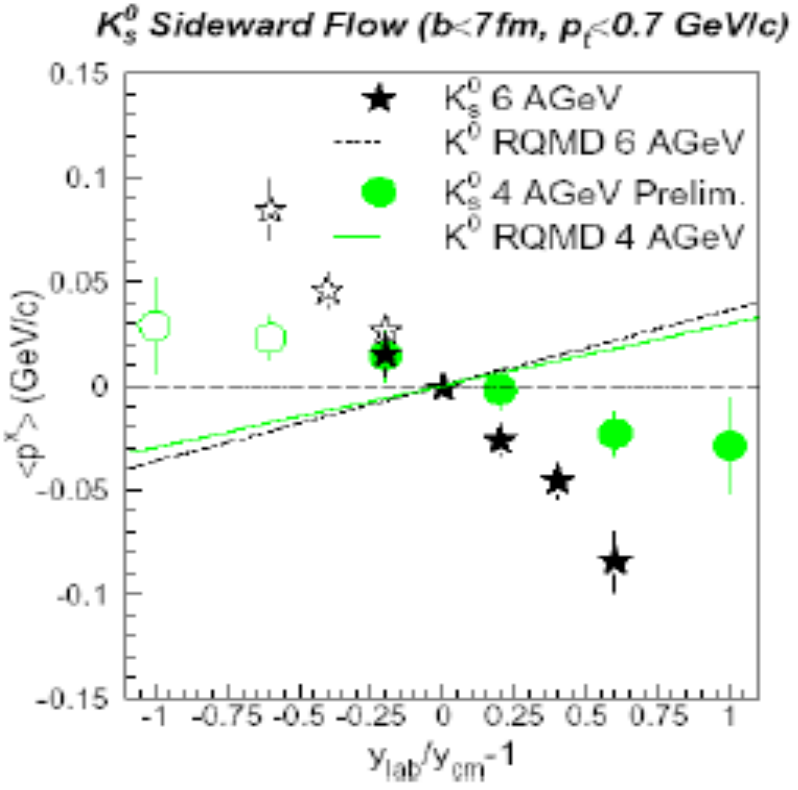
PHSD/PSD model shows no minimum in proton $v_1(\sqrt{s_{NN}})$ slope.

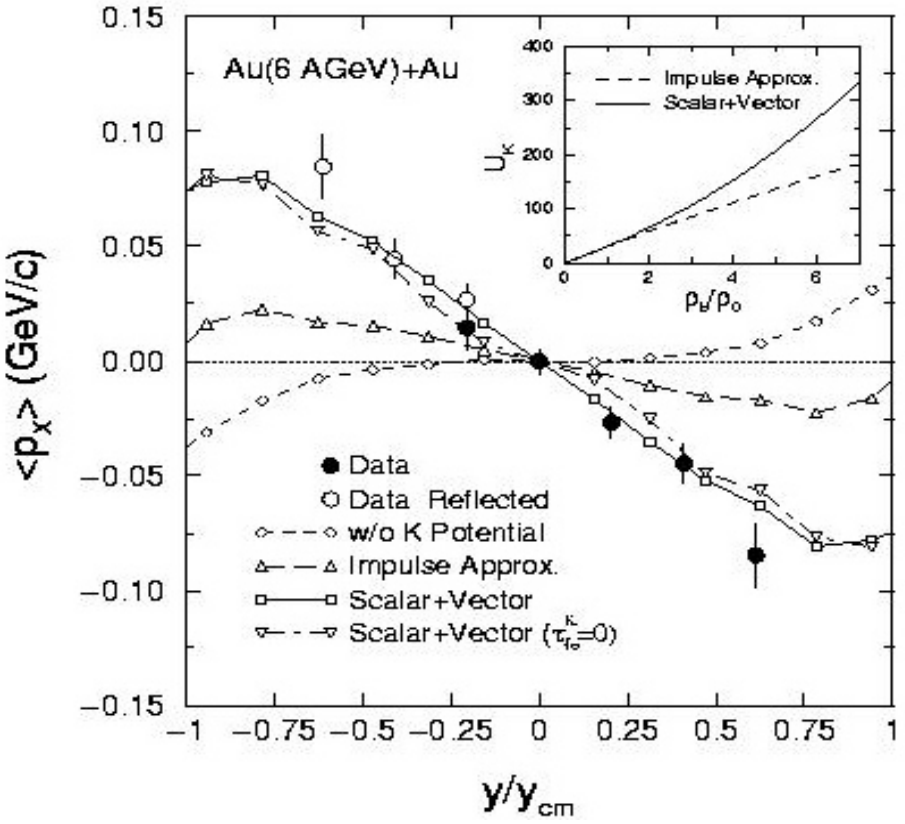
Directed flow puzzle in heavy-ion collisions ???

