

# **Analysis Note:**

## **Anti-flow of Kaon in Au+Au Collisions at**

$$\sqrt{s_{NN}} = 3 - 3.9 \text{ GeV}$$

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### **Abstract**

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In this note, we present the measurement of anti-flow of kaons in Au+Au collisions at  $\sqrt{s_{NN}} = 3.0, 3.2, 3.5, 3.9$  GeV with the STAR experiment under its fixed target configuration at RHIC. Directed flow of  $\pi^\pm, K^\pm, K_S^0, p$ , and  $\Lambda$  are presented in different centrality, transverse momentum and rapidity intervals.  $\pi^\pm, K^\pm$ , and  $K_S^0$  show anti-flow at low  $p_T$  ( $p_T < 0.6$  GeV/c) at  $\sqrt{s_{NN}} = 3.0, 3.2, 3.5, 3.9$  GeV. And the result have been compared with JAM model. Anti-flow of kaons at low  $p_T$  could be explained by shadowing effect from spectator.

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## 1. ANALYSIS SETUP

This section describes the setup of analysis. The first part of this section introduces STAR Fixed Target(FXT) mode. Second one is dataset and event selection used in the analysis. Third, badrun rejection and centrality determination are discussed.

### 1.1. Introduction of FXT

There are two modes at RHIC-STAR, Fixed Target mode and Collider mode. FXT mode of STAR experiment covers center of mass energy( $\sqrt{s_{NN}}$ ) from 3 to 13.7 GeV, which extends the measurement to lower energy intervals. In this way, FXT mode could reach higher baryon density region(up to 750 MeV). To achieve this goal, One piece of gold foil would be fixed at the end of Time Projection Chamber(TPC) as target.[1] And the accelerated gold beam from west would collide with it. Fig. 1 shows the schematic plot for fixed target mode.

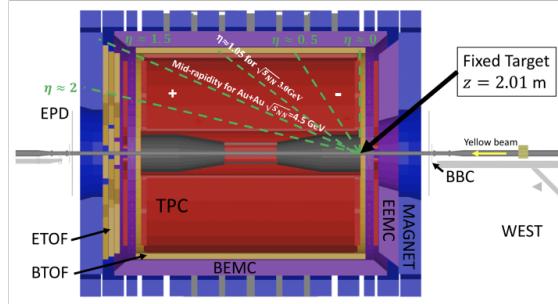


FIG. 1. The setup of Fixed Target mode at STAR.

The laboratory system should be transferred to the center of mass system, if one want to analysis physical observation conveniently. According to the Lorentz transformation, Rapidity(y) of the final state particle in the Center of Mass System(CMS) could be calculated as equation 1, where  $y_{lab}$  is rapidity of emitted particle in the laboratory frame,  $y_{beam}$  is rapidity of gold beam in the CMS. And we would discuss flow measurement based in the Center of Mass System.

$$y_{CMS} = y_{lab} - y_{beam} \quad (1)$$

TABLE I. Dataset and event cuts for  $\sqrt{s_{NN}} = 3, 3.2, 3.5, 3.9 \text{ GeV}$ .

$\sqrt{s_{NN}}$ (GeV)	production tag	library tag	trigger ID	Vz(cm)	Vr (cm)
3.0	P19ic	SL20d	620052	[198, 202]	2
3.2	?	?	?	[198, 202]	2
3.5	P21id	SL21d	720000	[198, 202]	2
3.9	?	?	?	[198, 202]	2

## 1.2. Dataset and event selection

In this analysis, four energies( $\sqrt{s_{NN}} = 3, 3.2, 3.5, 3.9 \text{ GeV}$ ) from fixed target mode are involved. The events from minimum bias trigger are selected. And vertex cut in the X and Y direction applied to exclude the events from beam pipe, vertex cut along the Z direction to ensure that selection events are from collision on the gold foil. The detailed trigger and vertex cut are summarized in the TABLE. I

## 1.3. Badrun rejection and centrality determination

Data production at STAR is run-by-run type, and the data is tagged with different run number. Run-by-run QA is necessary to reject the bad runs, which may caused by the broken detector et al. This job was finished by STAR QA group, and the badrun list used in this analysis could be found at the [summary page](#) from QA group.

Moreover, the centrality determination work is vital in Heavy Ion Collision. Glauber Monte Carlo(MC) simulation[2] would describe the reference multiplicity distribution, which is corrected by pile-up rejection and luminosity correction. The number of participant particle( $N_{part}$ ) and the number of collision particles( $N_{coll}$ ) can be extracted by the formula 2 in MC model.

$$\frac{dN_{ch}}{d\eta} = n_{pp} \left[ (1 - x) \frac{N_{part}}{2} + x N_{coll} \right] \quad (2)$$

This work was finished by STAR Centrality group, a class([StRefMultCorr](#)) is provided. One can call the class and get the refMult cut.

#### 1.4. Basic track selection

## 2. ANALYSIS METHOD

In this section, event plane reconstruction would be described firstly. Second part is identification for measured particles, including identified particles( $\pi^+$  and  $\pi^-$ ), and weak decay particles( $K_0^S$  and  $\Lambda$ ). Last one is efficiency correction, including TPC tracking efficiency, TOF matching efficiency and particle reconstruction efficiency.

### 2.1. Event plane reconstruction

Event plane method is one of common method in the anisotropic flow analysis, which could be used to estimate the reaction plane in the Heavy Ion Collision.[3] In this analysis, we used STAR detector Event Plane Detector(EPD), incorporating with Time Projection Chamber to reconstruct Event Plane(EP), where EPD is an upgrade detector in the STAR Beam Energy Scan phase II.[4] There are 12 supersectors on EPD. And 31 tiles on each supersector are connected via optical fiber bundles. The tile performance would be affected by its own quality and the signal intensity it received. So the correction for each tile is necessary, which would be introduced as follow.

Recentering and shifting method are two methods which we applied to correct the raw event plane distribution. EPD is divided to four ring groups to facilitate EP reconstruction. There are 16 rings/rows on EPD. It is divided equally to four groups, each group have four rings. Fig. 2 show groups at EPD, named as A, B, C and D. The best EP should be the one in the forward eta

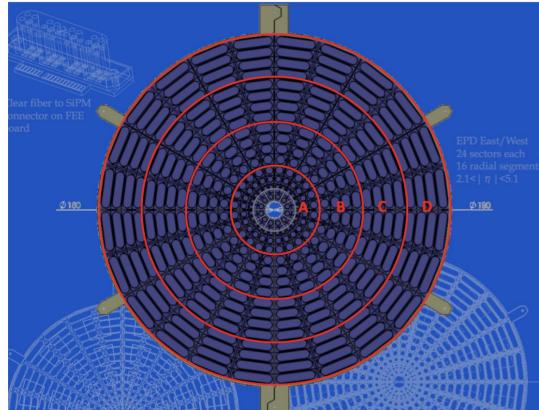


FIG. 2. The sketch of EPD groups.

range, where directed flow signal is greater than the one in middle eta range. [Analysis note](#) of one STAR published paper have approved it. We followed and chose EPD group A and B as target event plane in our analysis. In this way, we can get the largest resolution applied to our analysis according to equation 3

$$R_n \propto v_n \sqrt{M} \quad (3)$$

### 2.1.1. Recentering correction

The recentering calibration is applied to the flow vector( $\vec{Q}$ ), which could be decomposed into two components, as shown by equation 4, where  $w_i$  is EPD tile weight, using the calibrated value nMip(also known as ADC) based on the particle energy loss on each EPD tile, as shown by equation 5

$$\vec{Q} = \begin{pmatrix} Q_y \\ Q_x \end{pmatrix} = \begin{pmatrix} \sum_i w_i \sin(\phi_i) \\ \sum_i w_i \cos(\phi_i) \end{pmatrix} \quad (4)$$

$$w(\text{tile}) = \begin{cases} 0 & \text{if } nMIP < \text{threshold}(0.3) \\ \text{MAX} & \text{if } nMIP > \text{MAX}(2) \\ nMIP & \text{otherwise} \end{cases} \quad (5)$$

And the first order event plane angle could be obtained by equation 6, where  $\phi_i$  is emitted particle angle with respect to the laboratory system, sums goes over all hits from one event.

$$\Psi_1 = \tan^{-1} \frac{\sum_i w_i \sin(\phi_i)}{\sum_i w_i \cos(\phi_i)} \quad (6)$$

The recentering method is applied to the flow vertex  $\vec{Q}$ , so it's event by event calibration, Which is expressed by equation 7. The angle brackets denote averaging over all events in the same centrality and run ID.

$$\vec{Q}_{rc} = \begin{pmatrix} \vec{Q}_y - \langle \vec{Q}_y \rangle \\ \vec{Q}_x - \langle \vec{Q}_x \rangle \end{pmatrix} \quad (7)$$

### 2.1.2. Shifting correction

The shifting calibration is a mathematical method to correct the EP distribution after recentering calibration, which is based on Fourier transformation. In this analysis, a 20th order equation 8 was

implemented to the event plane distribution after recentering calibration.

$$\Psi_{1,\text{shift}} = \sum_i^N \frac{2}{i} [-\langle \sin(i\Psi_{1,rc}) \rangle \cos(i\Psi_{1,rc}) + \langle \cos(i\Psi_{1,rc}) \rangle \sin(i\Psi_{1,rc})] \quad (8)$$

The angle brackets in the equation denote averaging over all events in the same centrality and run ID. And the final EP angle after recentering and shifting calibration could be obtained by equation 9

$$\Psi_1 = \Psi_{1,rc} + \Psi_{1,\text{shift}} \quad (9)$$

Fig. 3 show event plane distribution at 3, 3.2, 3.5 and 3.9 GeV based on all EPD rings, where the black line show the raw distribution without any calibration, the blue line represents the EP after recentering calibration, and red line denote the event plane angle distribution after recentering and shifting calibration, which is "flat".

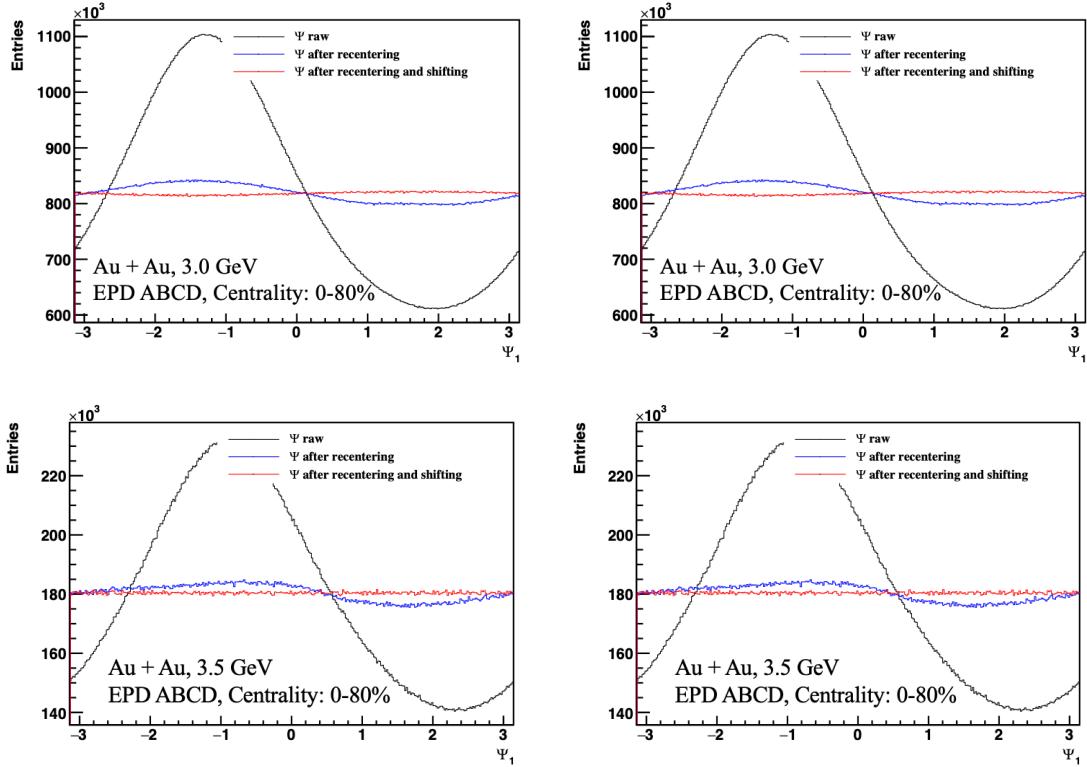


FIG. 3. The event plane distribution on EPD.

### 2.1.3. Event plane resolution

After recentering and shifting calibration, the event plane is ready for the flow calculation. While the finite multiplicity in the experiment would limit the estimation of the reaction plane angle. [5] So the event plane resolution would be brought to correct the observed flow coefficients, which could be expressed as equation 10

$$R_n = \langle \cos[n(\Psi_n - \Psi_r)] \rangle \quad (10)$$

Where  $\Psi_r$  is reaction plane angle,  $\Psi_n$  is the event plane angle. The angle brackets denote averaging over many events.

In the fixed target mode, one would not be able to get sub-events are equal, since the collision happens at the end of TPC. The resolution in different windows are not equal, one need at least three windows to determine the event plane resolution in each of them. [6] It could be expressed as

$$\langle \cos(n(\Psi_m^a - \Psi_r)) \rangle = \sqrt{\frac{\langle \cos(n(\Psi_m^a - \Psi_m^b)) \rangle \langle \cos(n(\Psi_m^a - \Psi_m^c)) \rangle}{\langle \cos(n(\Psi_m^b - \Psi_m^c)) \rangle}} \quad (11)$$

Where  $\Psi_m^a$  is the target event plane angle,  $\Psi_m^b$  and  $\Psi_m^c$  are the reference event plane angle.

In this analysis, we focus on directed flow( $v_1$ ) measurement, they are both based on first order event plane. so we substitute  $m = 1$  to the equation 11. According to the STAR published 3 GeV paper [7], One can get the largest resolution if chosen the forward eta window(EPD group A and B). We follow the method and take EPD group A and B as our target event plane. Other windows from EPD and TPC would be chosen as reference windows. They are divided as shown by Fig. 4 This figure is specific for 3.0 GeV. We note here eta could reach 2.4 for 3.2, 3.5 and 3.9 GeV data, since inner TPC was upgraded at these three energies. Two eta gaps were added in this analysis to reduce the non-flow effect. One eta gap is in the EPD group C which eta coverage is  $[-3.3, -3.0]$ (removed two EPD rings in C, here C' denotes group C after removing two rings), the other one is in the TPC which eta coverage is  $[-1.1, -1.0]$  for 3GeV, while  $[-1.15, -1.25]$  for 3.2, 3.5, and 3.9 GeV due to the wider eta coverage brought by iTPC.

The first order event plane resolution of EPD group AB at 3.0, 3.2, 3.5, and 3.9 GeV was shown by Fig. 5. EPD group AB was chosen as the target event plane, and another two reference event plane were needed according to three sub-event plane method. In this analysis, the maximum  $R_1$ (EPD-AB vs. EPD-C' and TPC-B) was chosen as default resolution to measure directed flow,

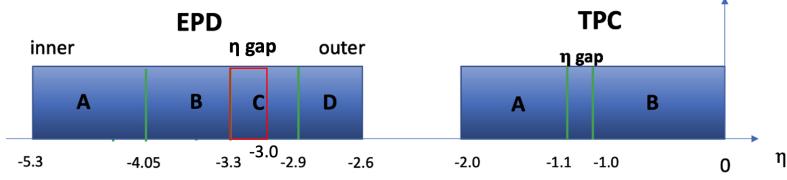


FIG. 4. The sketch of EPD and TPC groups.

which could be expressed as:

$$v_n = \frac{v_n^{\text{obs}}}{R_n} \quad (12)$$

The other two set of resolution were used to estimate the systematic uncertainty brought by resolution.

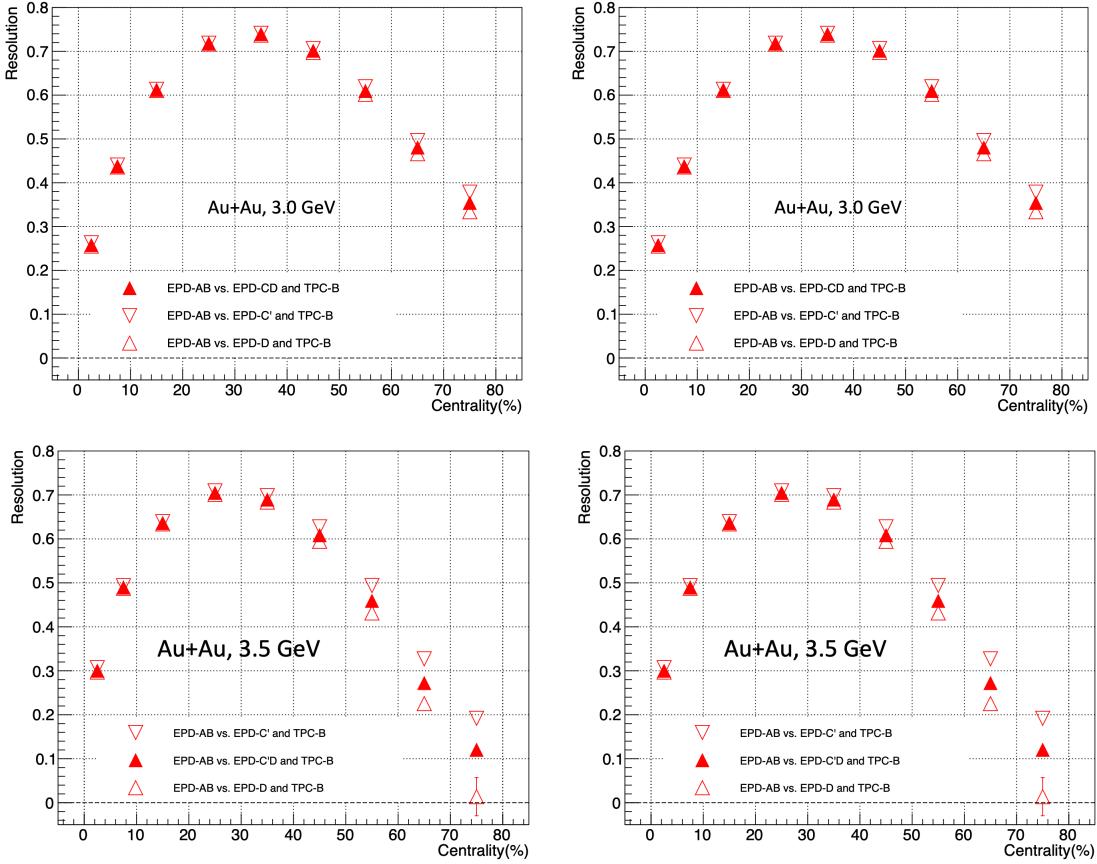


FIG. 5. The first order event plane resolution of EPD group AB at 3.0, 3.2, 3.5, and 3.9 GeV.

## 2.2. Particle identification

### 2.2.1. $\pi, K, p$ identification

Time Projection Chamber(TPC)[8] and Time of Flight(TOF)[9] were used to identify pion, kaon, and proton. The identification are based on particle ionization energy loss( $dE/dx$ ) in TPC and time of particle flight measured by TOF. The theoretic particle ionization energy loss could be described by Bichsel function, which are shown by dashed line in left panel of Fig. 6. The  $dE/dx$  value would be transfored to  $n\sigma_{particle}$  to facilitate applying the PID cut. The  $n\sigma_{particle}$  can be expressed as:

$$n\sigma_{particle} \propto \ln \left[ \left\langle \frac{dE}{dX} \right\rangle_{\text{particle}} / \left\langle \frac{dE}{dX} \right\rangle_{\text{Bichsel}} \right] \quad (13)$$

In this analysis, we take the  $n\sigma_{particle}$  shift into account which is due to detector issue and data calibration issue. For example, the  $n\sigma_{proton}$  distribution in momentum windows are shown by Fig. 7. The background and signal peak were fitted with Gaussian function, and proton purity could reach more than 95% up to momentum at 1.2 GeV/c. At higer momentum region( $p > 1.2\text{GeV}/c$ ), the signal and background peak are merged, it's unable to assure proton purity greater than 95% with TPC along. In that case, TOF was involved to help identify particle at high momentum.

