Measurement of Directed Flow of Identified Particles in Au+Au $\sqrt{s_{NN}}$=4.5 GeV Fixed-target Collisions at STAR

Hiroki Kato for the STAR Collaboration

WWND2019

Jan. 9, 2019

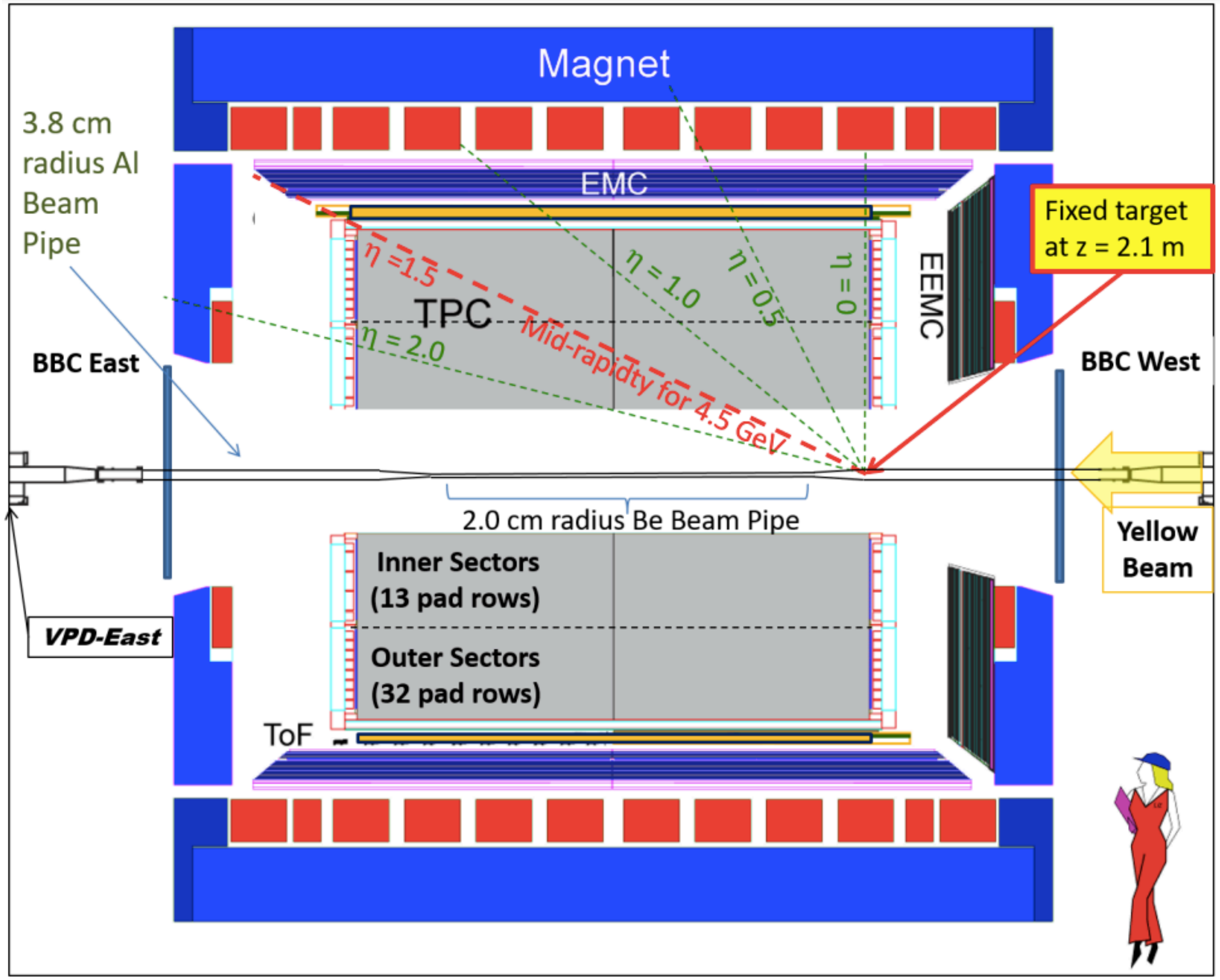
Tomonaga Center for the History of the Universe