Kaon flow may help.

Konchakovski et. al. Phys. Rev. C **90,** 014903 (2014)

Directed flow of Kaons at AGS Energies



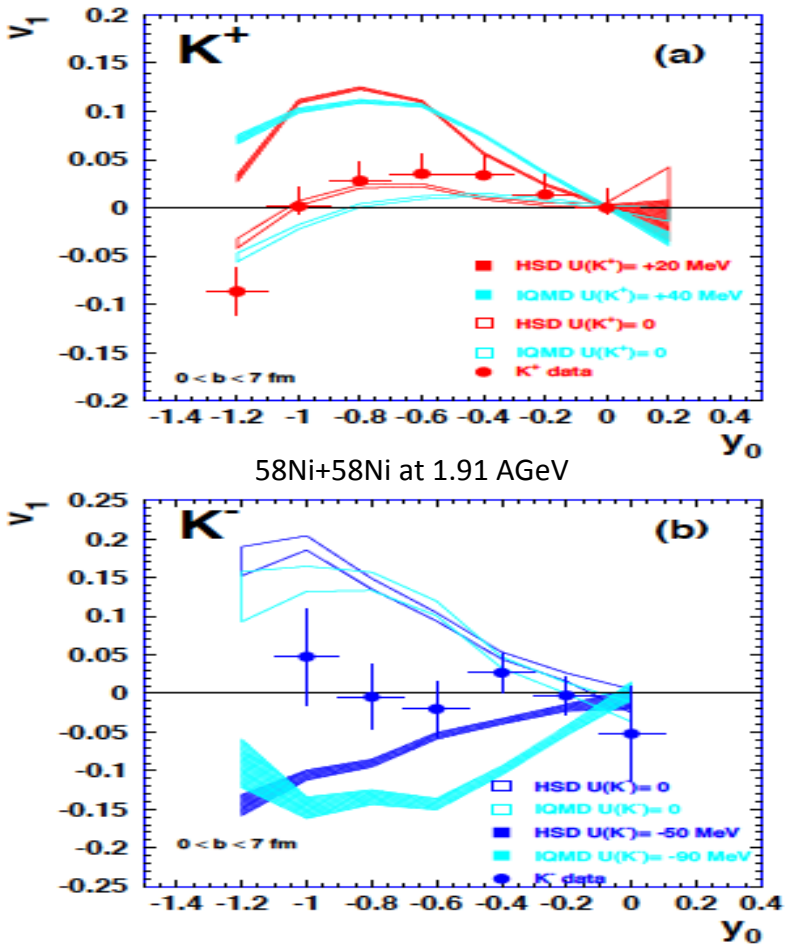


- K^0 shows strong antiflow
- Incident Energy dependence
- Possible evidence for in-medium potential