The right panel of Fig. 6 show rigidity dependence of mass square( $m^2$ ) distribution measured by TOF, the  $m^2$  could be calculated by the formula:  $m^2 = p^2(1/\beta^2 - 1)$ , where velocity  $\beta = L/cT$ . At hign momentum, we used  $m^2$  distribution instead to study the particle purity. The  $m^2$  distribution is after  $n\sigma_{particle}$  cut from TPC. For example, Fig. 8 show proton  $m^2$  distribution in momentum windows after  $|n\sigma_{proton} - shift| < 3$  cut. And Student-t function was applied to fit the signal peak and the background peak. By that way, proton identification could reach  $p = 4.2 \text{ GeV}/c$ , and the purity is greater than 95%. Purity of pion and kaon is greater than 95% and 90%, respectively. The detailed PID cuts are shown by the TABLE V in the appendix for 3, 3.2, 3.5, and 3.9 GeV.

The accaptance of  $\pi, K, p$  at 3.5 GeV are shown by Fig. 9, the black box show the measured arear, where the rapidity cut is  $-1 < y_{CM} < 0$ , and  $p_T$  cut are  $0.2 < p_T < 1.6, 0.4 < p_T < 2.0$  for  $\pi/K$ , proton, respectively. For other energies, 3(Fig. 34), 3.2, and 3.9 GeV, the acceptance plots could be found in the appendix.

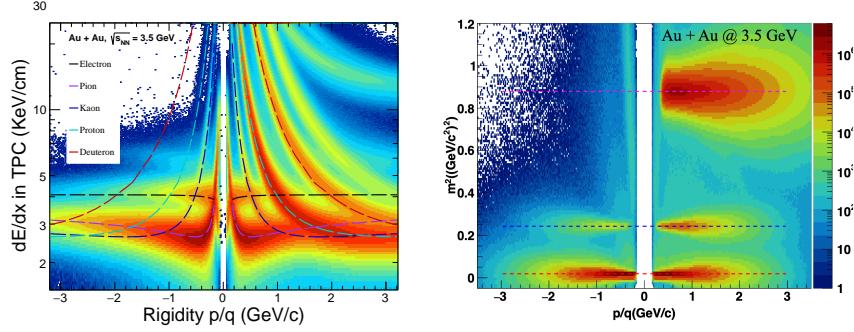


FIG. 6. Left: rigidity dependence of particle ionization energy loss in TPC, Right: rigidity dependence of particle mass square distribution measured by TOF in Au + Au collisions at  $\sqrt{s_{NN}} = 3.5$  GeV.

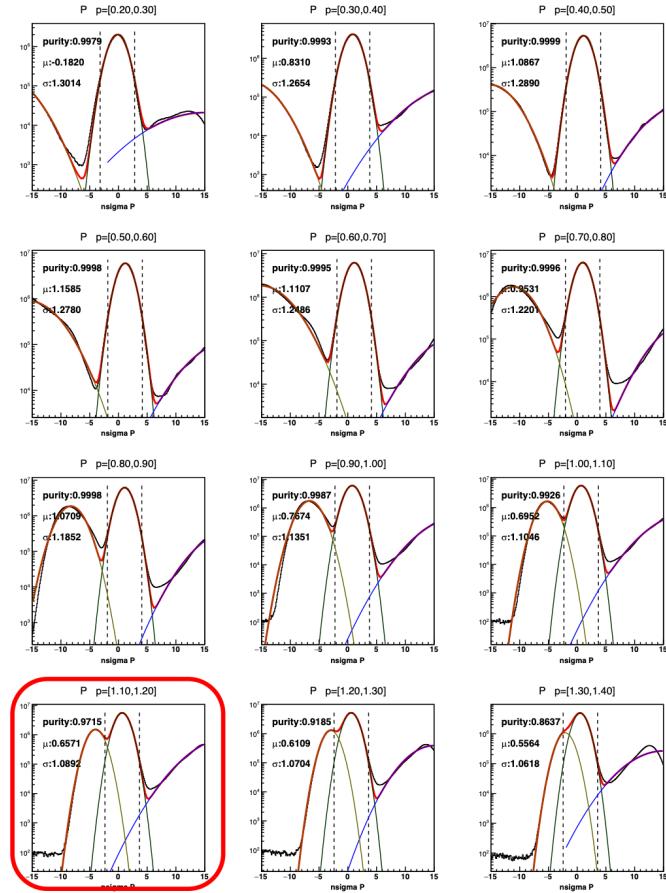


FIG. 7.  $n\sigma_{proton}$  distribution in momentum windows from TPC at  $\sqrt{s_{NN}} = 3.5$  GeV.

### 2.2.2. $K_S^0, \Lambda$ identification

For the weak decay particles  $K_S^0$  and  $\Lambda$ , they are reconstructed by Kalman Filter(KF) particle package[10], where the covariance matrix of reconstructed tracks are considered to construct a set

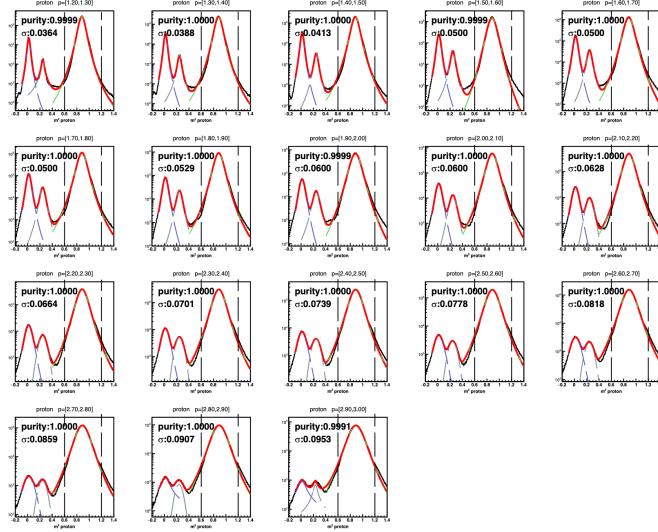


FIG. 8.  $m^2$  distribution in momentum windows from TOF at  $\sqrt{s_{NN}} = 3.5$  GeV.

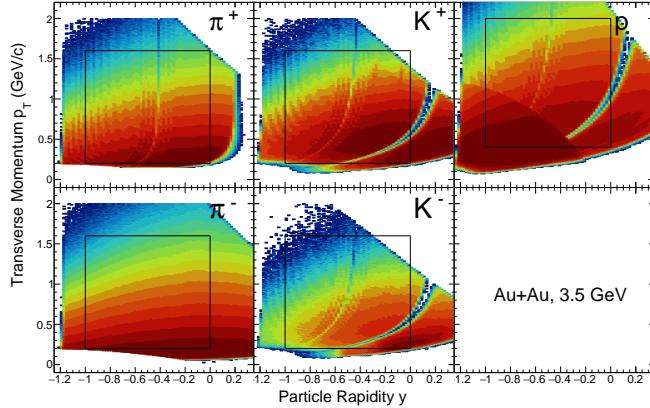


FIG. 9.  $\pi, K, p$  density distribution as function of rapidity and transverse momentum at  $\sqrt{s_{NN}} = 3.5$  GeV.

of topological variable. The track and topological cuts for daughters are listed in the TABLE. II. Note that only  $\pi^+$  was required to have  $m^2$  cut to avoid contamination from proton.

The acceptance of  $K_S^0$  and  $\Lambda$  are shown by Fig. 10. The black box show the kinematic region

Daughters' track cuts	$nHitsFit > 15$	$ n\sigma_{\pi,p} - shift  < 3$ , $\pi^+ : -0.06 < m^2 < 0.1$	$0.04 < Error(dE/dx) < 0.12$	$nHitsdEdx > 5$
Topological cuts	$\chi^2_{prim,\pi} < 10$	$\chi^2_{prim,p} < 10$		

TABLE II. Daughters' track cuts and topological cuts applied for  $K_S^0, \Lambda$  in KF particle

chosen in this analysis, where the rapidity cut is  $-1 < y_{CM} < 0$ , and  $p_T$  cut are  $0.2 < p_T < 1.6, 0.4 < p_T < 2.0$  for  $K_S^0$  and  $\Lambda$ , respectively. The acceptance plots could be found in the appendix for other energies(3GeV(Fig. 35), 3.2 GeV, 3.9 GeV).

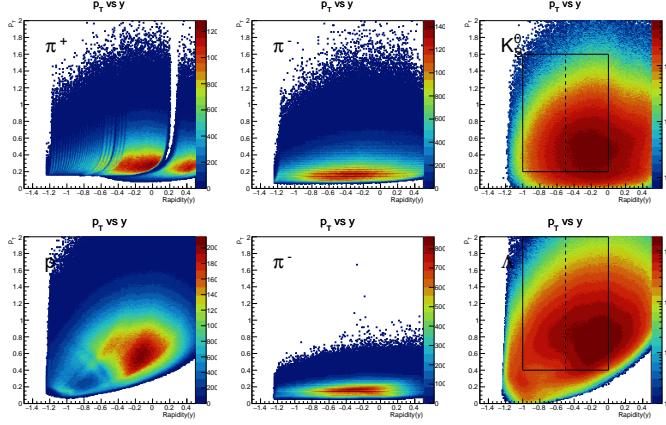


FIG. 10.  $K_S^0$  and  $\Lambda$ (and their daughters) density distribution as function of rapidity and transverse momentum at  $\sqrt{s_{NN}} = 3.5$  GeV.

### 2.3. Efficiency correction

The efficiency correction would help to restore the particle which was not tracked by the detector. In this analysis, TPC tracking efficiency and TOF matching efficiency are taken into account for  $\pi, K$ , and  $p$ . For the weak decay particles( $K_S^0$  and  $\Lambda$ ) which are reconstructed by KF particle package, the reconstruction efficiency was applied instead.

The GEANT model[11] was used to simulate particle going through the detector based on Monte Carlo method, which could estimate the particle number loss due to the detector acceptance and the efficiency of reconstructing particle track. For  $K_S^0$  and  $\Lambda$ , the GEANT model can also estimate the particle reconstruction efficiency.

The TPC tracking efficiency as function of rapidity and transverse momentum could be obtained by the formula 14

$$\epsilon_{TPC}(p_T, y) = \frac{\text{Number of Real Tracks}}{\text{Number of MC Tracks}} \quad (14)$$

The embedding data used in this analysis could be found at the RCF:

`/star/u/xgn1992/Strangeness/Phi/3p85GeV_fixTarget/SL19e/Simulation/Embedding`  
for 3 GeV, `/star/data105/embedding/production_4p59_fixedTarget_2019` for 3.2 GeV.

The TPC tracking efficiency for  $\pi, K, p$  are shown by Fig. 11 at 3.2 GeV. The black box show the measured rapidity and transverse momentum interval, where the rapidity cut is  $-1 < y_{CM} < 0$ , and  $p_T$  cut are  $0.2 < p_T < 1.6, 0.4 < p_T < 2.0$  for  $\pi/K$  and  $p$ , respectively. For other energies, the TPC tracking efficiency can be found in the appendix.(3GeV(Fig 36), 3.5GeV, 3.9GeV)

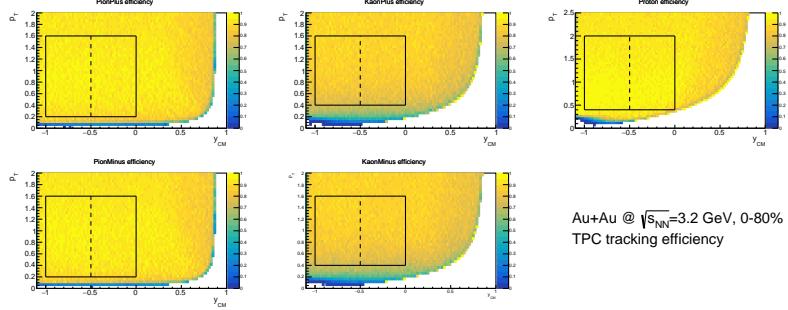


FIG. 11. TPC tracking efficiency of  $\pi, K, p$  as function of rapidity  $y$  and transverse momentum  $p_T$  at  $\sqrt{s_{NN}} = 3.2$  GeV.

The TOF can improve the particle identification capability at high momentum region, which is necessary for kaon identification, discussed in the PID section. While some particles which have tracks in TPC can not travel into TOF, and are not recorded by TOF. The TOF matching efficiency could compensate to the un-recorded part, which can be expressed by the formula 15. Note that TPC tracks are required within  $|n\sigma_{particle} - shift| < 3$ , and TOF tracks just are required the TOF match flag is greater than zero.

$$\epsilon_{TPC}(p_T, y) = \frac{\text{Number of TOF Tracks}}{\text{Number of TPC Tracks}} \quad (15)$$

The TOF matching efficiency for  $\pi, K, p$  are shown by Fig. 12 at 3.2 GeV. The black box show the measured rapidity and transverse momentum interval, where the rapidity cut is  $-1 < y_{CM} < 0$ , and  $p_T$  cut are  $0.2 < p_T < 1.6, 0.4 < p_T < 2.0$  for  $\pi/K$  and  $p$ , respectively. For other energies, the TOF matching efficiency can be found in the appendix.(3GeV(Fig 37), 3.5GeV, 3.9GeV)

The reconstruction efficiency for  $K_S^0$  and  $\Lambda$  can be obtained by the formula 16, which are shown by Fig. 13 at 3.2 GeV. The black box show the measured rapidity and transverse momentum interval, where the rapidity cut is  $-1 < y_{CM} < 0$ , and  $p_T$  cut are  $0.2 < p_T < 1.6, 0.4 < p_T < 2.0$  for  $K_S^0$  and  $\Lambda$ , respectively. Note that the track and topological cuts applied are identical with identification cuts which is shown by the TABLE. II. For other energies, the TPC tracking

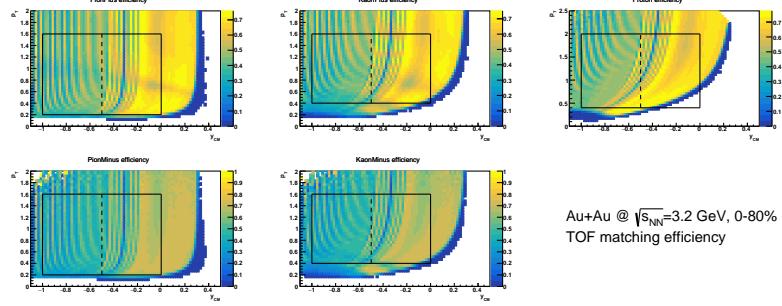


FIG. 12. TOF matching efficiency of  $\pi, K, p$  as function of rapidity  $y$  and transverse momentum  $p_T$  at  $\sqrt{s_{NN}} = 3.2$  GeV.

efficiency can be found in the appendix.(3GeV(Fig 38), 3.5GeV, 3.9GeV)

$$\epsilon(p_T, y) = \frac{\text{Number of Reconstructed Tracks}}{\text{Number of MC Tracks}} \quad (16)$$

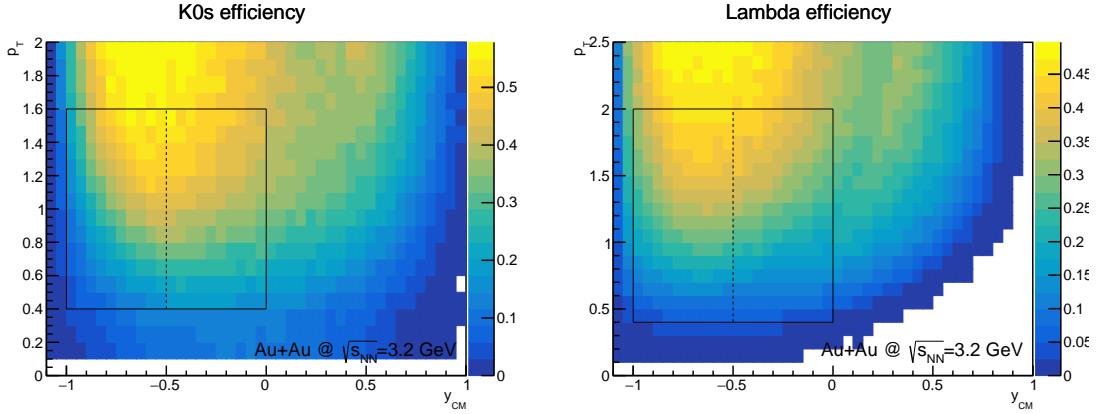


FIG. 13. Reconstruction efficiency of  $K_S^0$ (Left),  $\Lambda$ (Right) as function of rapidity  $y$  and transverse momentum  $p_T$  at  $\sqrt{s_{NN}} = 3.2$  GeV.

### 3. RESULTS

In this section,  $v_1$  of  $\pi, K, p, K_S^0$  and  $\Lambda$  are presented as function of rapidity and transverse momentum at  $\sqrt{s_{NN}} = 3.0, 3.2, 3.5, 3.9$  GeV.  $\pi, K, p v_1$  were extracted based on event plane method,  $K_S^0$  and  $\Lambda v_1$  were extracted by invariant mass method. And the systematic uncertainty study was involved at the end of section.

### 3.1. Directed flow of $\pi$ , $K$ , $p$

#### 3.1.1. Rapidity dependence of $v_1$

Fig. 14 shows rapidity dependence of pions, kaons, and proton  $v_1$  within 0-10%, 10-40%, 40-60% centrality at  $\sqrt{s_{NN}} = 3.5$  GeV, where the  $p_T$  cut are  $0.2 < p_T < 1.6$   $GeV/c$ ,  $0.4 < p_T < 1.6$   $GeV/c$ ,  $0.4 < p_T < 2.0$   $GeV/c$  for pions, kaons, and proton, respectively.

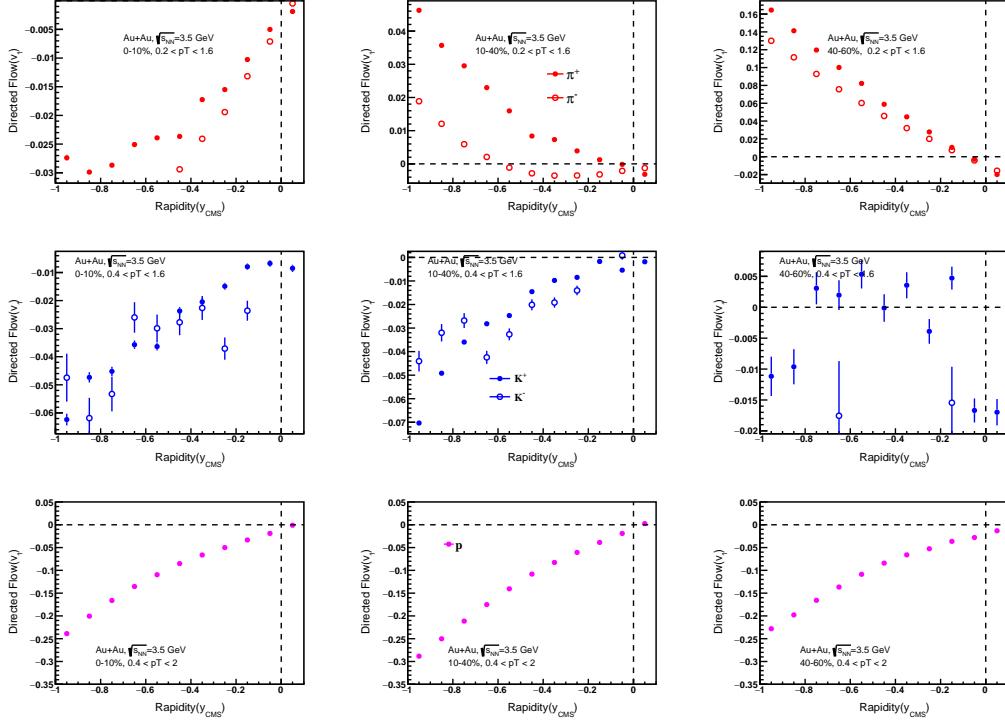


FIG. 14.  $v_1$  of pions, kaons, and proton as function of rapidity at  $\sqrt{s_{NN}} = 3.5$  GeV.