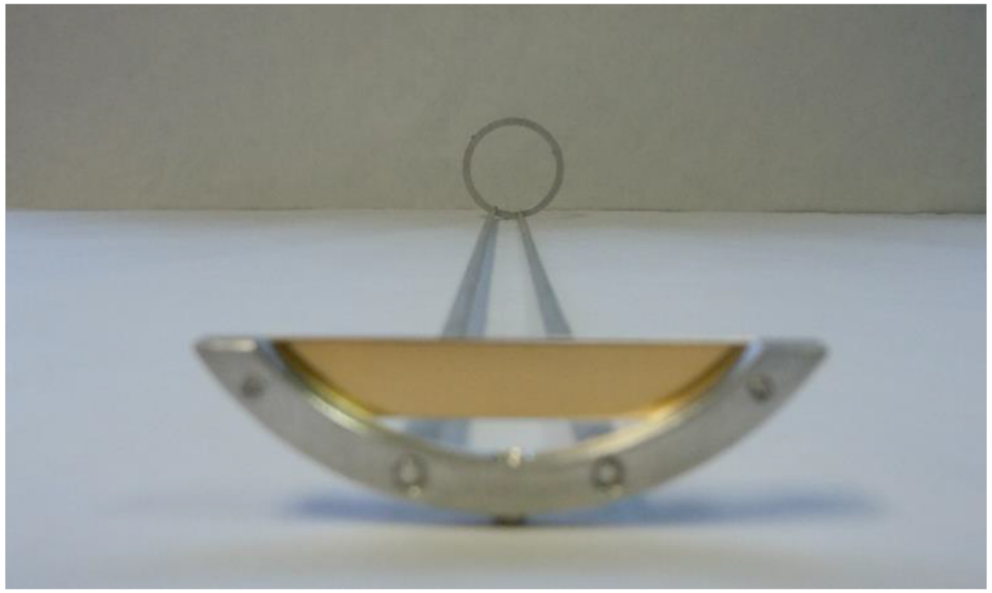
筑波大学
University of Tsukuba

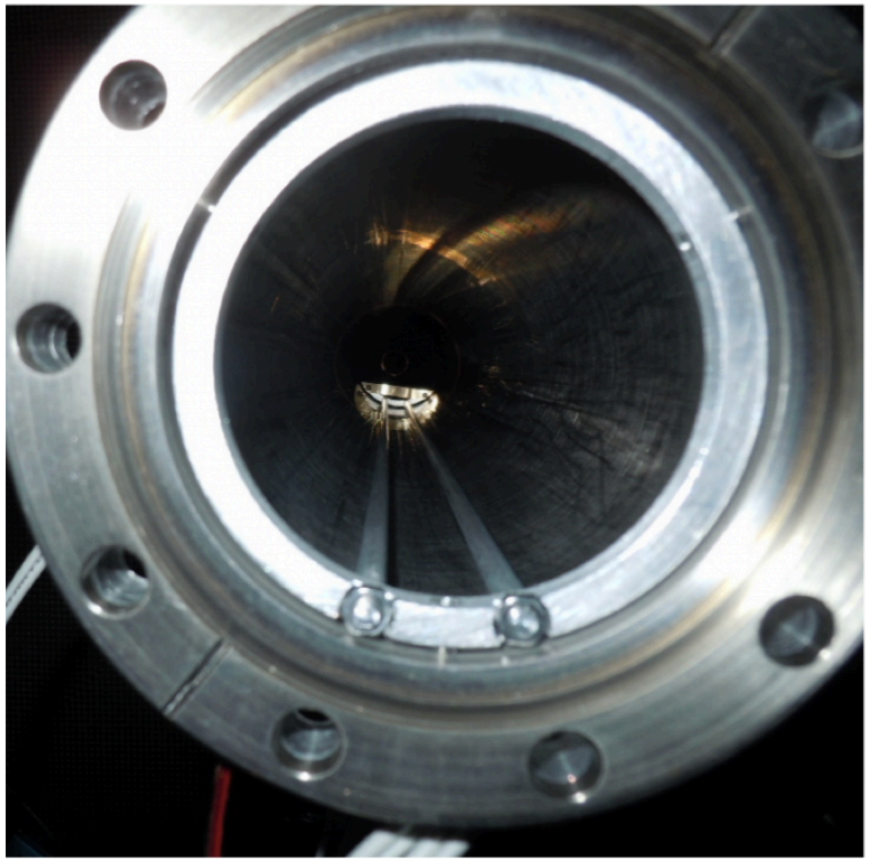
Outline

- ✓ Recent flow analysis in the STAR fixed-target program
- ✓ Motivation
- ✓ Analysis method (EP method)
- ✓ p_T dependence of directed flow
- ✓ Rapidity dependence of directed flow
- ✓ v_1 slope
- ✓ Summary and Outlook

STAR fixed-target program (FXT)