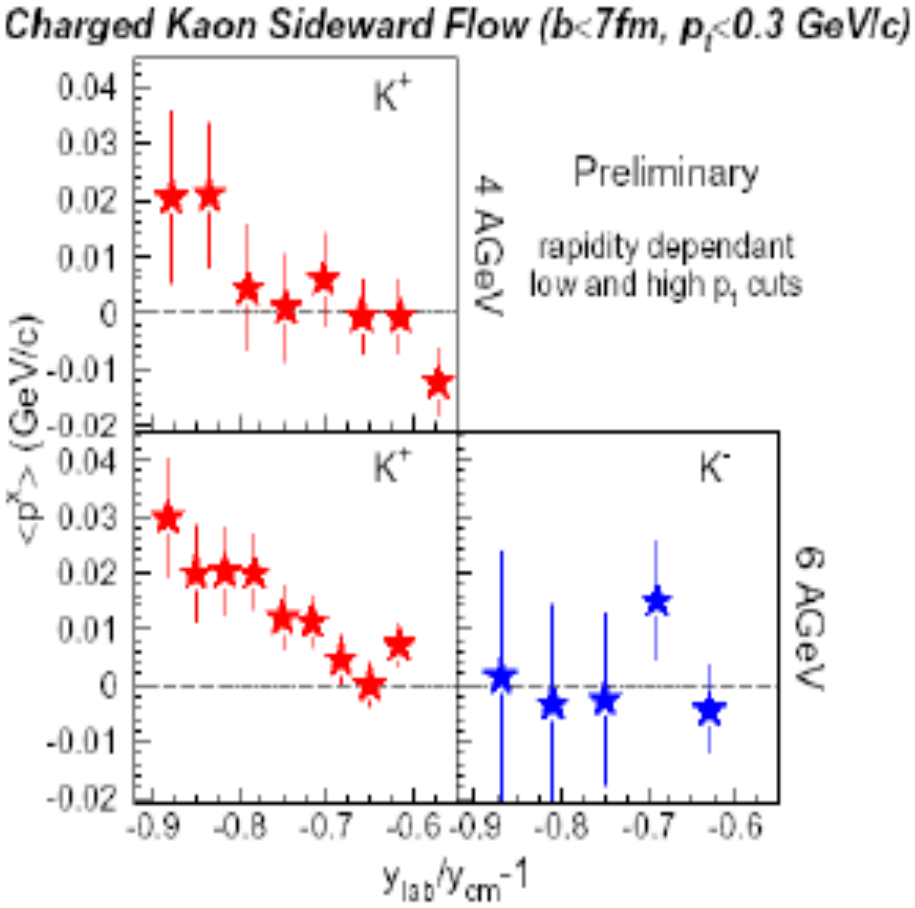
P. Chung et al. (E895), PRL 85, 940 (2000)
S. Pal et al., PRC 62, 061903(2000)

Directed flow of Kaons at AGS and FOPI Energies

FOPI, Phys. Rev. C 90, 025210(2014)