#### 3.1.2. Transverse momentum dependence of $v_1(y)$

Fig. 15 shows rapidity dependence of pion  $v_1$  within  $p_T$  windows in 10-40% centrality at  $\sqrt{s_{NN}} = 3.5$  GeV. And results in other centralities could be found in the appendix(0-10%(Fig. 40), 40-60%(Fig. 39)) Note that the solid and dashed line in the plots are cubic function:  $v_1(y) = a*y + b*y^3$ . The coefficient of the linear term "a" is so called  $v_1$  slope in the mid-rapidity( $dv_1/dy|_{y=0}$ ).

The  $p_T$  dependence of  $v_1$  slope is summarized in the Fig. 16 for  $\sqrt{s_{NN}} = 3.5$  GeV. Pion  $v_1$  strength in the mid-rapidity show strong  $p_T$  and centrality dependence, in the very-central

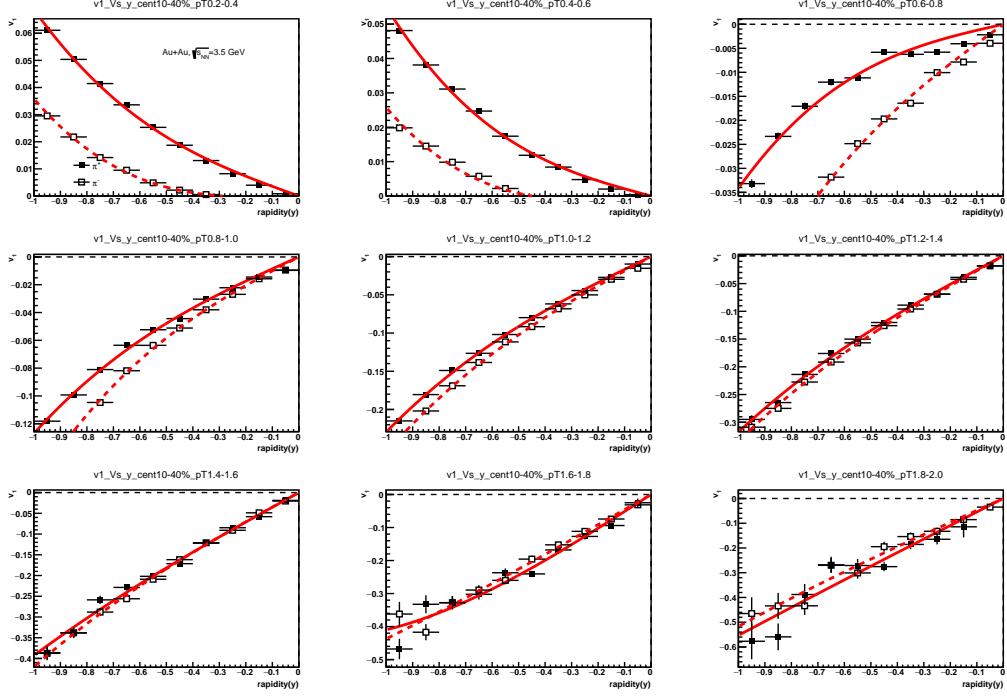


FIG. 15.  $v_1$  of pions as function of rapidity within  $p_T$  windows in 10-40% centrality at  $\sqrt{s_{NN}} = 3.5$  GeV.

collisions(0-10%), there is no anti-flow(negative  $v_1$  slope) at low  $p_T$  for pions, while the slopes at low  $p_T$  turn to negative in the mid-central and peripheral collisions. In particular, the negative slopes are largest in magnitude in the peripheral collisions. The centrality dependence of  $v_1$  slope indicates that the pion anti-flow at low  $p_T$  is due to shadowing effect from spectator.

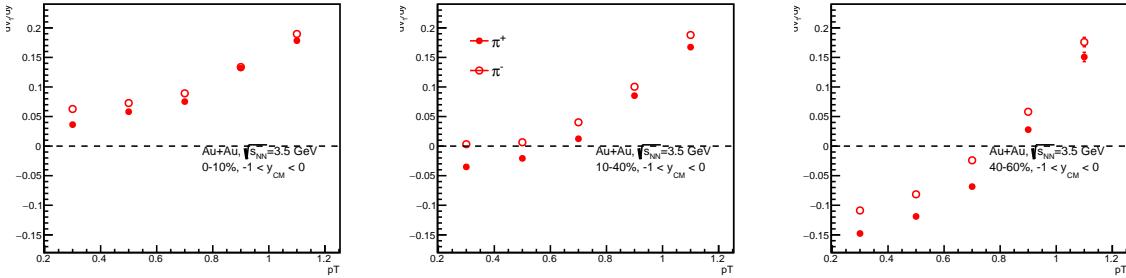


FIG. 16.  $dv_1/dy|_{y=0}$  of pions as function of  $p_T$  at  $\sqrt{s_{NN}} = 3.5$  GeV.

Fig. 17 and Fig. 18 show  $p_T$  dependence of  $v_1$  slope for kaons and proton, respectively. The fitting plots could be found in the appendix.(Kaons:0-10%(Fig. 43), 10-40%(Fig. 42), 40-60%(Fig. 41). proton: 0-10%(Fig. 46), 10-40%(Fig. 45), 40-60%(Fig. 44)). Kaons show anti-flow at low  $p_T$  in the three centralities, while proton baryon didn't show anti-flow at low pT(positive

slope in the three centralities). The particle species dependence implies that the shadowing effect impact on the lighter meson and result in anti-flow at low  $p_T$ . The heavy baryon may go through the participant matter and remaining spectator without suffering strong shadowing effect as mesons.

For other energies, Fig. 47, Fig. 48, and Fig. 49 in the appendix show  $p_T$  dependence of  $v_1$  slope for pions, kaons, and proton at  $\sqrt{s_{NN}} = 3.0$  GeV, respectively.

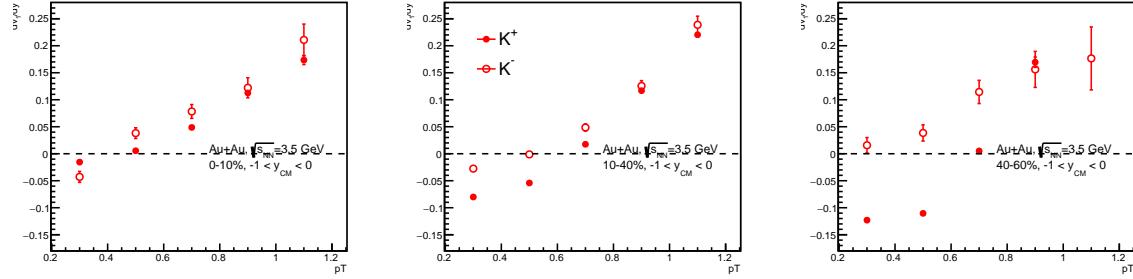


FIG. 17.  $dv_1/dy|_{y=0}$  of kaons as function of  $p_T$  at  $\sqrt{s_{NN}} = 3.5$  GeV.

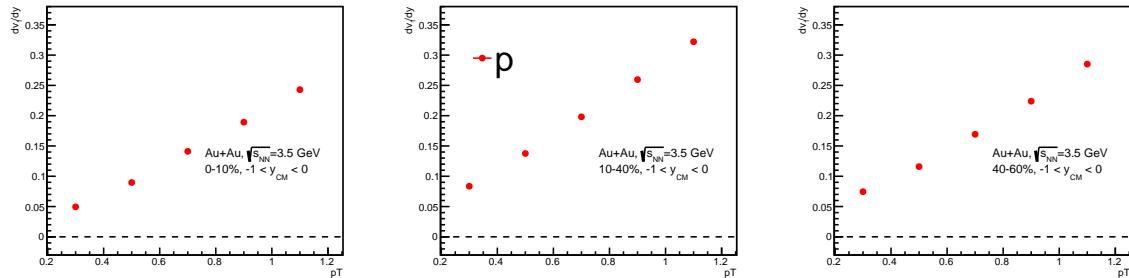


FIG. 18.  $dv_1/dy|_{y=0}$  of proton as function of  $p_T$  at  $\sqrt{s_{NN}} = 3.5$  GeV.

### 3.1.3. Systematic uncertainty

The systematic uncertainty study could take random uncertainties into account [12], which are brought by detector effect, particle identification, and flow measurement method, etc. In this analysis, we take track quality cuts (DCA and nHitsFit), PID cuts ( $n\sigma_{particle}$  and  $m^2$ ), and resolution as systematic uncertainty sources. TABLE III show the systematic uncertainty sources chosen for directed measurement of  $\pi$ ,  $K$ ,  $p$ . We assume that these sources are uncorrelated. According to Barlow Test [12], the differences between the default source and the variation are required to be

Cuts	Default	var1	var2
DCA(<)	3	1	2
nHitsFit(>)	15	20	25
$n\sigma_{particle}(<)$	3	2	2.5
$m_\pi^2$	[-0.1,0.15]	[-0.05,0.1]	
$m_K^2$	[0.16,0.36]	[0.18,0.32]	
$m_p^2$	[0.6, 1.2]	[0.7, 1.1]	
$R_{11}$	EPD-C'	EPD-D	

TABLE III. Systematic uncertainty sources for  $\pi$ , K, p, Note that EPD-C' is EPD-AB vs. EPD-C' and TPC-B, and EPD-D is EPD-AB vs. EPD-D and TPC-B, which are shown in the Fig. 5

smaller than the one of their statistical uncertainties, otherwise it would not be taken as systematic uncertainty since the statistical fluctuation dominants. At last, the maximum deviation from the default value was chosen as the systematic uncertainty. The total systematic uncertainties could be obtained by the equation 17.

$$sys.Unc_{total} = \sqrt{\left(y_{DCA} - y_{def}\right)^2 + \left(y_{nHitsFit} - y_{def}\right)^2 + \left(y_{n\sigma} - y_{def}\right)^2 + \left(y_{m^2} - y_{def}\right)^2 + \left(y_{Res} - y_{def}\right)^2} \quad (17)$$

Fig. 19 illustrates the rapidity dependence of  $v_1$  for pions from various systematic sources at  $\sqrt{s_{NN}} = 3.5$  GeV.  $v_1$  of pions in the mid-central collisions are shown by Fig. 20, where the bands stand for the systematic errors. And Fig. 21 show  $v_1(y)$  of  $\pi^+$  within narrow  $p_T$  windows, the  $v_1$  slopes extracted in the mid-rapidity are summarized with Fig. 22. At last, Fig. 23 illustrates  $p_T$  dependence of  $v_1$  slope for pions, where  $\pi^+$  shows anti-flow at low  $p_T$ ,  $\pi^-$  shows positive slopes. It might be explained by Columb effect. For other particles(kaons and proton) and other energies, the similary plots could be found in the appendix.

### 3.2. Directed flow of $K_S^0, \Lambda$

Invariant mass method is applied to extract  $v_1$  of  $K_S^0$  and  $\Lambda$ . The ideal of this method is to seperate  $v_1$  of signal from backgroud, where the  $v_1$  of signal and backgroud could be expressed as equation 18. Note that "Sig" denotes the signal yield, "Bg" denotes the backgroud yield, and  $v_1$

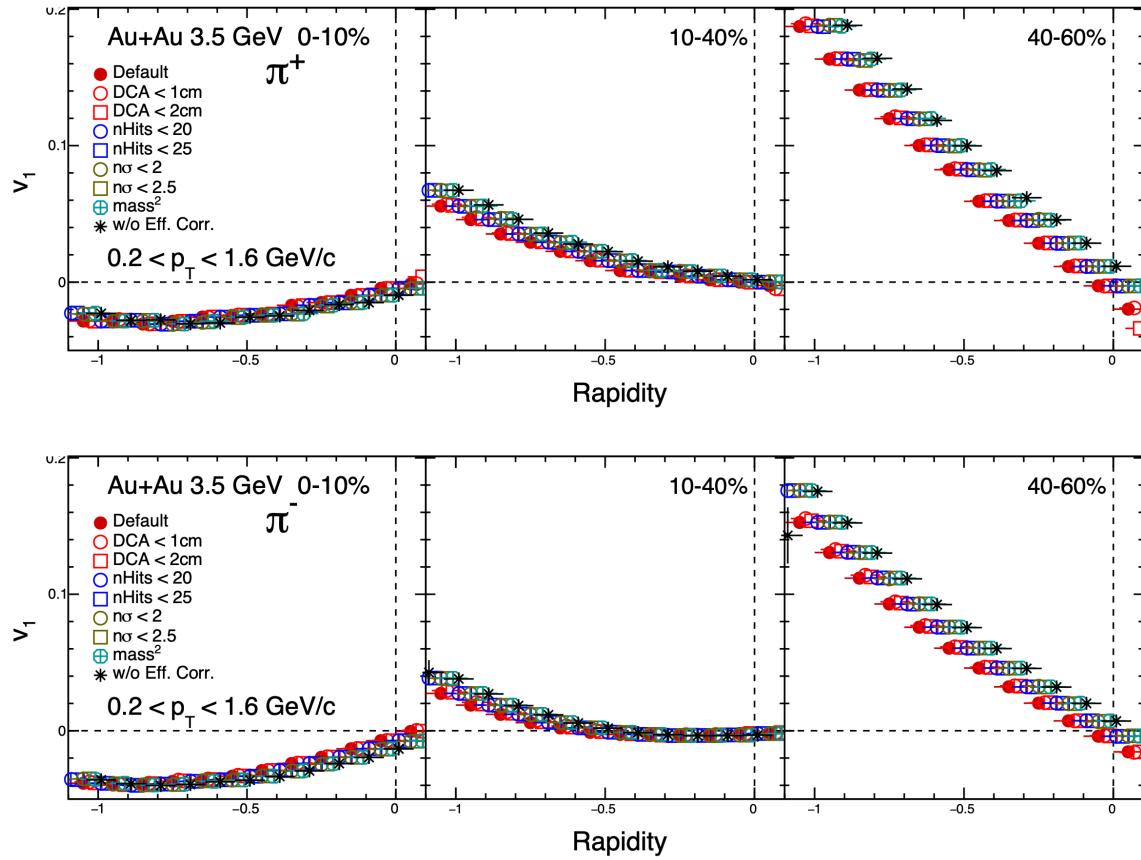


FIG. 19.  $v_1$  of pions as function of rapidity from systematic sources at  $\sqrt{s_{NN}} = 3.5$  GeV.

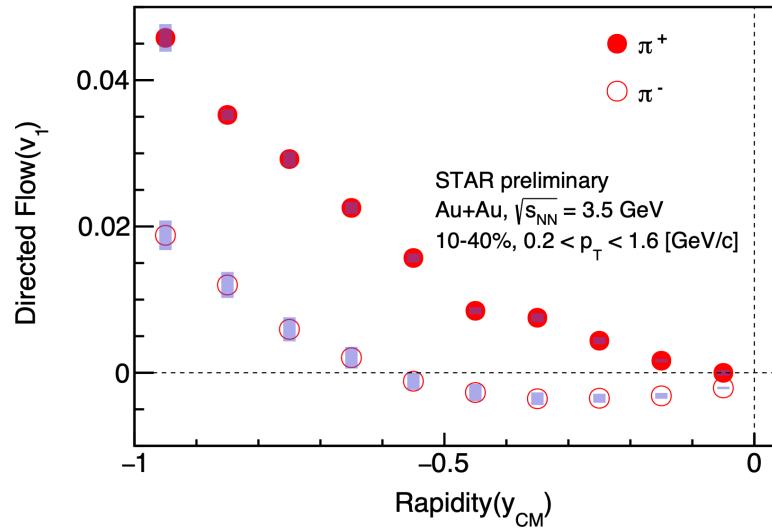


FIG. 20.  $v_1$  of pions as function of rapidity at  $\sqrt{s_{NN}} = 3.5$  GeV.

of background is taken as the second order polynomial function,  $v_1^{Sig+Bg}$  is calculated by  $v_1^{Sig+Bg} = <$

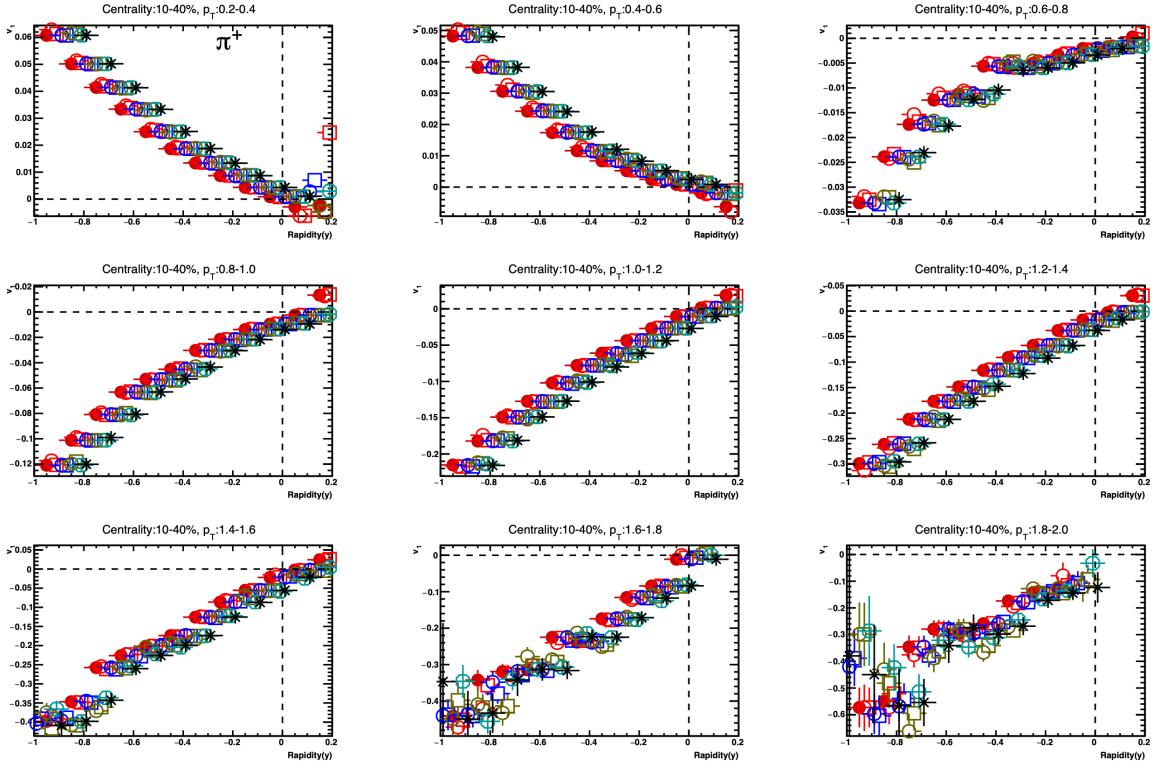


FIG. 21.  $v_1$  of  $\pi^+$  as function of rapidity within  $p_T$  windows at  $\sqrt{s_{NN}} = 3.5$  GeV.

$\cos(\phi - \Psi_{EP}) > /R_1$ . Then,  $v_1^{Sig}$  in various rapidity bins could be extracted by fitting the invariant mass distribution, which are shown by Fig. 24

$$v_1^{Sig+Bg}(m_{inv}) = \frac{Sig}{Sig + Bg} v_1^{Sig} + \frac{Bg}{Sig + Bg} v_1^{Bg} \quad (18)$$

### 3.2.1. Rapidity dependence of $v_1$

Fig. 25 shows rapidity dependence of  $K_S^0$  and  $\Lambda$   $v_1$  within 10-40% centrality at  $\sqrt{s_{NN}} = 3.5$  GeV, where the  $p_T$  cut are  $0.4 < p_T < 1.6$  GeV/c,  $0.4 < p_T < 2.0$  GeV/c for  $K_S^0$  and  $\Lambda$ , respectively.

### 3.2.2. Transverse momentum dependence of $v_1(y)$

Fig. 26 shows rapidity dependence of  $K_S^0$  and  $\Lambda$   $v_1$  within  $p_T$  windows in 10-40% centrality at  $\sqrt{s_{NN}} = 3.5$  GeV. Note that the solid and dashed line in the plots are cubic function:  $v_1(y) = a * y + b * y^3$ . The coefficient of the linear term "a" is so called  $v_1$  slope in the mid-rapidity( $dv_1/dy|_{y=0}$ ).