1.3M events from half hour test run

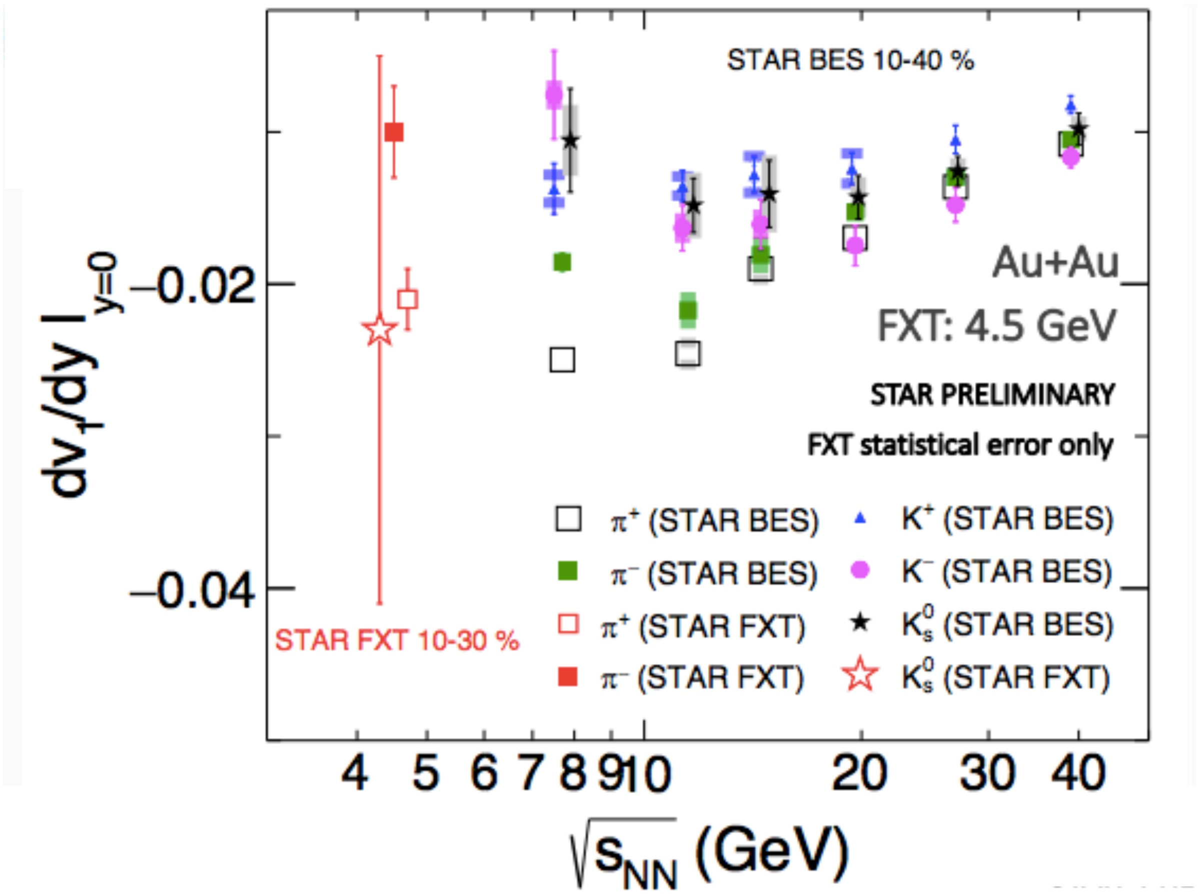
top 30% central trigger.