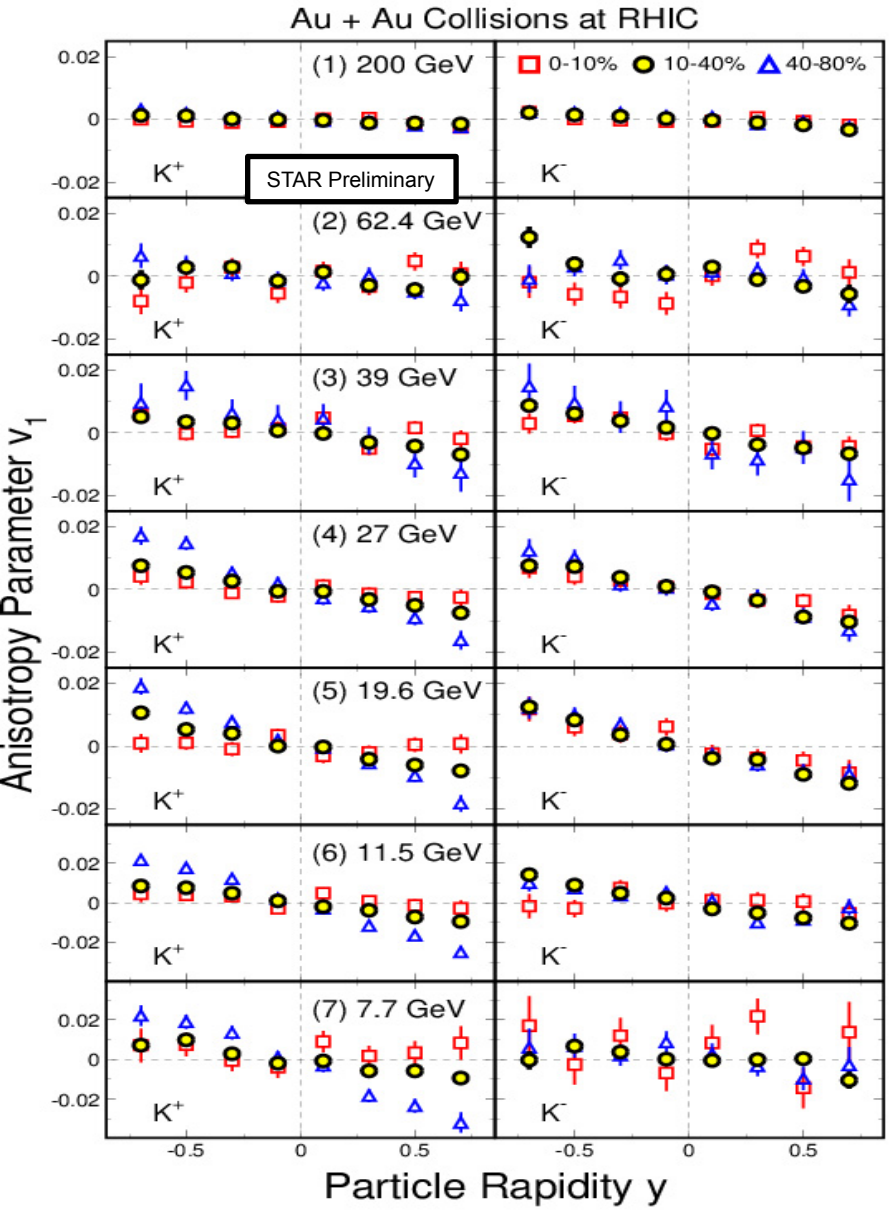


Nucl, Phys. A 698, 495 (2002)



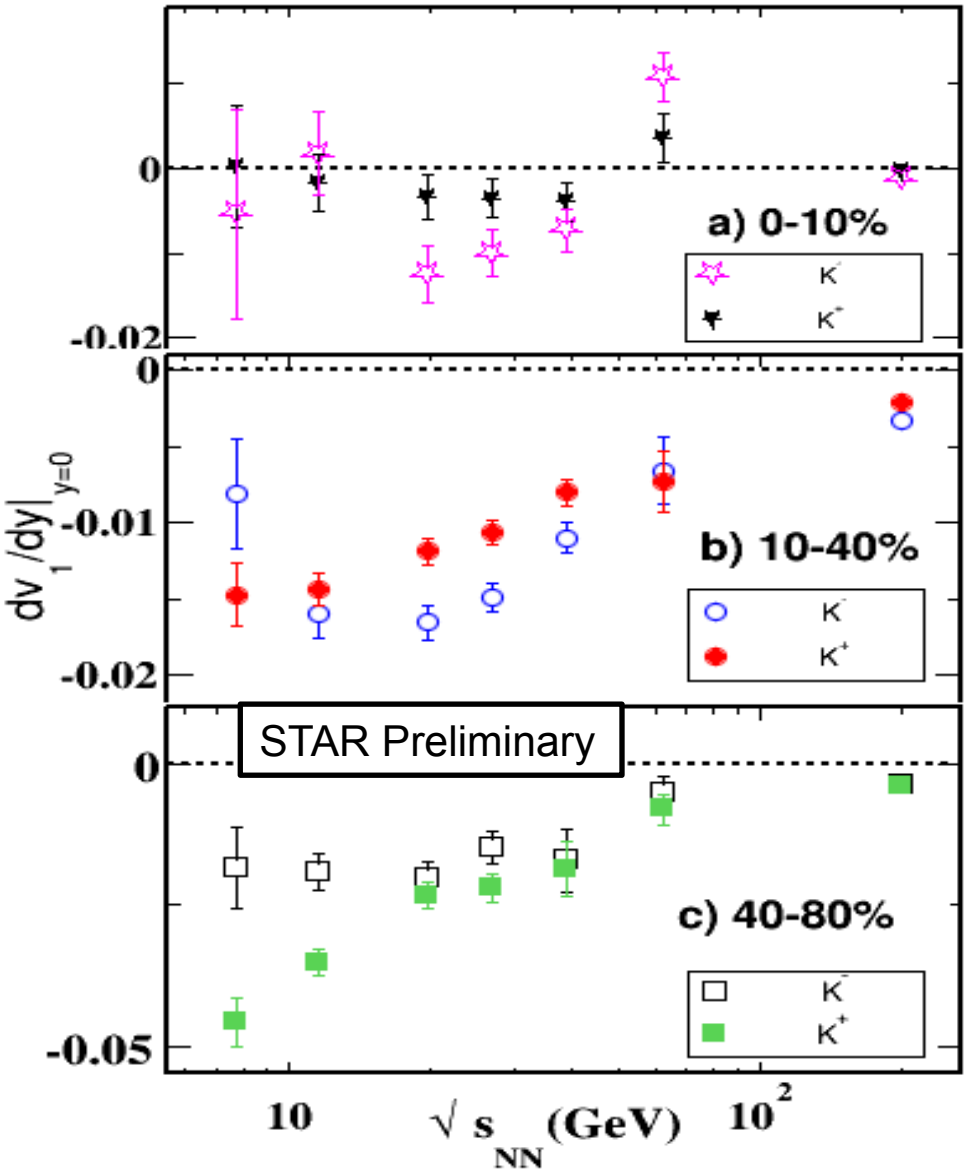
- K^+ shows antiflow, like K^0 : K^- flow : poor statistics shows no flow
- Possible evidence for attractive K^-N and repulsive K^+N potential