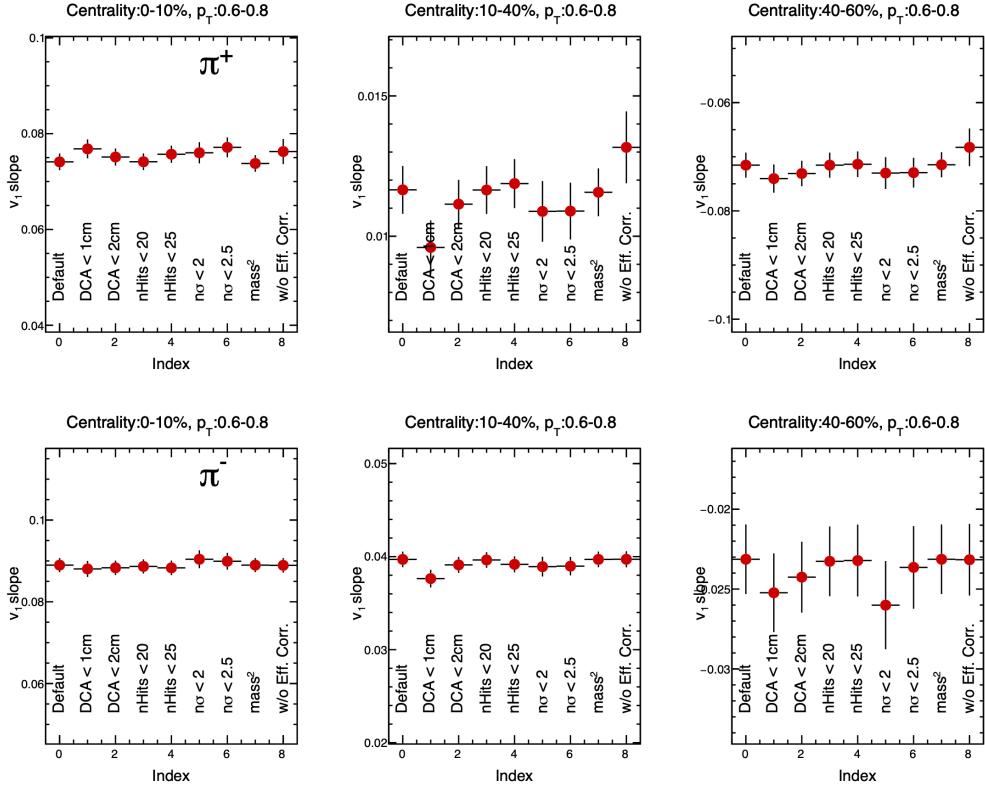


FIG. 22.  $v_1$  slope of pions as function of systematic sources at  $\sqrt{s_{NN}} = 3.5$  GeV.

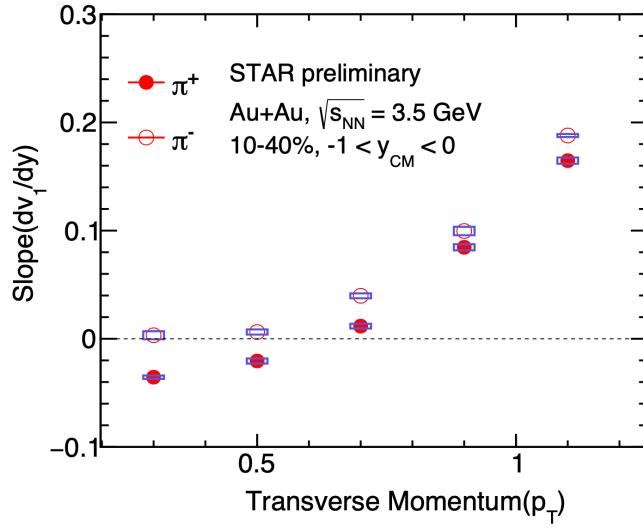


FIG. 23.  $v_1$  slope of pions as function of transverse momentum at  $\sqrt{s_{NN}} = 3.5$  GeV.

Fig. 27 show  $p_T$  dependence of  $v_1$  slope for  $K_S^0$  and  $\Lambda$ , respectively.  $K_S^0$  show negative  $v_1$  slopes at low  $p_T$  ( $p_T < 0.6$  GeV/c), which behaviors like charged kaons, while there is no anti-flow for  $\Lambda$

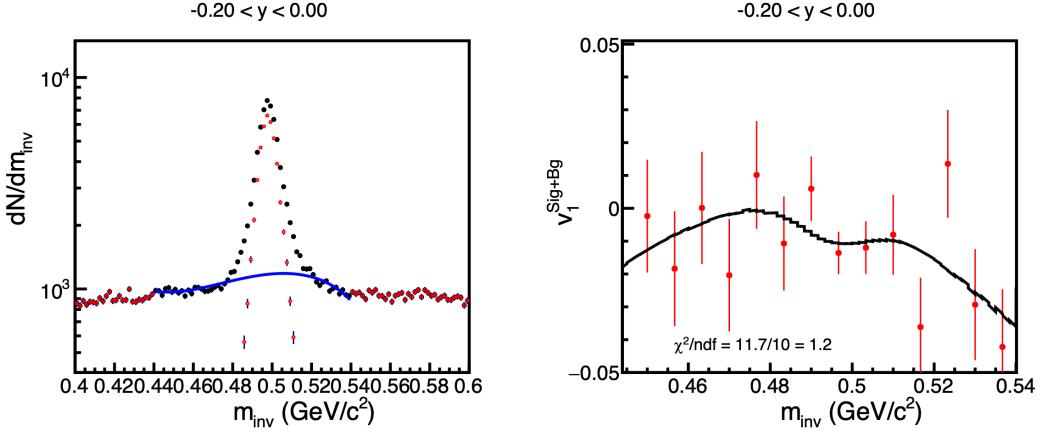


FIG. 24. Invariant mass distribution of  $K_S^0$  in 10-40% centrality at  $\sqrt{s_{NN}} = 3.5$  GeV.

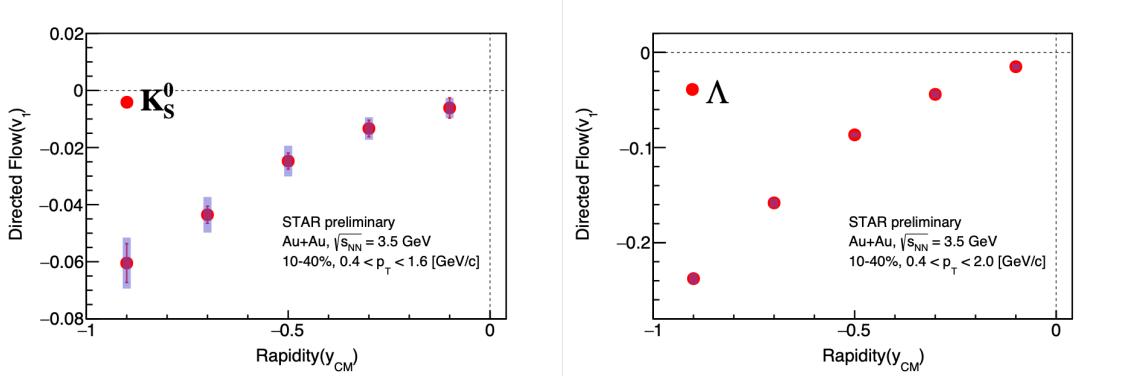


FIG. 25.  $v_1$  of  $K_S^0$  and  $\Lambda$  as function of rapidity at  $\sqrt{s_{NN}} = 3.5$  GeV.

at low  $p_T$ .

### 3.2.3. Systematic uncertainty

For systematic uncertainty estimate of  $K_S^0$  and  $\Lambda$   $v_1$ , which are reconstructed by KF particle package, we take track quality cut (nHitsFit), PID cuts ( $n\sigma_{particle}$  and  $\chi^2_{prim}$  of daughters), and resolution as systematic uncertainty sources. TABLE IV show the systematic uncertainty sources chosen for directed measurement of  $\pi$ ,  $K$ ,  $p$ . We assume that these sources are uncorrelated. According to Barlow Test [12], the differences between the default source and the variation are required to be smaller than the one of their statistical uncertainties, otherwise it would not be taken as systematic uncertainty since the statistical fluctuation dominants. At last, the maximum deviation from the default value was chosen as the systematic uncertainty. The total systematic

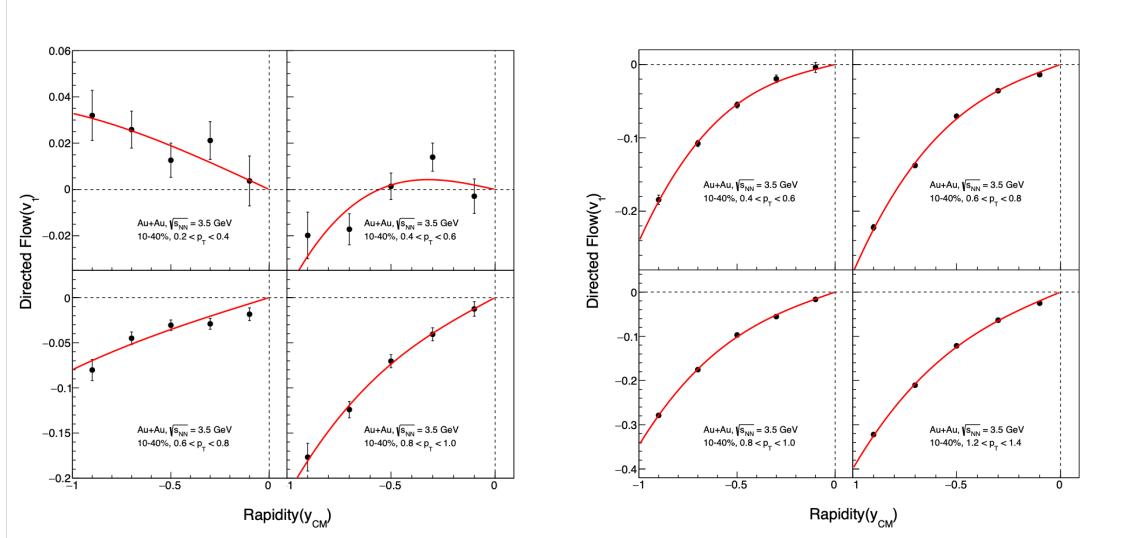


FIG. 26.  $v_1$  of  $K_S^0$  (left) and  $\Lambda$  (right) as function of rapidity within  $p_T$  windows in 10-40% centrality at  $\sqrt{s_{NN}} = 3.5$  GeV.

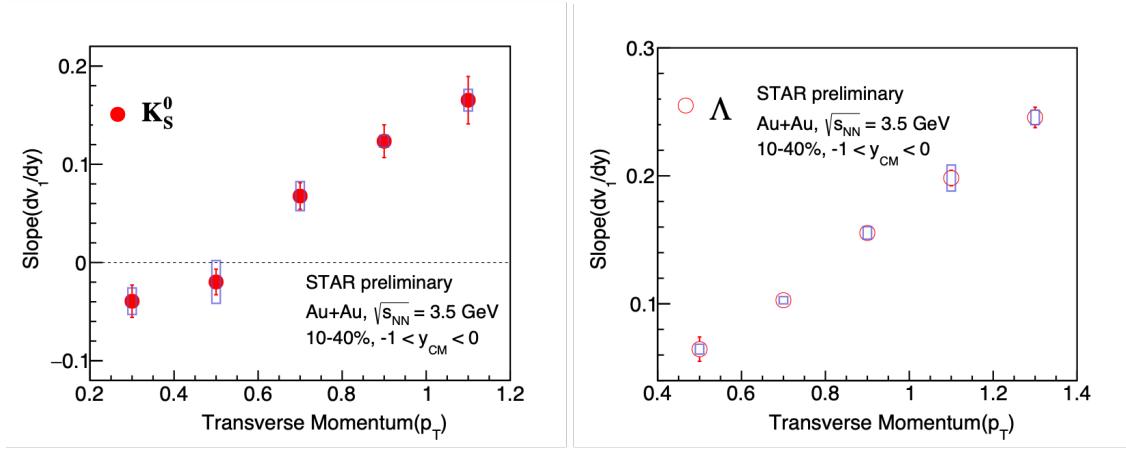


FIG. 27.  $v_1$  slope of  $K_S^0$  (left) and  $\Lambda$  (right) as function of  $p_T$  in 10-40% centrality at  $\sqrt{s_{NN}} = 3.5$  GeV.

uncertainties could be obtained by adding uncertainties brought from each sources in quadrature, which could be expressed as the equation 19.

$$sys.Unc_{total} = \sqrt{\left(y_{nHitsFit} - y_{def}\right)^2 + \left(y_{\chi_{prim}^2} - y_{def}\right)^2 + \left(y_{n\sigma} - y_{def}\right)^2 + \left(y_{Res} - y_{def}\right)^2} \quad (19)$$

Fig. 28 and Fig. 29 illustrate the rapidity dependence of  $v_1$  from various systematic sources at  $\sqrt{s_{NN}} = 3.5$  GeV for  $K_S^0$  and  $\Lambda$ , respectively. Fig. 30 and Fig. 31 show  $v_1(y)$  within narrow  $p_T$  windows of  $K_S^0$  and  $\Lambda$ , respectively. The  $v_1$  slopes extracted in the mid-rapidity are summarized

Cuts	Default	var1	var2
nHitsFit(>)	15	20	25
$\chi^2_{prim}$	10	5	15
$n\sigma_{particle}$	3	2	2.5
$R_{11}$	EPD-C'	EPD-D	

TABLE IV. Systematic uncertainty sources for  $K_S^0$  and  $\Lambda$ . Note that EPD-C' is EPD-AB vs. EPD-C' and TPC-B, and EPD-D is EPD-AB vs. EPD-D and TPC-B, which are shown in the Fig. 5

with Fig. 32 and Fig. 33.

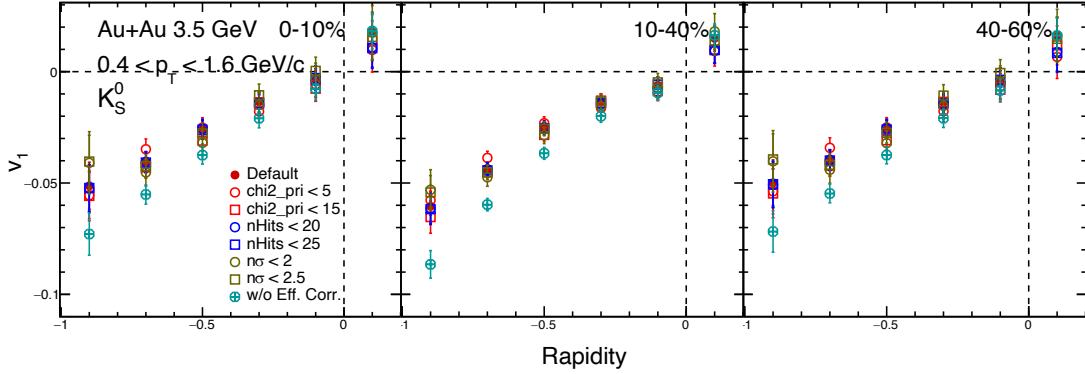


FIG. 28.  $v_1$  of  $K_S^0$  as function of rapidity from systematic sources at  $\sqrt{s_{NN}} = 3.5$  GeV.

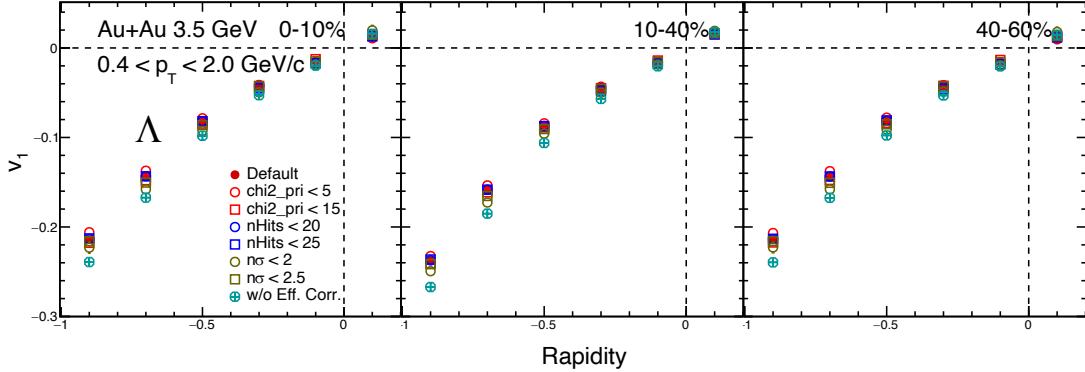


FIG. 29.  $v_1$  of  $\Lambda$  as function of rapidity from systematic sources at  $\sqrt{s_{NN}} = 3.5$  GeV.

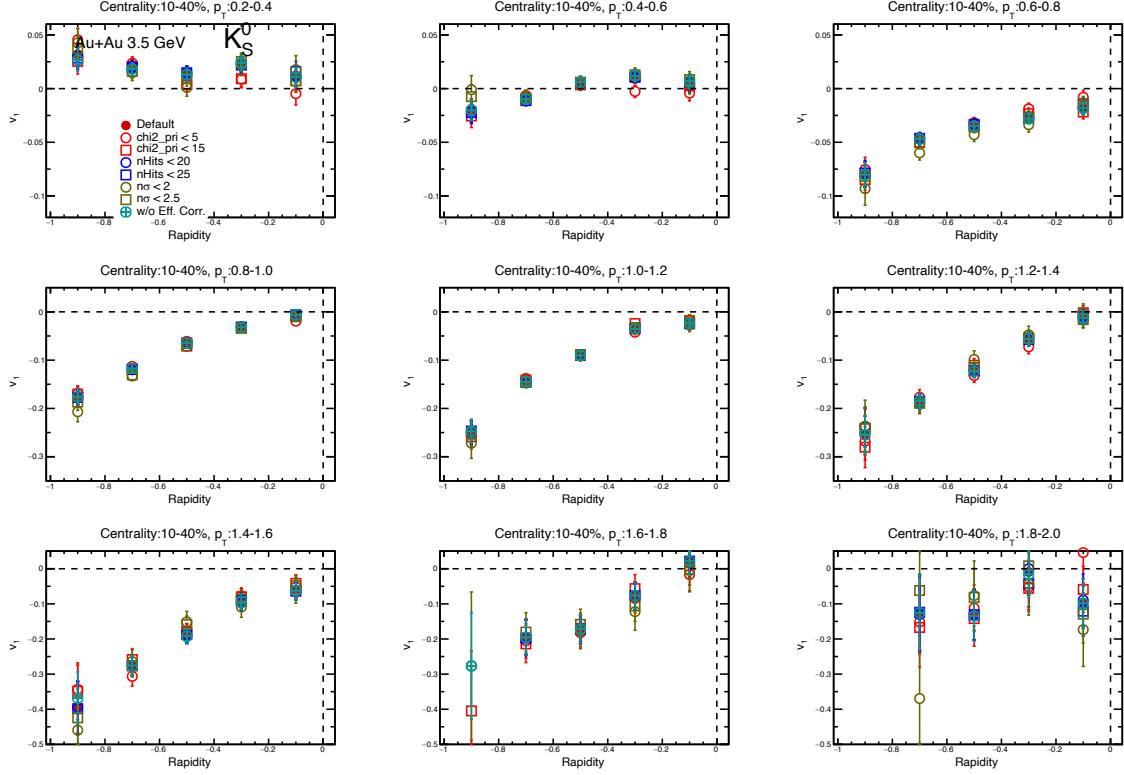


FIG. 30.  $v_1$  of  $K_S^0$  as function of rapidity within  $p_T$  windows at  $\sqrt{s_{NN}} = 3.5$  GeV.

#### 4. SUMMARY

We present directed flow measurement for  $\pi^\pm$ ,  $K^\pm$ ,  $p$  and  $K_S^0$ ,  $\Lambda$  in Au + Au collisions at  $\sqrt{s_{NN}} = 3.0$ , 3.2, 3.5, and 3.9 GeV. The  $p_T$  dependence of  $v_1$  slope in the mid-rapidity shows that there is anti-flow at low  $p_T$  ( $p_T < 0.6$  GeV/c) for  $\pi^+$  and kaons ( $K^\pm$ ,  $K_S^0$ ) in the mid-central 10 - 40% collisions. By contrast, the baryons (proton and lambda) don't show anti-flow low  $p_T$ . Moreover, the centrality dependence of  $dv_1/dy$  shows that more negative  $v_1$  slope could be observed in the more peripheral collisions. It indicates that the anti-flow might be related with spectator shadowing effect. At last, the JAM model calculation can reproduce anti-flow at low  $p_T$  without incorporating kaon potential. With the data measurement and model calculation, we conclude that the spectator shadowing effect can lead to anti-flow of kaons, no need of the earlier claimed kaon potential.

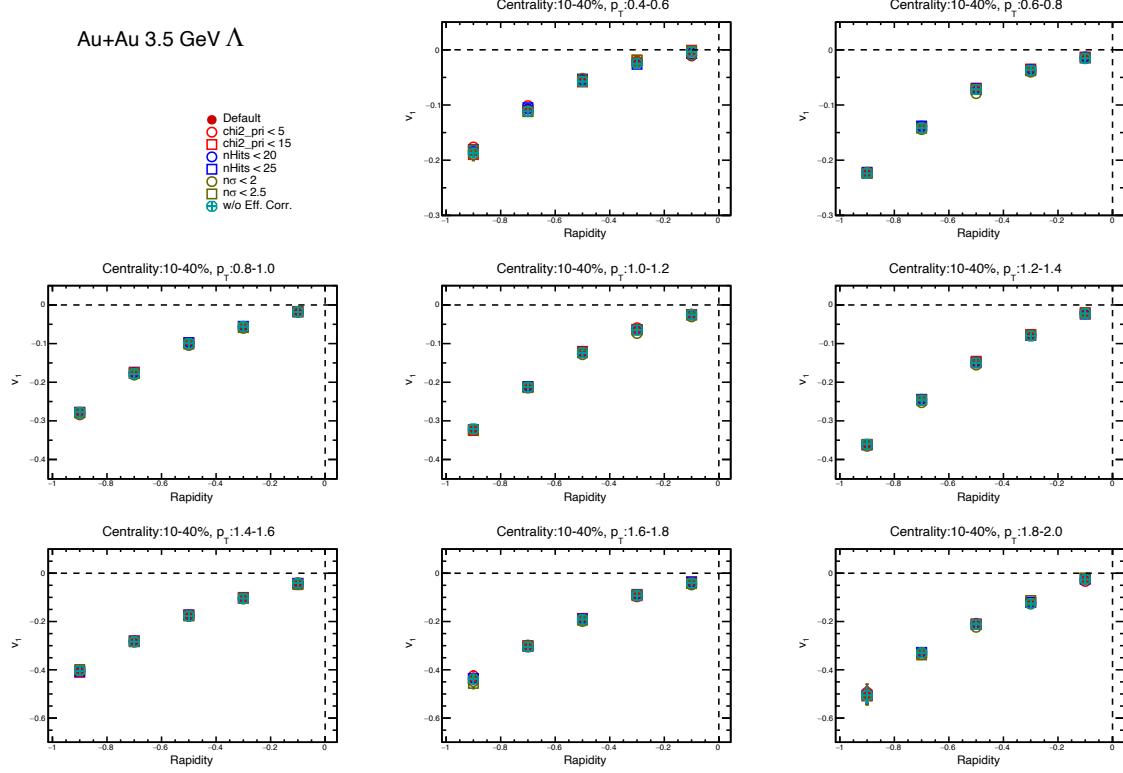


FIG. 31.  $v_1$  of  $\Lambda$  as function of rapidity within  $p_T$  windows at  $\sqrt{s_{NN}} = 3.5$  GeV.

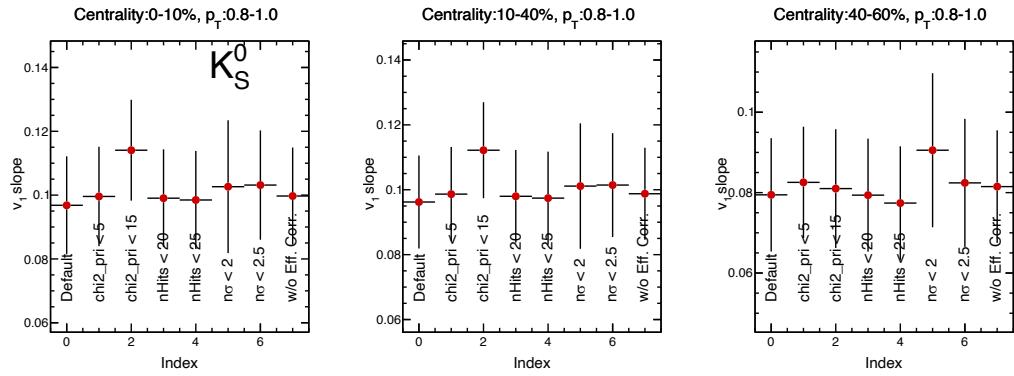


FIG. 32.  $v_1$  slope of  $K_S^0$  as function of systematic sources at  $\sqrt{s_{NN}} = 3.5$  GeV.

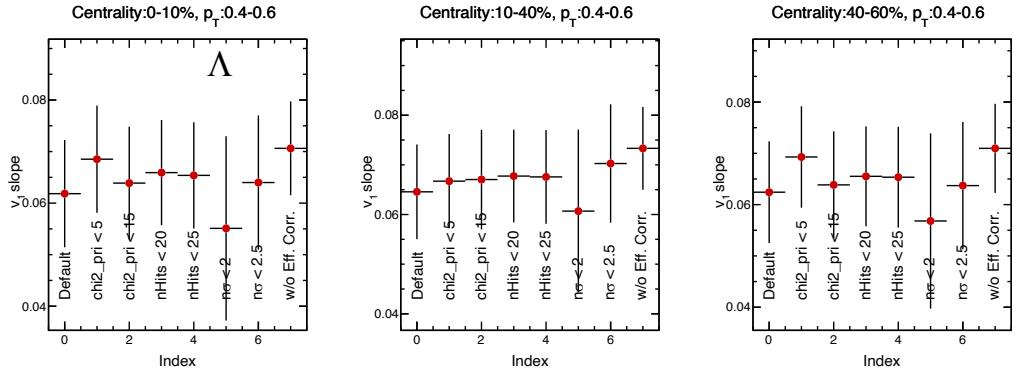


FIG. 33.  $v_1$  slope of  $\Lambda$  as function of systematic sources at  $\sqrt{s_{NN}} = 3.5$  GeV.

	$\pi^+$	$\pi^-$	$K^+$	$K^-$	$p$
3.0 GeV	$ n\sigma_\pi  < 3,$ $-0.1 < m^2 < 0.15$	$ n\sigma_\pi  < 3,$ $-0.1 < m^2 < 0.15$	$ n\sigma_K  < 3,$ $0.16 < m^2 < 0.36$	$ n\sigma_K  < 3,$ $0.16 < m^2 < 0.36$	$p < 2GeV/c,$ $ n\sigma_p - shift  < 2;$ $p > 2GeV/c,$ $ n\sigma_p - shift  < 2,$ $0.6 < m^2 < 1.2$
3.2 GeV	$0.2 < p < 0.7GeV/c,$ $ n\sigma_\pi - shift  < 3;$ $0.7 < p < 3.0GeV/c,$ $ n\sigma_\pi - shift  < 3,$ $-0.1 < m^2 < 0.15$	$0.2 < p < 3.7GeV/c,$ $ n\sigma_\pi - shift  < 3$	$0.2 < p < 2.1GeV/c,$ $ n\sigma_K - shift  < 3,$ $0.16 < m^2 < 0.36;$ $2.1 < p < 2.6GeV/c,$ $ n\sigma_K - shift  < 3,$ $0.2 < m^2 < 0.33$	$0.2 < p < 1.3GeV/c,$ $ n\sigma_K - shift  < 3,$ $0.16 < m^2 < 0.36;$ $1.3 < p < 2.1GeV/c,$ $ n\sigma_K - shift  < 3,$ $0.19 < m^2 < 0.36$	$0.2 < p < 1.3GeV/c,$ $ n\sigma_p - shift  < 3;$ $1.3 < p < 4.5GeV/c,$ $ n\sigma_p - shift  < 3,$ $0.6 < m^2 < 1.2$
3.5 GeV	$0.2 < p < 0.7GeV/c,$ $ n\sigma_\pi - shift  < 3;$ $0.7 < p < 3.0GeV/c,$ $ n\sigma_\pi - shift  < 3,$ $-0.1 < m^2 < 0.15$	$0.2 < p < 3.7GeV/c,$ $ n\sigma_\pi - shift  < 3$	$0.2 < p < 2.3GeV/c,$ $ n\sigma_K - shift  < 3,$ $0.16 < m^2 < 0.36;$ $2.3 < p < 2.7GeV/c,$ $ n\sigma_K - shift  < 3,$ $0.2 < m^2 < 0.33$	$0.2 < p < 1.6GeV/c,$ $ n\sigma_K - shift  < 3,$ $0.16 < m^2 < 0.36;$ $1.6 < p < 2.4GeV/c,$ $ n\sigma_K - shift  < 3,$ $0.19 < m^2 < 0.36$	$0.2 < p < 1.2GeV/c,$ $ n\sigma_p - shift  < 3;$ $1.2 < p < 4.5GeV/c,$ $ n\sigma_p - shift  < 3,$ $0.6 < m^2 < 1.2$
3.9 GeV	$0.2 < p < 0.7GeV/c,$ $ n\sigma_\pi - shift  < 3;$ $0.7 < p < 3.0GeV/c,$ $ n\sigma_\pi - shift  < 3,$ $-0.1 < m^2 < 0.15$	$0.2 < p < 3.7GeV/c,$ $ n\sigma_\pi - shift  < 3$	$0.2 < p < 2.1GeV/c,$ $ n\sigma_K - shift  < 3,$ $0.16 < m^2 < 0.36;$ $2.1 < p < 2.6GeV/c,$ $ n\sigma_K - shift  < 3,$ $0.2 < m^2 < 0.33$	$0.2 < p < 1.3GeV/c,$ $ n\sigma_K - shift  < 3,$ $0.16 < m^2 < 0.36;$ $1.3 < p < 2.1GeV/c,$ $ n\sigma_K - shift  < 3,$ $0.19 < m^2 < 0.36$	$0.2 < p < 1.2GeV/c,$ $ n\sigma_p - shift  < 3;$ $1.2 < p < 4.5GeV/c,$ $ n\sigma_p - shift  < 3,$ $0.6 < m^2 < 1.2$

TABLE V. PID cut for  $\pi, K, p$  at 3.0, 3.2, 3.5, 3.9 GeV

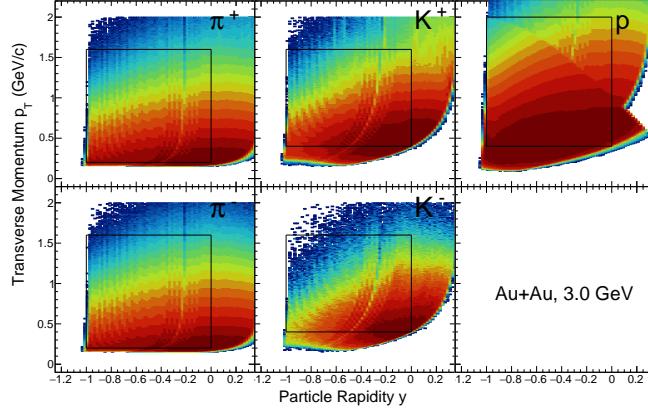


FIG. 34.  $\pi, K, p$  density distribution as function of rapidity and transverse momentum at  $\sqrt{s_{NN}} = 3.0$  GeV.

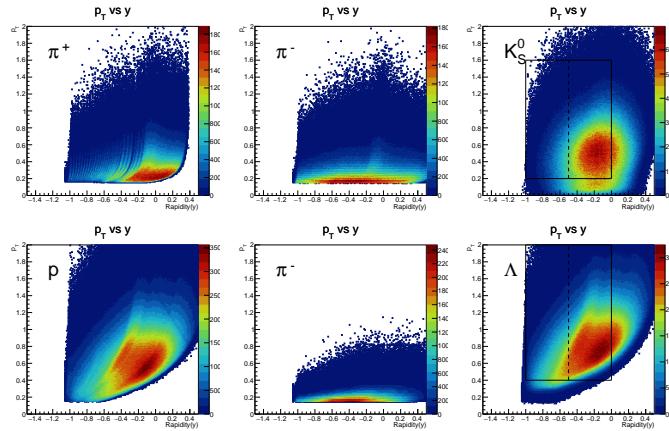


FIG. 35.  $K_S^0$  and  $\Lambda$ (and their daughters) density distribution as function of rapidity and transverse momentum at  $\sqrt{s_{NN}} = 3.0$  GeV.

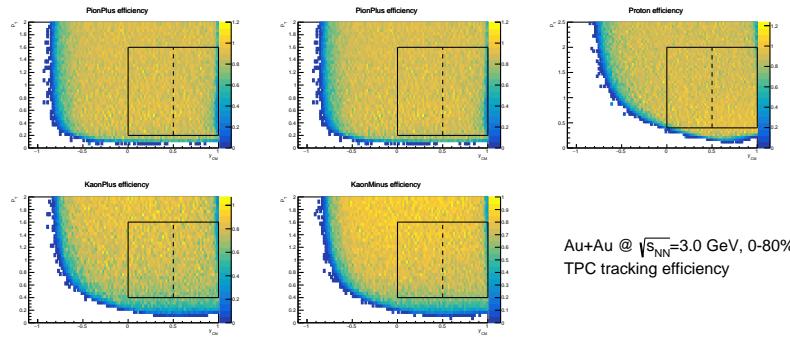


FIG. 36. TPC tracking efficiency of  $\pi, K, p$  as function of rapidity  $y$  and transverse momentum  $p_T$  at  $\sqrt{s_{NN}} = 3.0$  GeV.

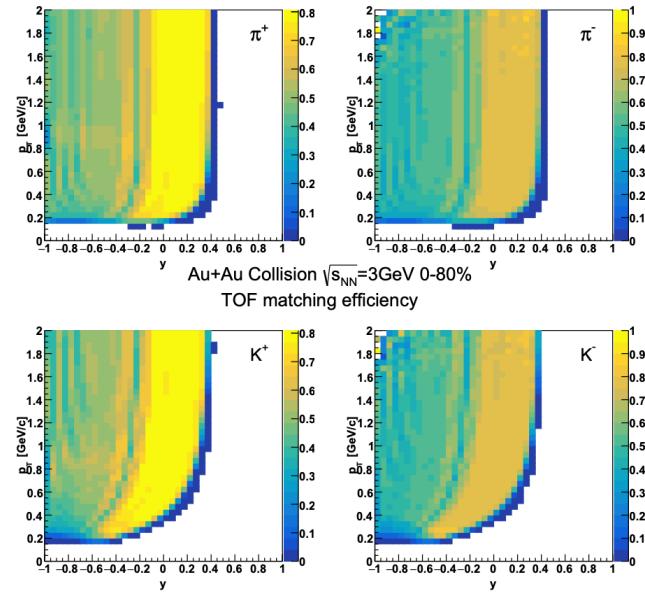


FIG. 37. TOF matching efficiency of  $\pi, K$  as function of rapidity  $y$  and transverse momentum  $p_T$  at  $\sqrt{s_{NN}} = 3.0 \text{ GeV}$ .

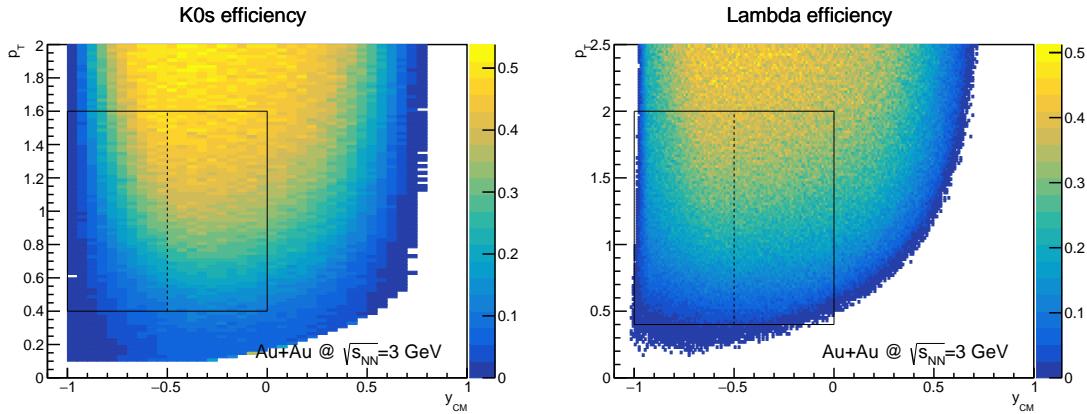


FIG. 38. Reconstruction efficiency of  $K_S^0$  (Left),  $\Lambda$  (Right) as function of rapidity  $y$  and transverse momentum  $p_T$  at  $\sqrt{s_{NN}} = 3.0 \text{ GeV}$ .

## Appendix A: Appendix

## Appendix B: PID cuts and acceptance plots

## Appendix C: $v_1$ plots for other energies

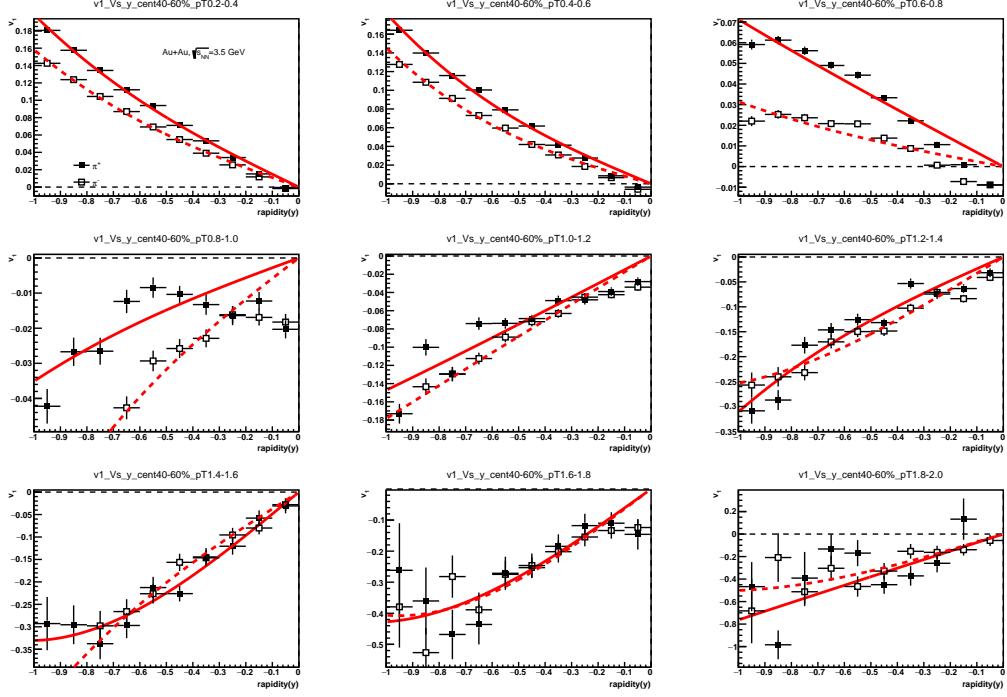


FIG. 39.  $v_1$  of pions as function of rapidity within  $p_T$  windows in 40-60% centrality at  $\sqrt{s_{NN}} = 3.5$  GeV.