Beam energy dependence of K^+ and K^- directed flow



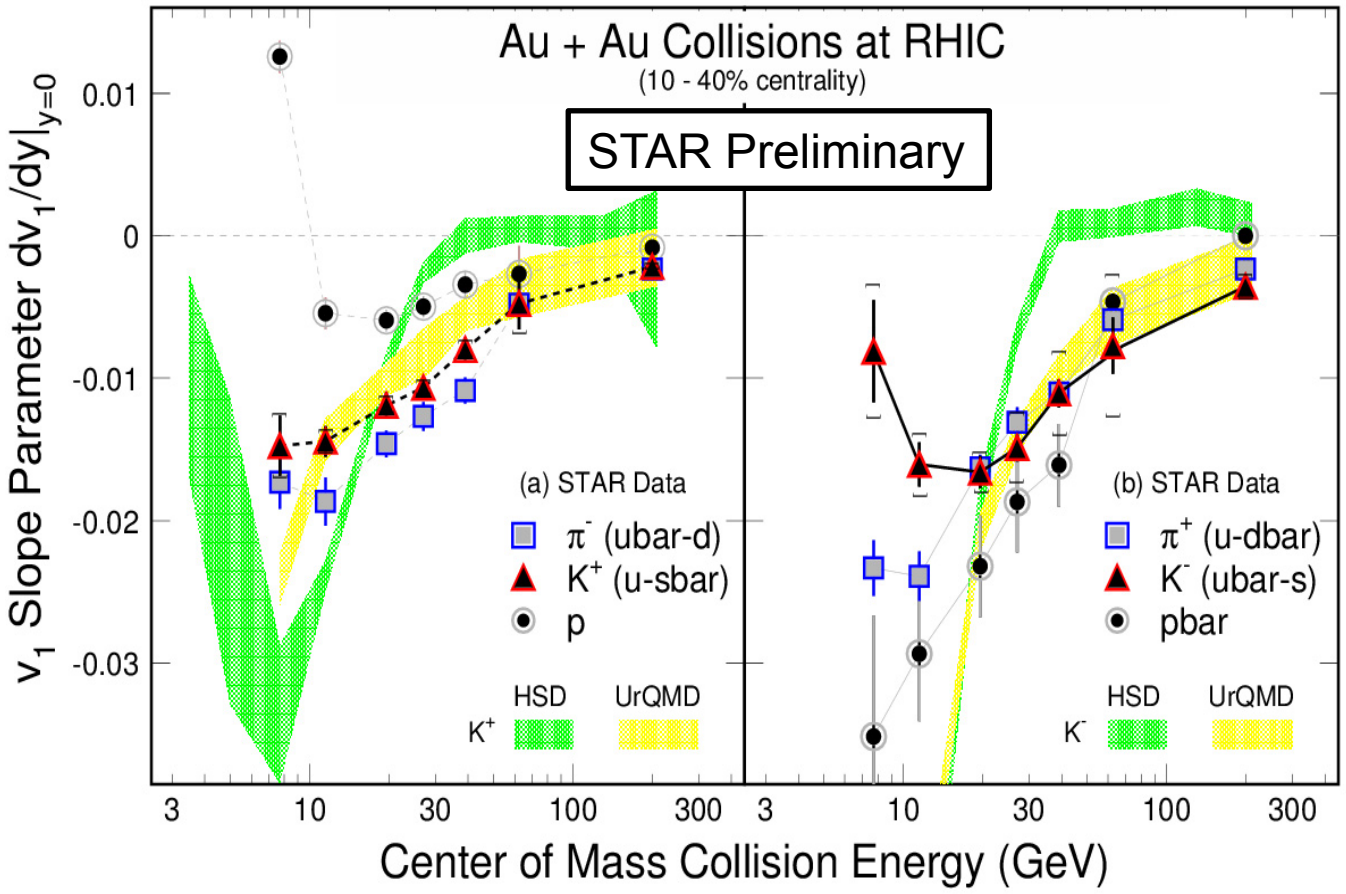
- Rapidity dependence of directed flow, $v_1(y)$, for K^+ (left column) and K^- (right column) in Au + Au collisions for seven beam energies and three centrality intervals, as indicated.
- The plotted error bars show statistical errors only.
- K+ and K- flow is mostly negative at all energies and all centralites.