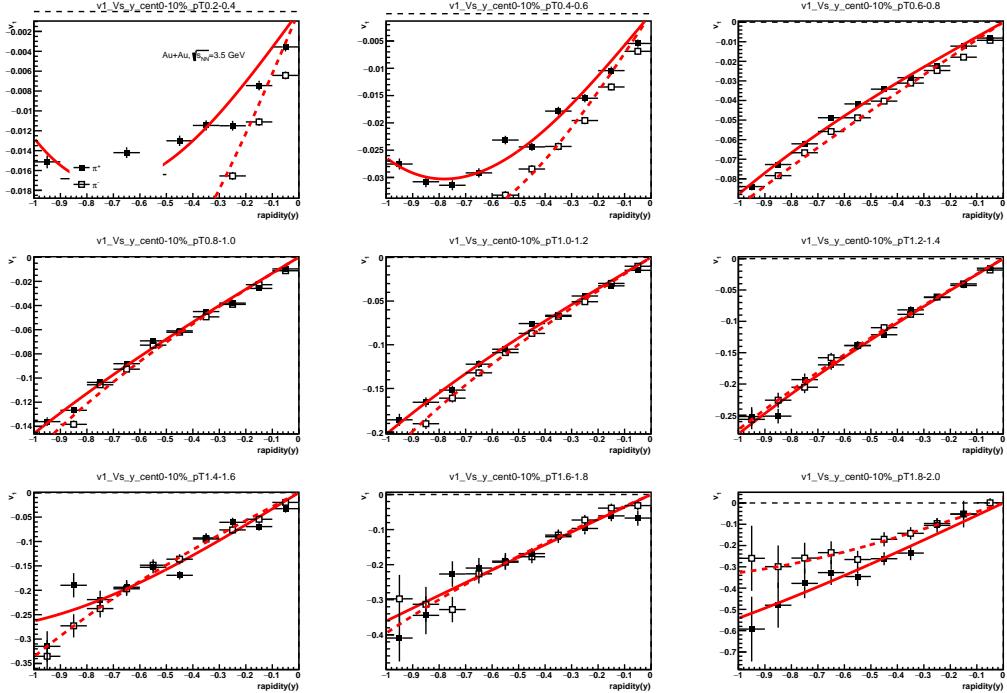


FIG. 40.  $v_1$  of pions as function of rapidity within  $p_T$  windows in 0-10% centrality at  $\sqrt{s_{NN}} = 3.5$  GeV.

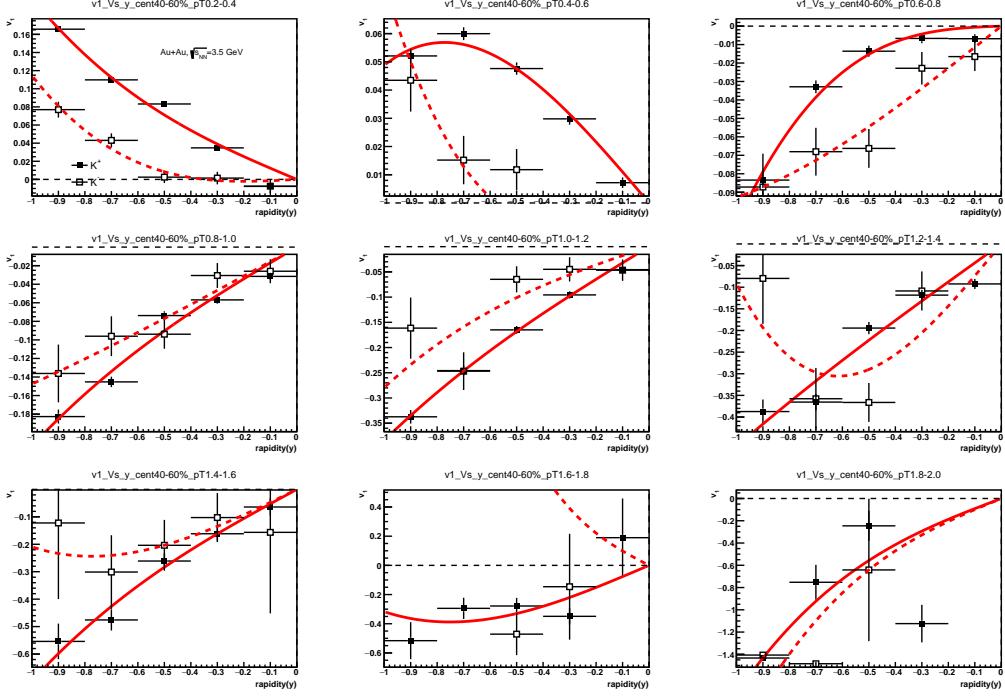


FIG. 41.  $v_1$  of kaons as function of rapidity within  $p_T$  windows in 40-60% centrality at  $\sqrt{s_{NN}} = 3.5$  GeV.

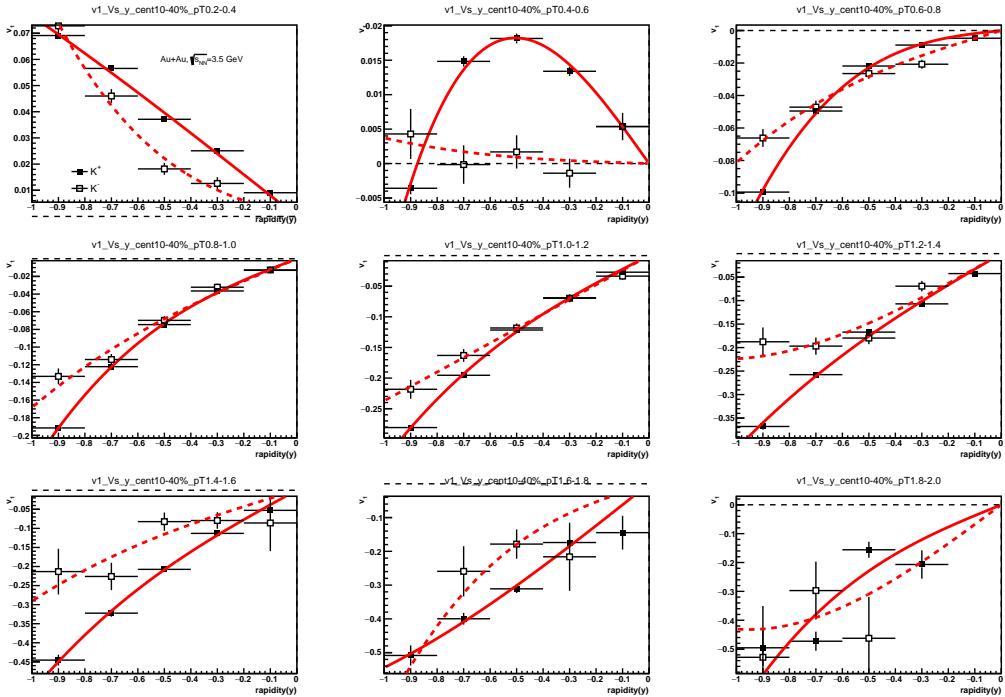


FIG. 42.  $v_1$  of kaons as function of rapidity within  $p_T$  windows in 10-40% centrality at  $\sqrt{s_{NN}} = 3.5$  GeV.

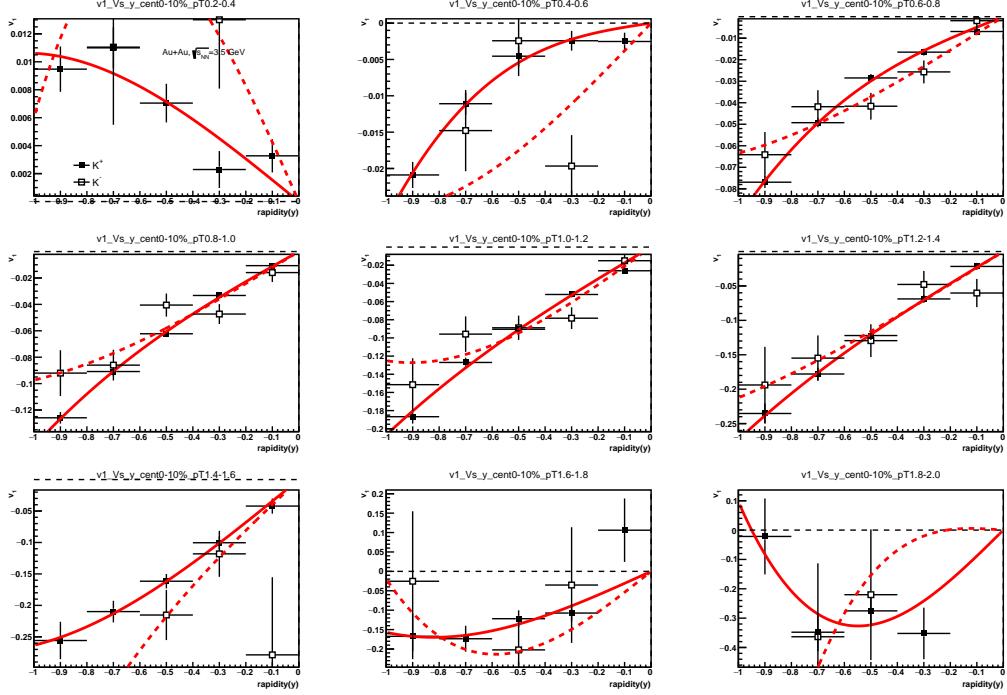


FIG. 43.  $v_1$  of kaons as function of rapidity within  $p_T$  windows in 0-10% centrality at  $\sqrt{s_{NN}} = 3.5$  GeV.

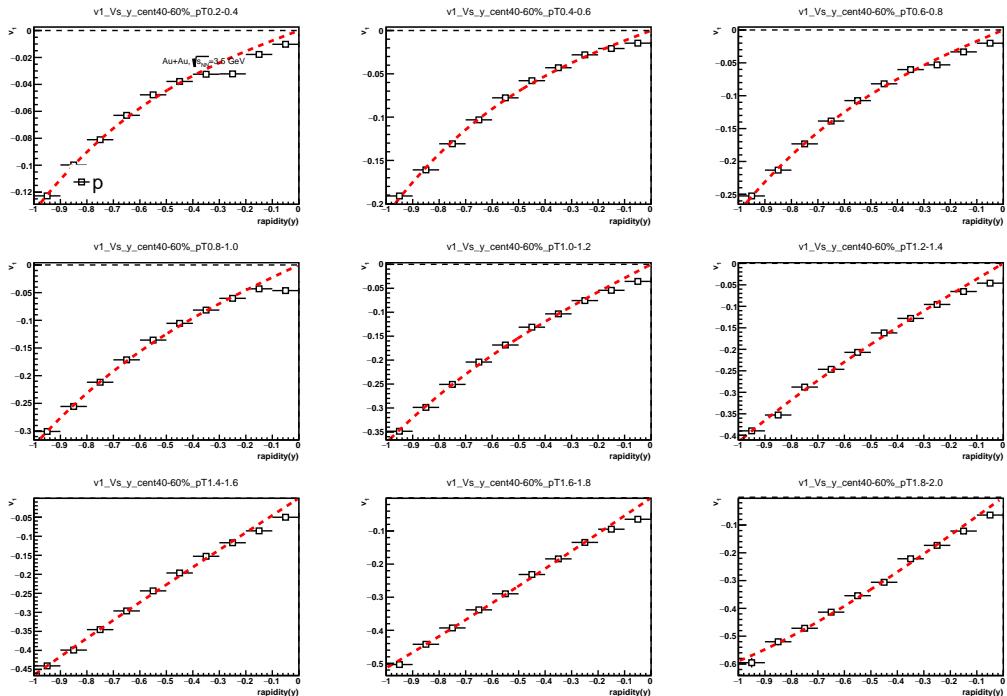


FIG. 44.  $v_1$  of proton as function of rapidity within  $p_T$  windows in 40-60% centrality at  $\sqrt{s_{NN}} = 3.5$  GeV.

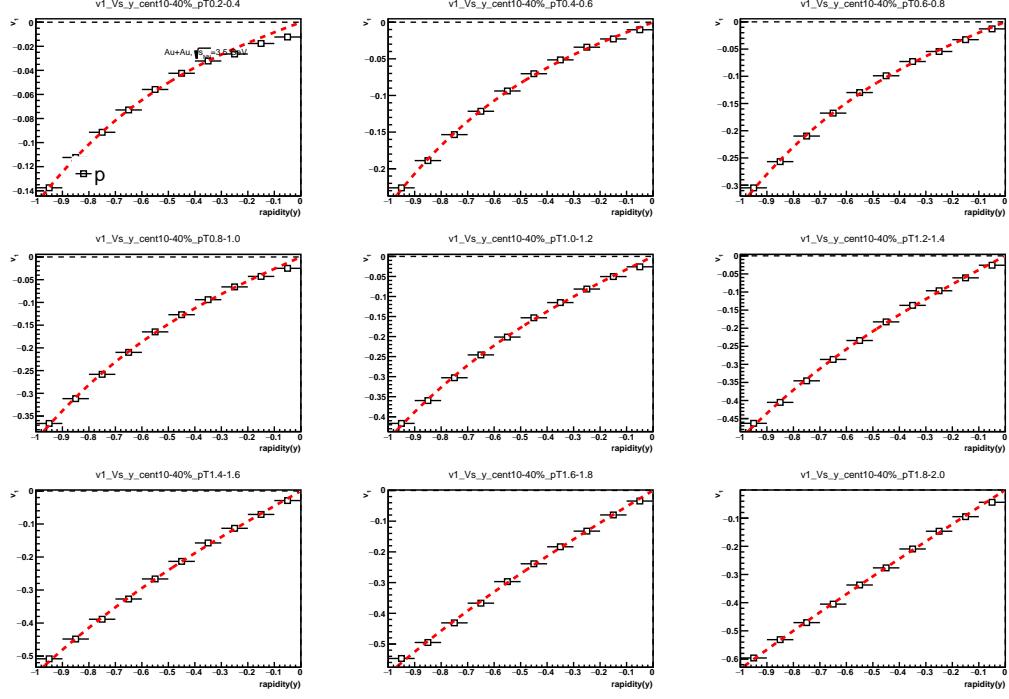


FIG. 45.  $v_1$  of proton as function of rapidity within  $p_T$  windows in 10-40% centrality at  $\sqrt{s_{NN}} = 3.5$  GeV.

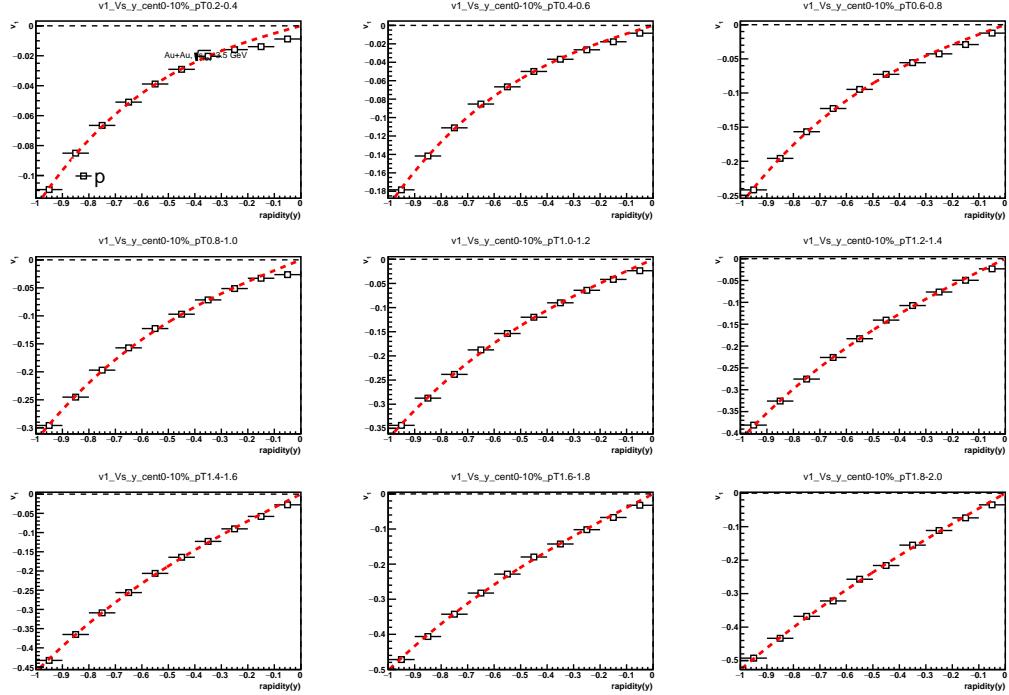


FIG. 46.  $v_1$  of proton as function of rapidity within  $p_T$  windows in 0-10% centrality at  $\sqrt{s_{NN}} = 3.5$  GeV.

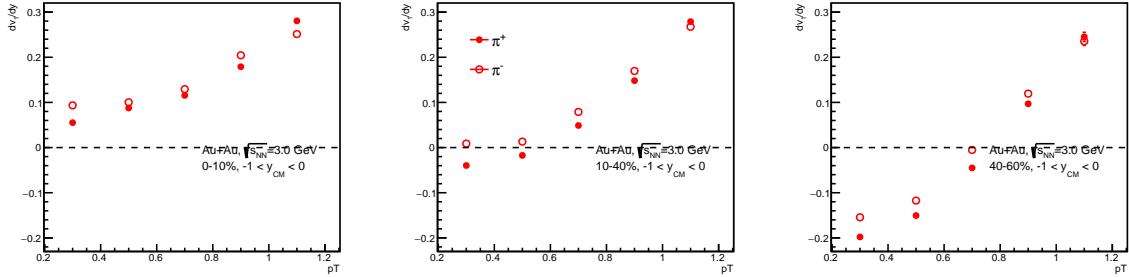


FIG. 47.  $dv_1/dy|_{y=0}$  of pions as function of  $p_T$  at  $\sqrt{s_{NN}} = 3.0$  GeV.

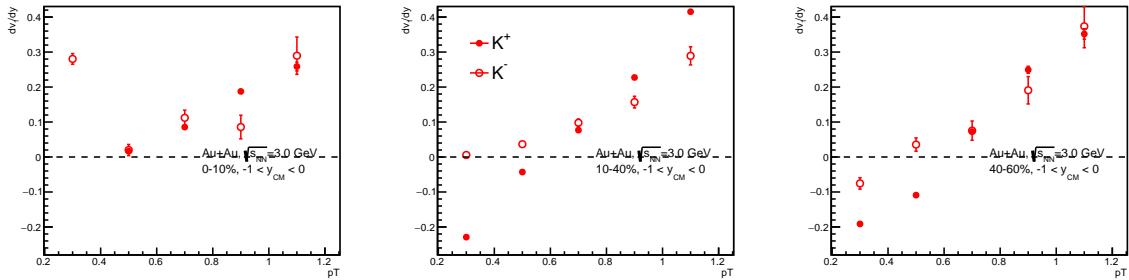


FIG. 48.  $dv_1/dy|_{y=0}$  of kaons as function of  $p_T$  at  $\sqrt{s_{NN}} = 3.0$  GeV.

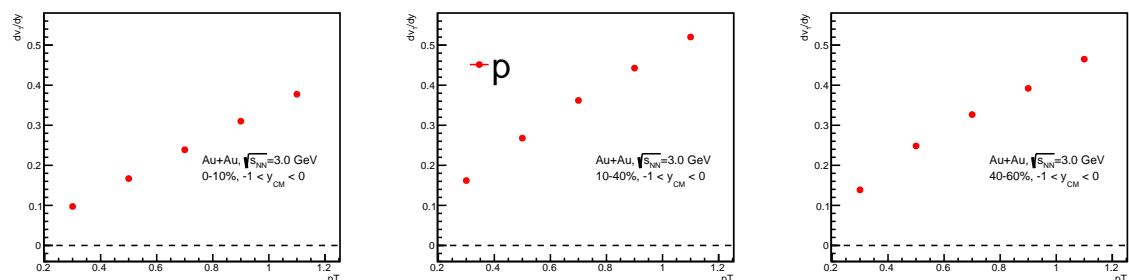


FIG. 49.  $dv_1/dy|_{y=0}$  of proton as function of  $p_T$  at  $\sqrt{s_{NN}} = 3.0$  GeV.

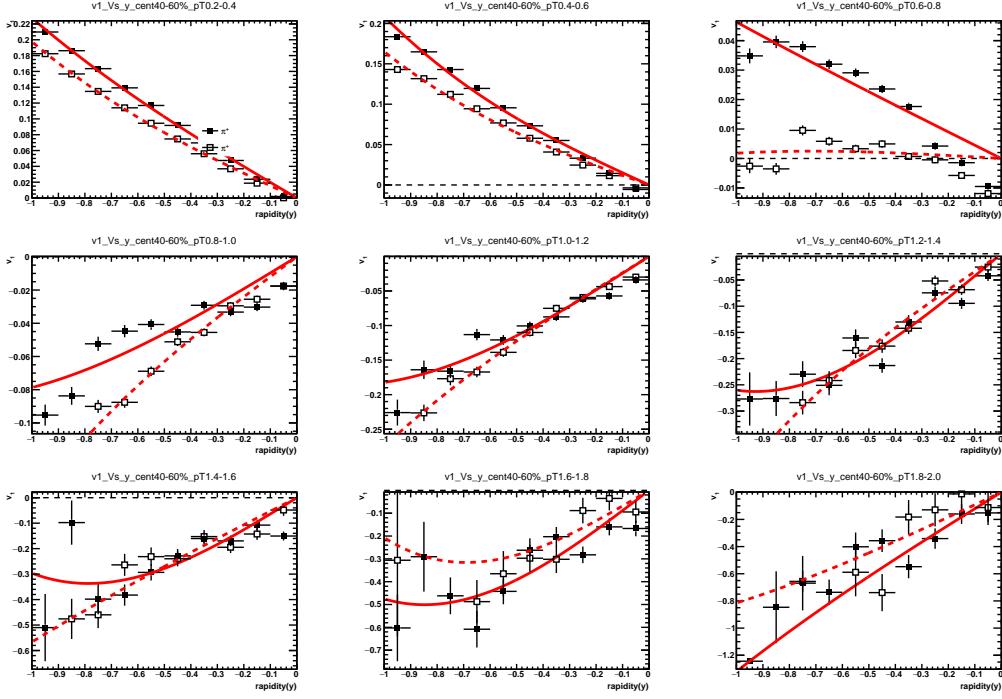


FIG. 50.  $v_1$  of pions as function of rapidity within  $p_T$  windows in 40-60% centrality at  $\sqrt{s_{NN}} = 3.0$  GeV.

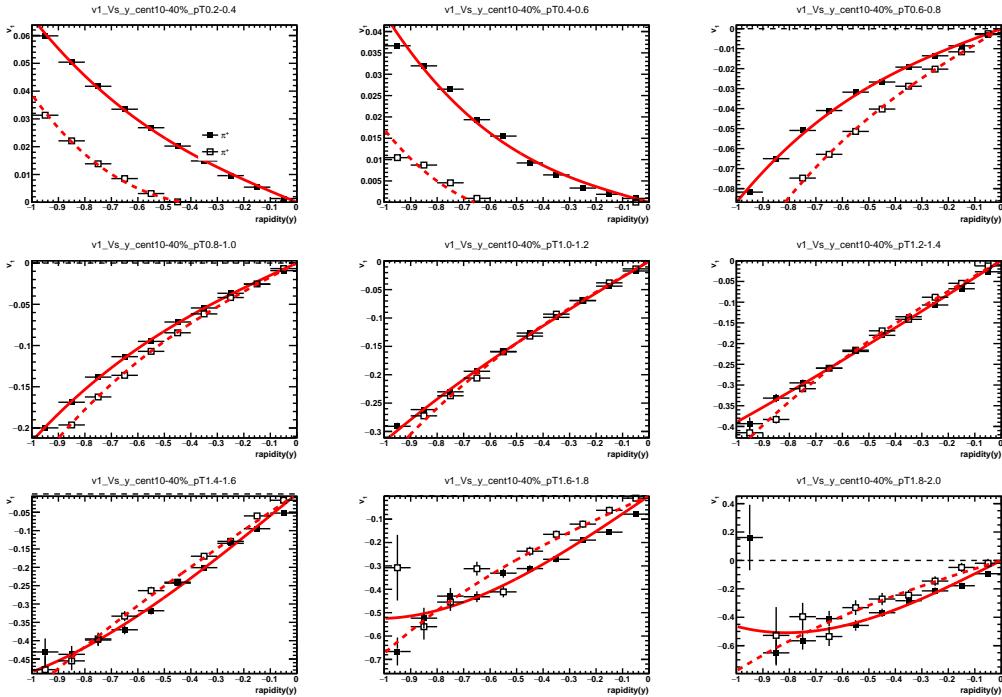


FIG. 51.  $v_1$  of pions as function of rapidity within  $p_T$  windows in 10-40% centrality at  $\sqrt{s_{NN}} = 3.0$  GeV.

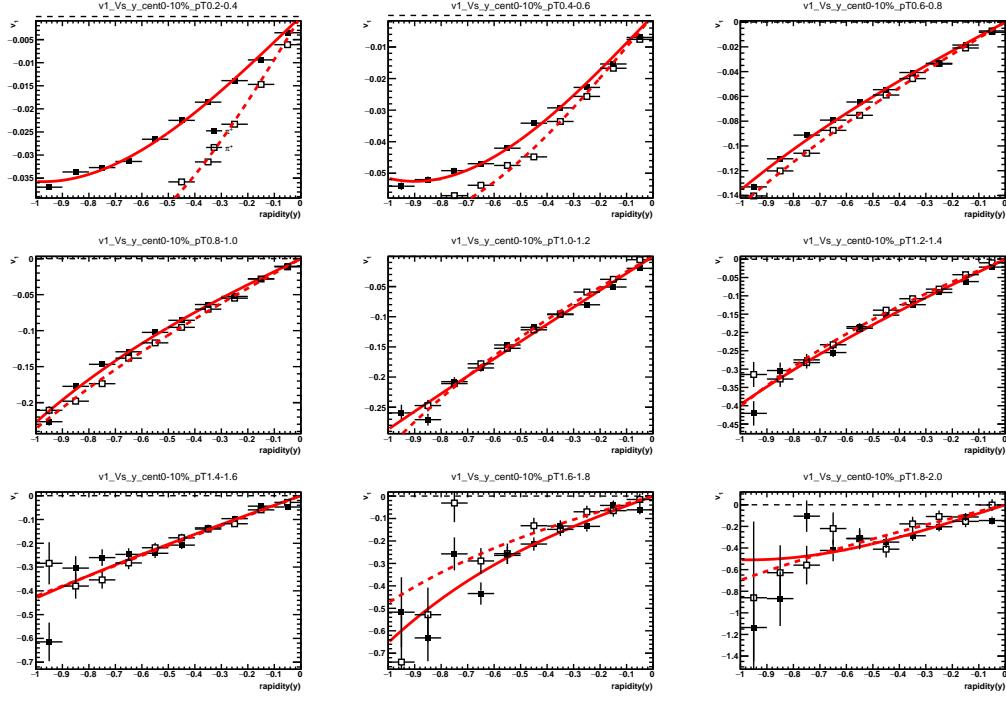


FIG. 52.  $v_1$  of pions as function of rapidity within  $p_T$  windows in 0-10% centrality at  $\sqrt{s_{NN}} = 3.0$  GeV.

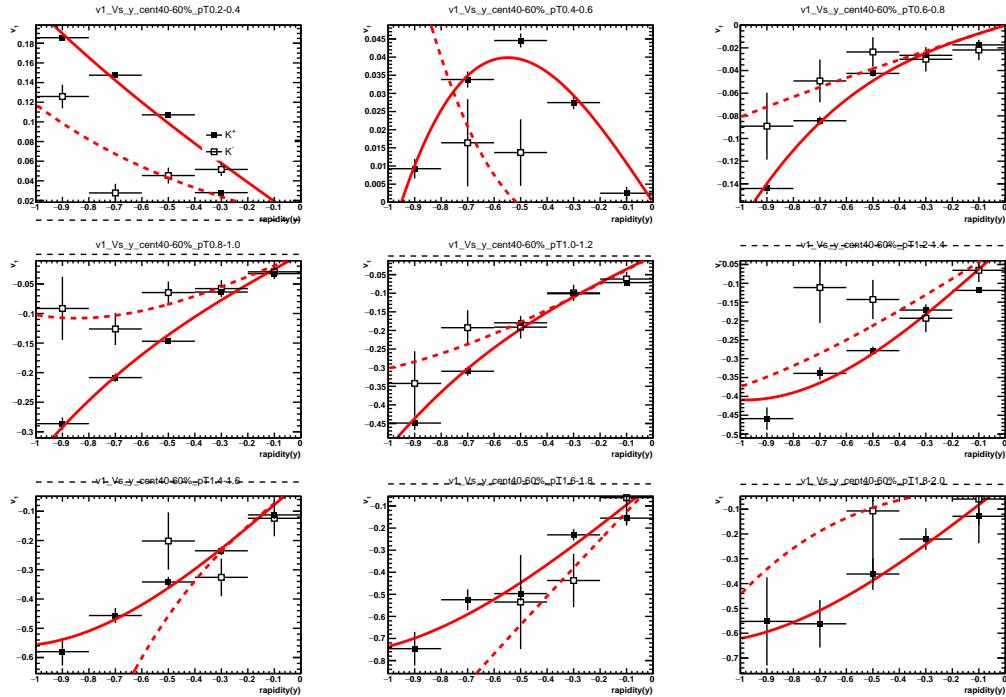


FIG. 53.  $v_1$  of kaons as function of rapidity within  $p_T$  windows in 40-60% centrality at  $\sqrt{s_{NN}} = 3.0$  GeV.

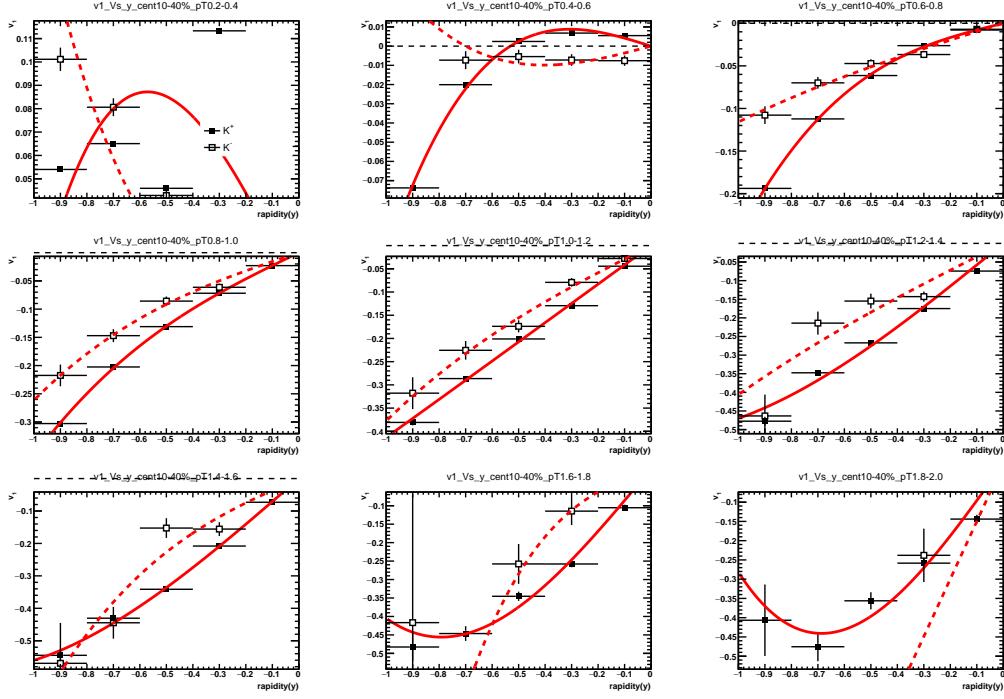


FIG. 54.  $v_1$  of kaons as function of rapidity within  $p_T$  windows in 10-40% centrality at  $\sqrt{s_{NN}} = 3.0$  GeV.

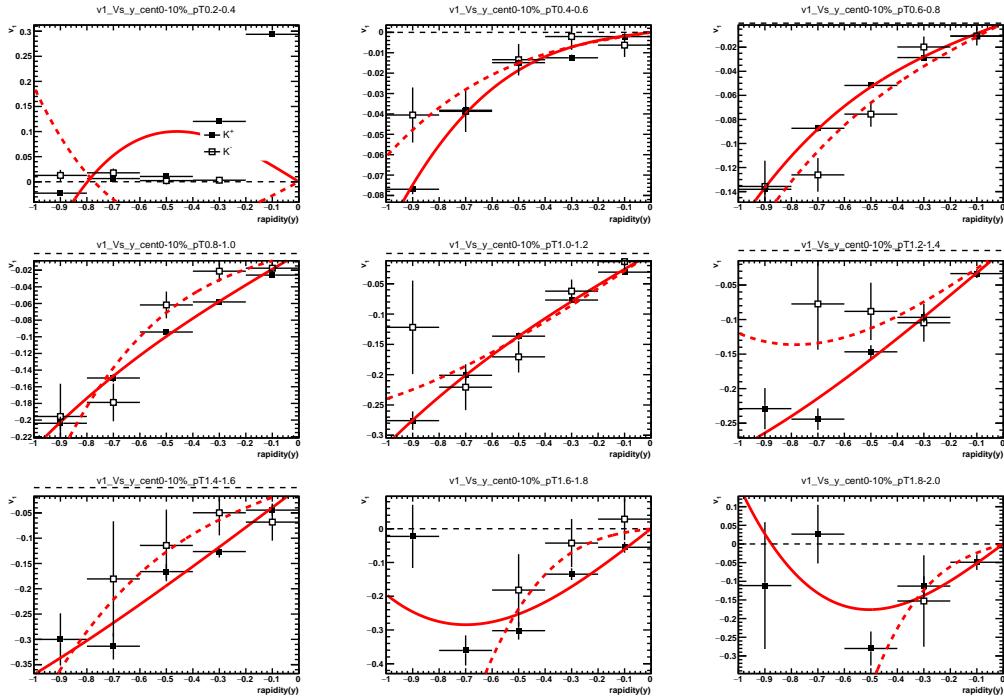


FIG. 55.  $v_1$  of kaons as function of rapidity within  $p_T$  windows in 0-10% centrality at  $\sqrt{s_{NN}} = 3.0$  GeV.

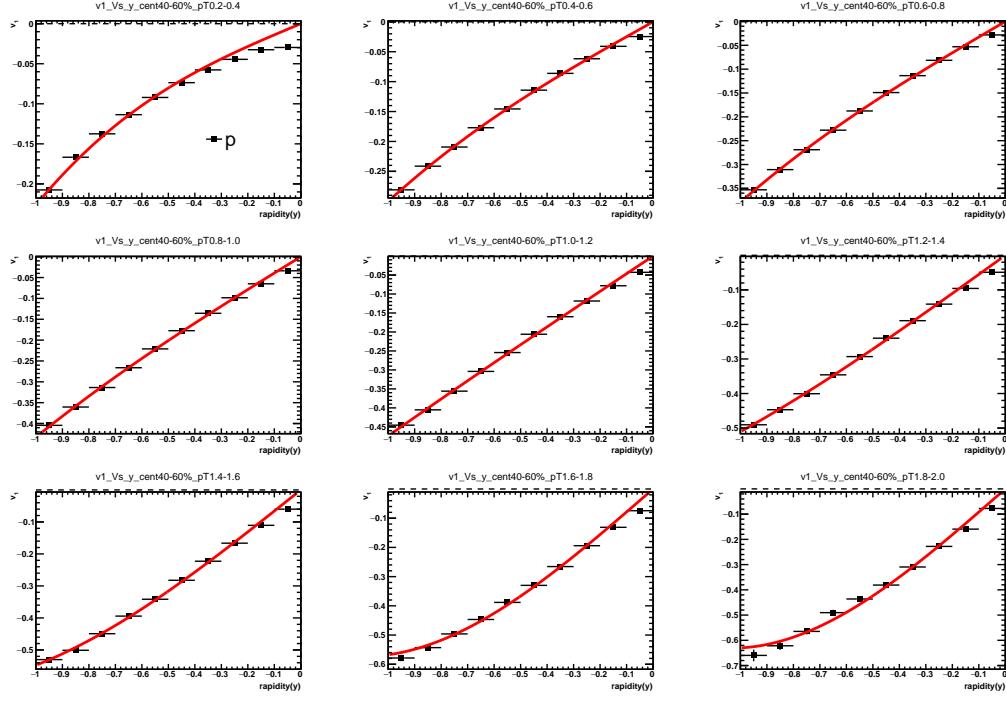


FIG. 56.  $v_1$  of protons as function of rapidity within  $p_T$  windows in 40-60% centrality at  $\sqrt{s_{NN}} = 3.0$  GeV.

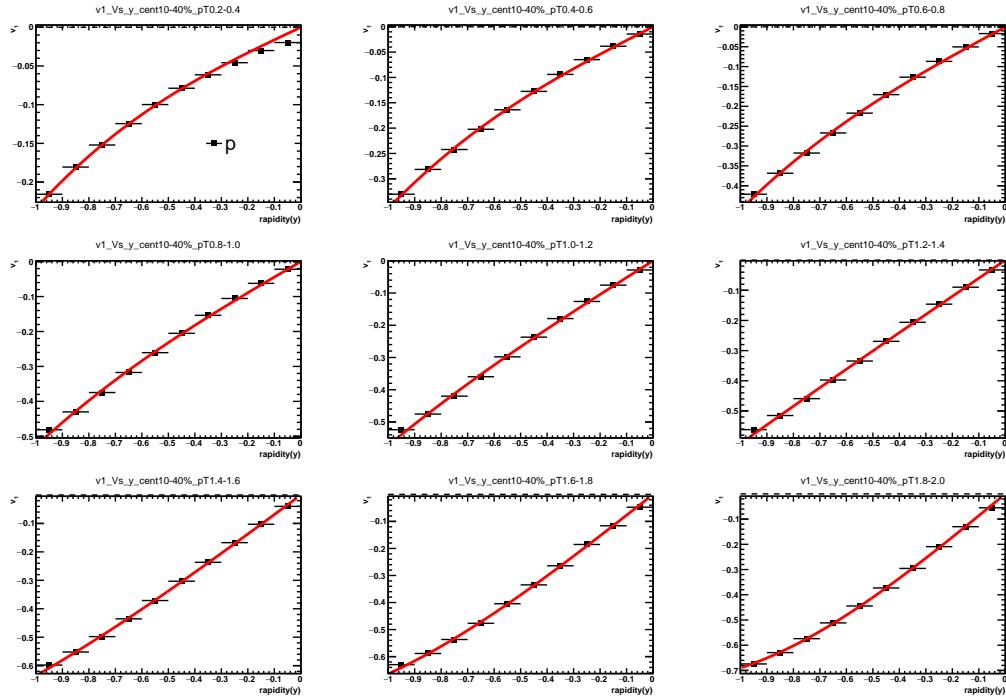


FIG. 57.  $v_1$  of protons as function of rapidity within  $p_T$  windows in 10-40% centrality at  $\sqrt{s_{NN}} = 3.0$  GeV.

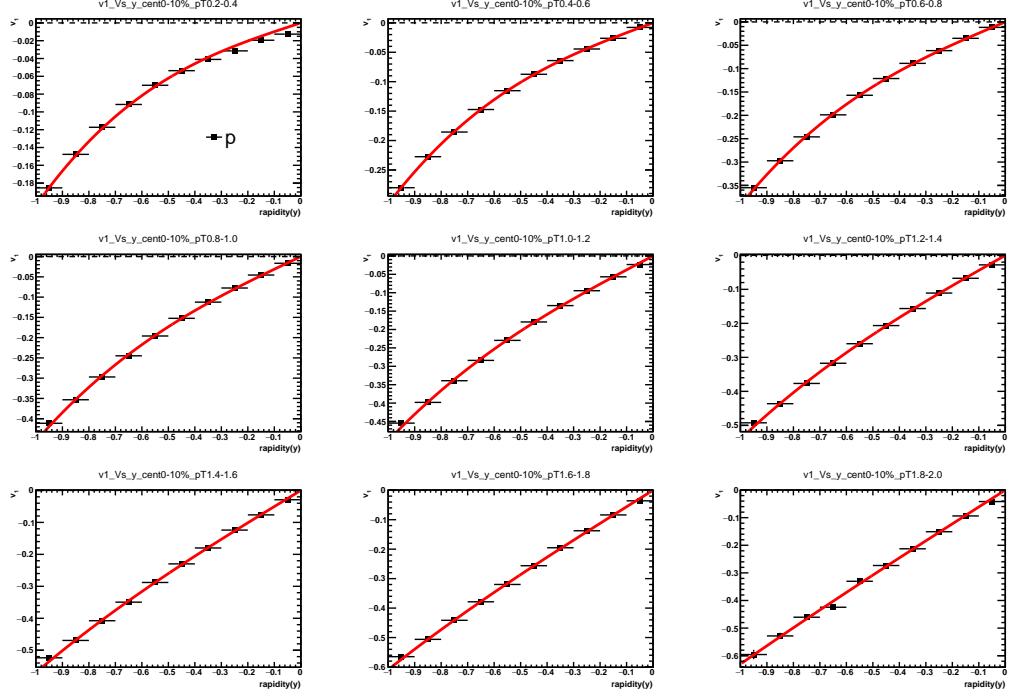


FIG. 58.  $v_1$  of protons as function of rapidity within  $p_T$  windows in 0-10% centrality at  $\sqrt{s_{NN}} = 3.0$  GeV.