Beam energy dependence of K^+ and K^- directed flow slope



- $dv_1/dy|_{y=0}$ slopes are extracted using a linear fit over the y range [-0.7, 0.7].
- The plotted error bars show statistical errors only.
- K^+ and K^- flow slope is mostly negative at all energies and all centralites

Beam energy dependence of K^+ and K^- directed flow slope



- At $\sqrt{s_{NN}}$ = 7.7 GeV, produced particles including Charged Kaons show opposite ordering than that of proton
- At $\sqrt{s_{NN}}$ > 30 GeV, all observed particles seem to show a similar beam energy dependence

Beam energy dependence of the slope dv_1/dy near midrapidity for intermediate centrality (10-40%). Predictions from Hadron String Dynamics (HSD) [2] and UrQMD [3] are shown as shaded bands.

[1] L. Adamczyk *et al.* (STAR collaboration), Phys. Rev. Lett. **112,** 162301 (2014).
[2] W. Cassing *et al.*, arXiv:1408.4313.
[3] S. A. Bass *et al.*, Prog. Part. Nucl. Phys. **41**, 255 (1998); M. Bleicher *et al.*, J. Phys. G **25**, 1859 (1999).

Summary/Outlook

- Proton & net-proton dv_1/dy both show a prominent minimum. The net protons show a double sign-change. **No model calculation seems to capture the qualitative experimental trend for all particles at all energies**
- Charged kaons and all other produced hadrons show opposite sign of the mid-rapidity slope parameter compared to protons at the lowest collision energy, $\sqrt{s_{NN}}$ = 7.7 GeV. Transported baryon number plays a dominant role at lower collision enengies.
- In the higher energy region, $\sqrt{s_{NN}}$ > 30 GeV, all observed particles seem to show a similar beam energy dependence, and the difference among them reduces as the energy increases. Pair production becomes dominant at these energies.
- The transport model HSD, with the mean-field on, and UrQMD provide a reasonable comparison to data at the high energy region, but fail at low energy.
- The present measurements may help to further constrain the medium properties in terms of mean-field and the interplay of quark and baryon transport.