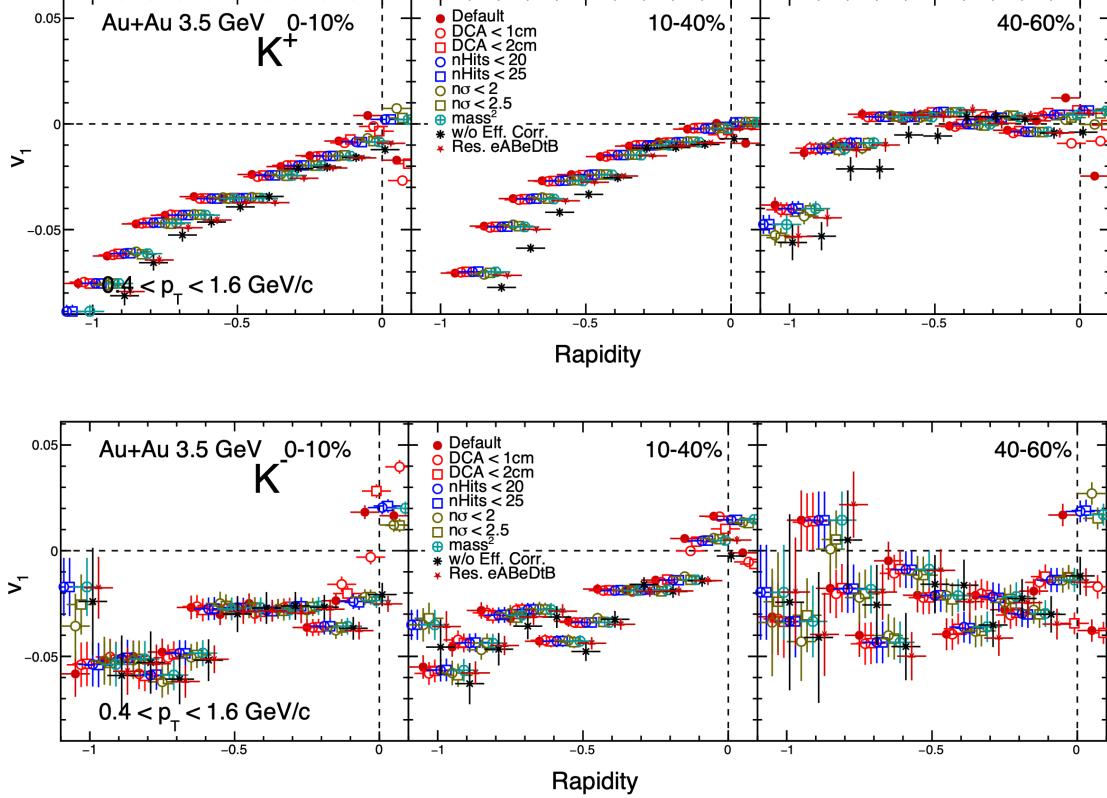


FIG. 59.  $v_1$  of kaons as function of rapidity from systematic sources at  $\sqrt{s_{NN}} = 3.5$  GeV.

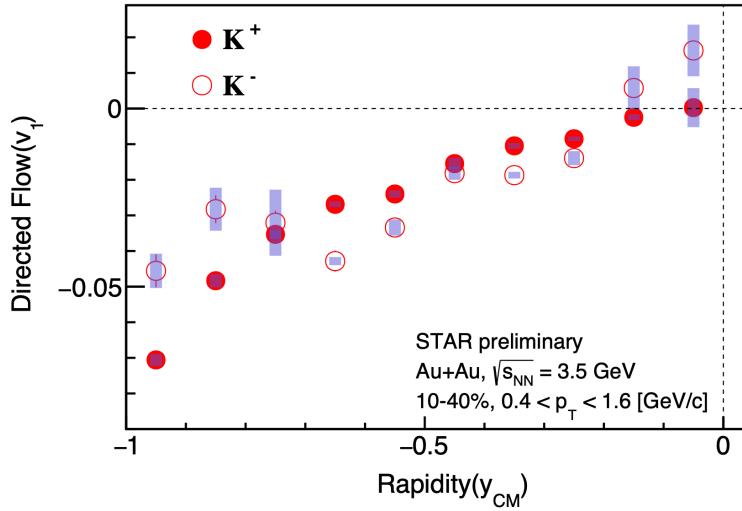


FIG. 60.  $v_1$  of kaons as function of rapidity at  $\sqrt{s_{NN}} = 3.5$  GeV.

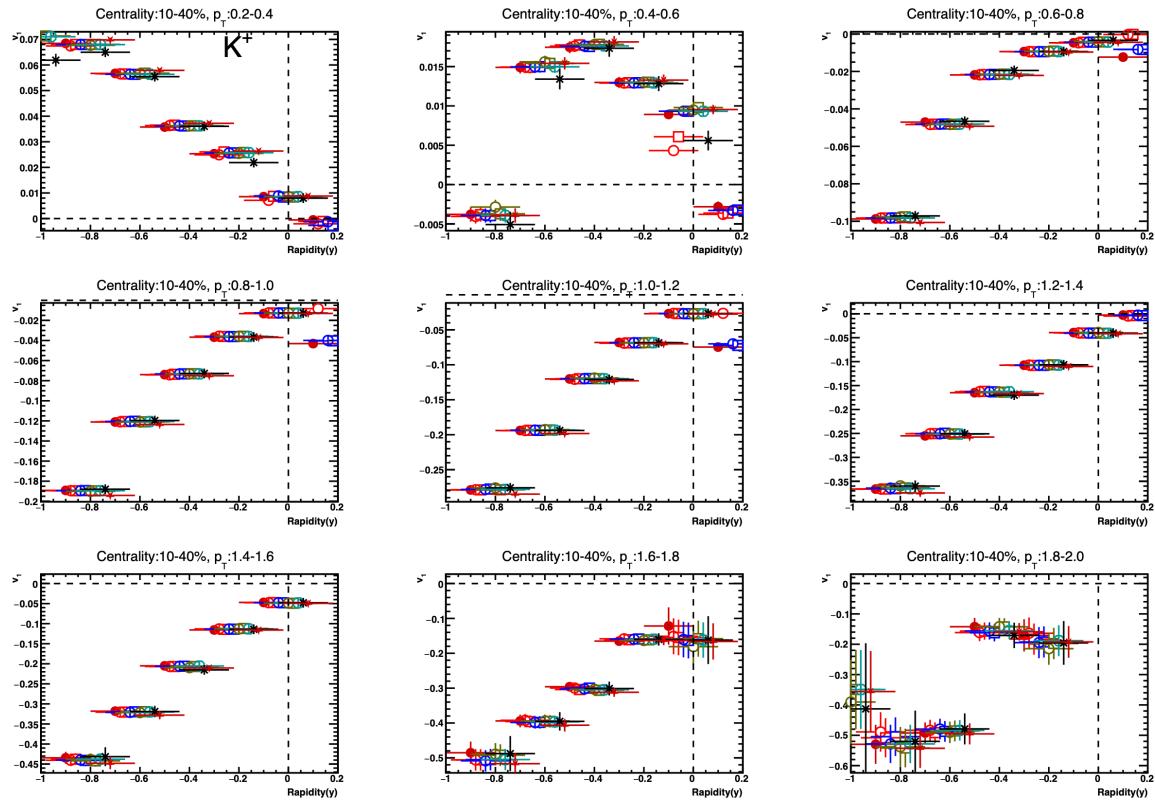


FIG. 61.  $v_1$  of  $K^+$  as function of rapidity within  $p_T$  windows at  $\sqrt{s_{NN}} = 3.5$  GeV.

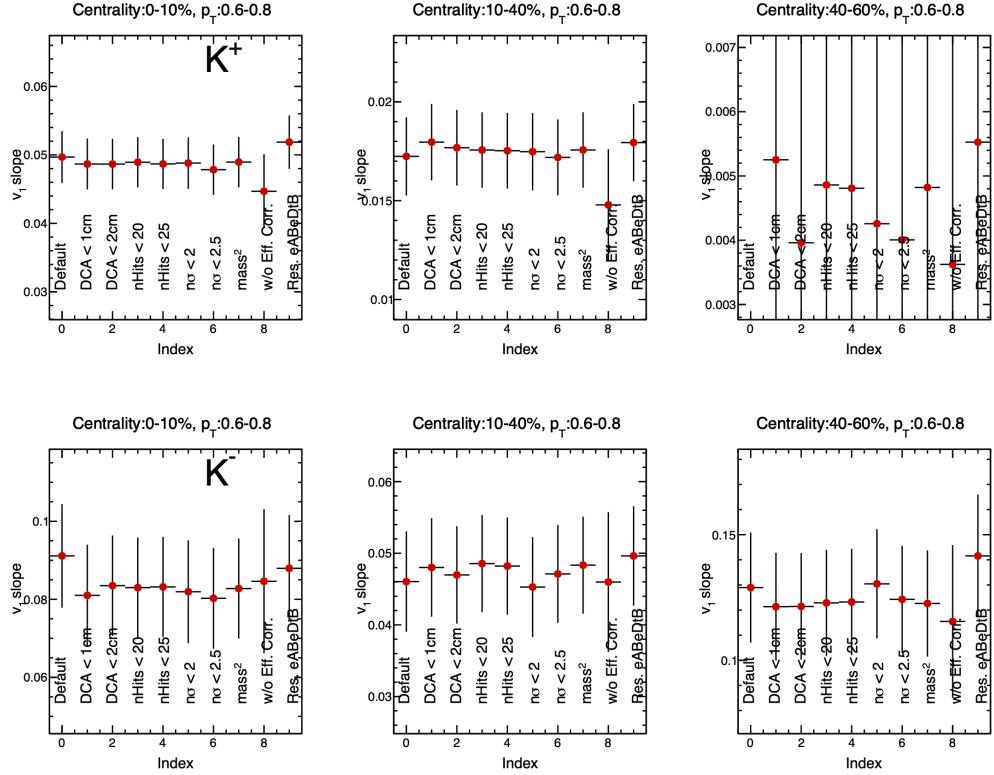


FIG. 62.  $v_1$  slope of kaons as function of systematic sources at  $\sqrt{s_{NN}} = 3.5$  GeV.

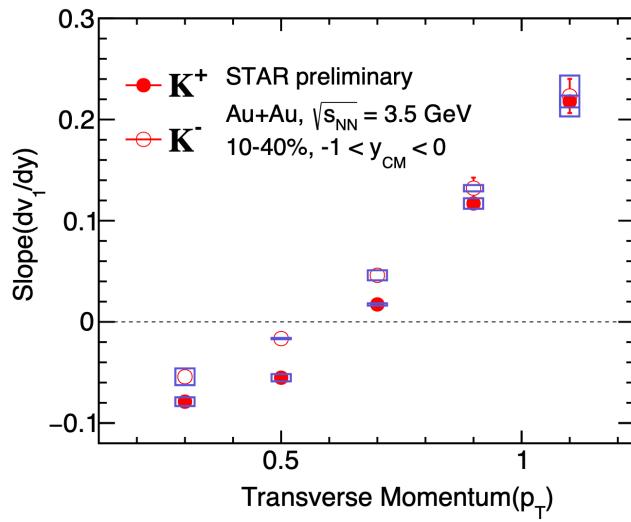


FIG. 63.  $v_1$  slope of kaons as function of transverse momentum at  $\sqrt{s_{NN}} = 3.5$  GeV.

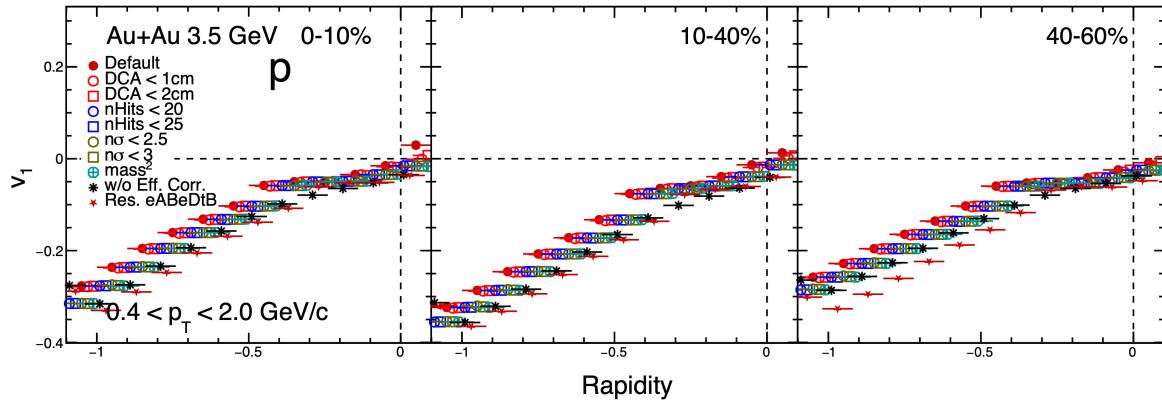


FIG. 64.  $v_1$  of proton as function of rapidity from systematic sources at  $\sqrt{s_{NN}} = 3.5$  GeV.

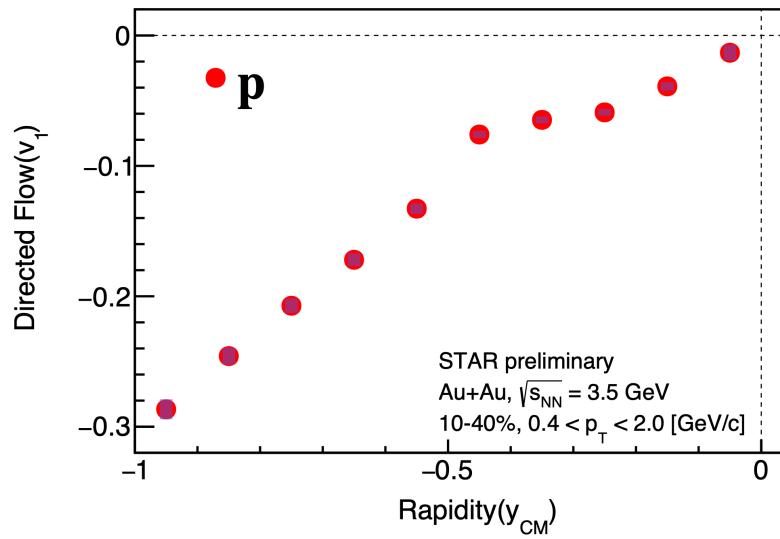
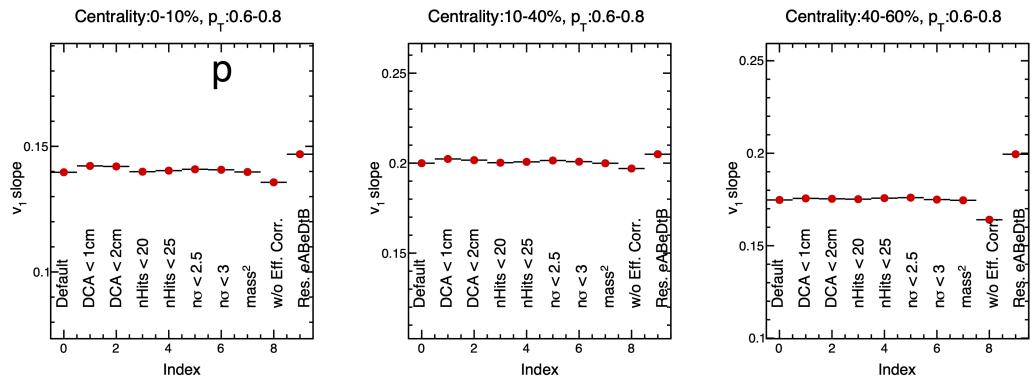
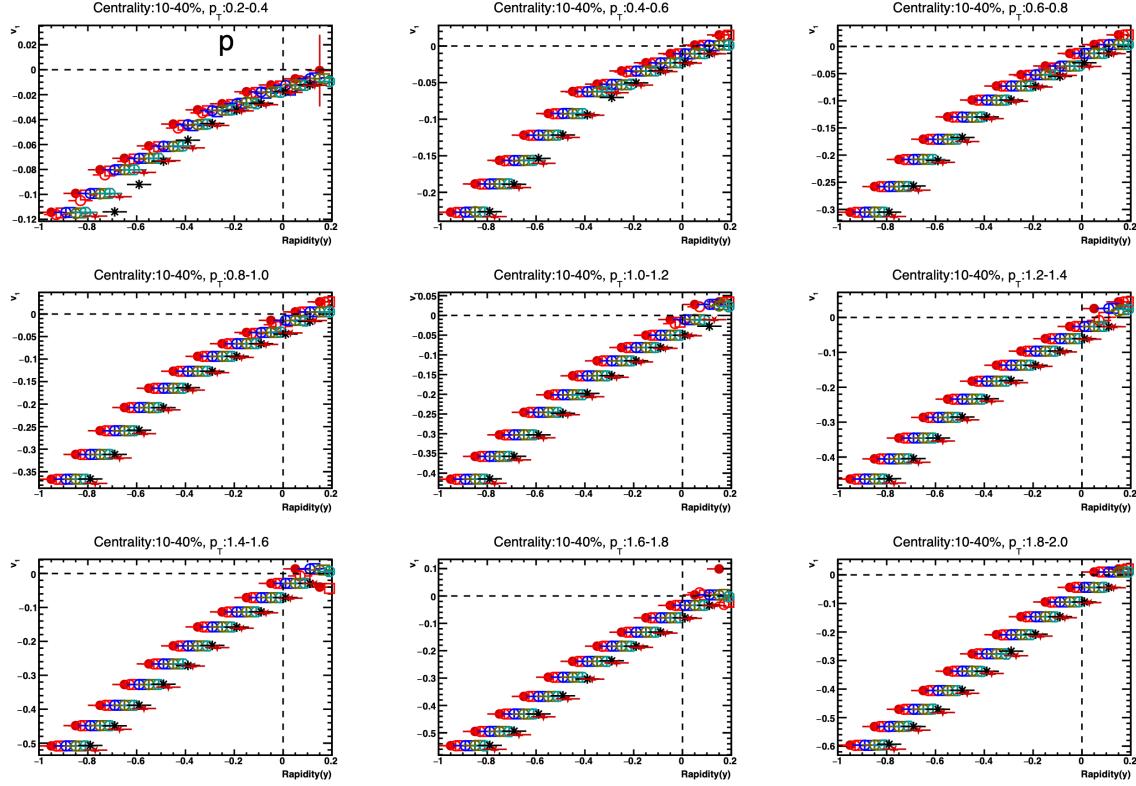


FIG. 65.  $v_1$  of proton as function of rapidity at  $\sqrt{s_{NN}} = 3.5$  GeV.



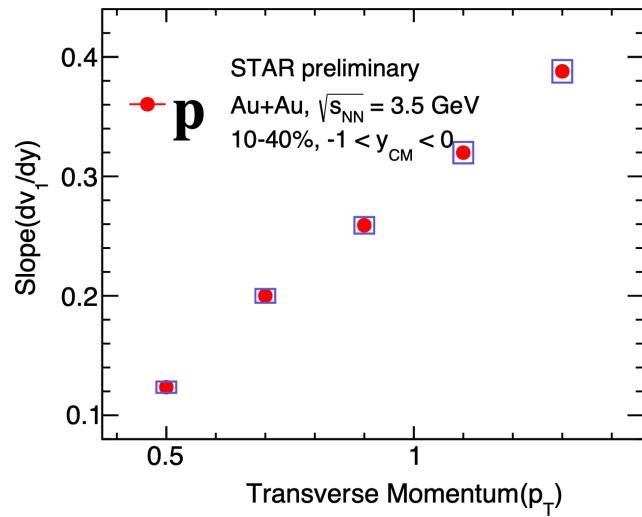


FIG. 68.  $v_1$  slope of proton as function of transverse momentum at  $\sqrt{s_{NN}} = 3.5 \text{ GeV}$ .

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