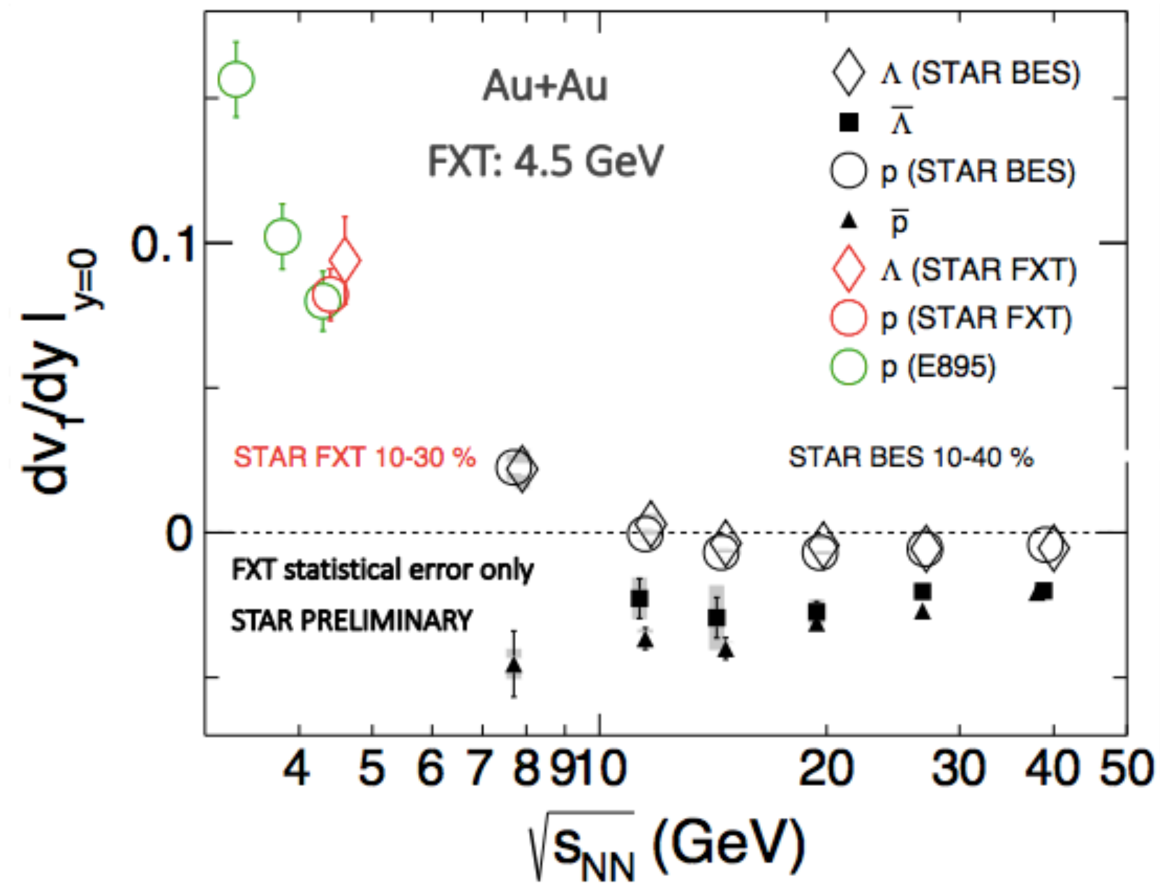
Au+Au $\sqrt{s_{NN}}$=4.5 GeV

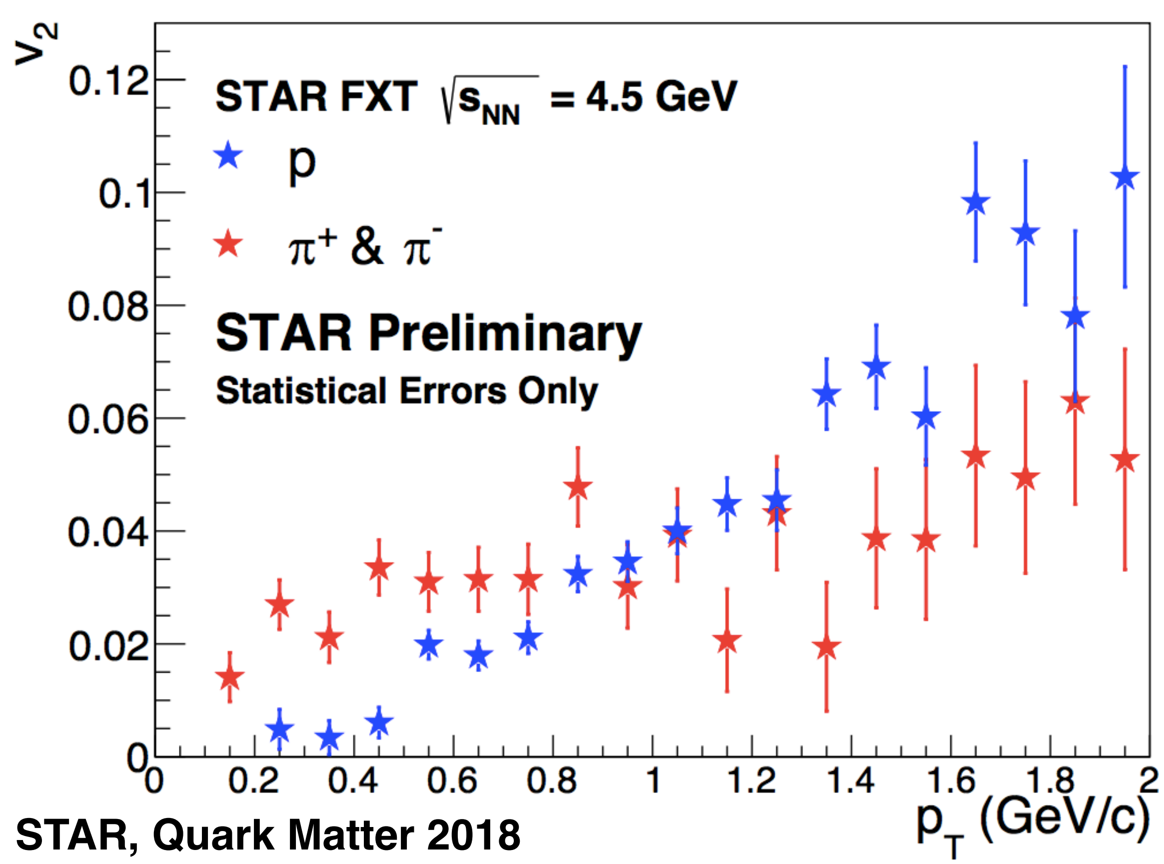
Previous flow results from FXT

E895 PRL 84(2000) 5488

STAR PRL 112(2014) 162301







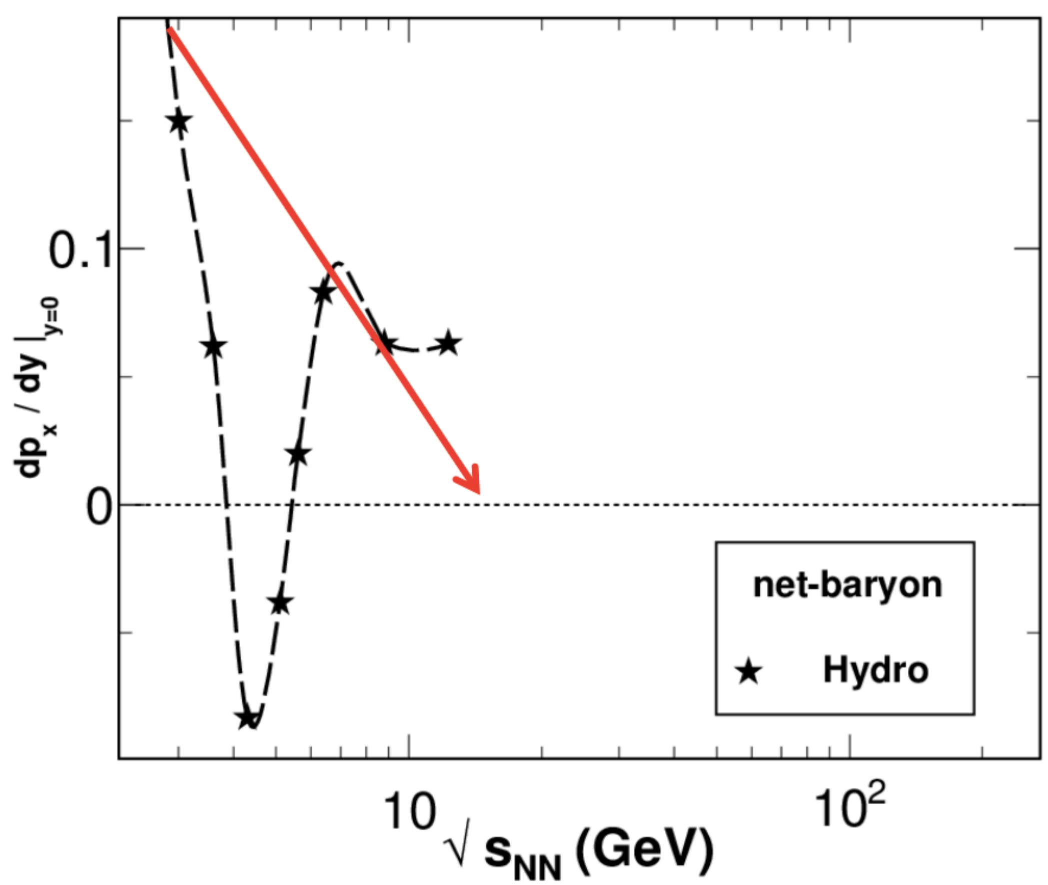
STAR, Quark Matter 2018

- ✓ Consistent with previous results from AGS and allows more detailed study.
- ✓ The first measurement of pion elliptic flow at this collision energy (4.5 GeV).
- ✓ The FXT program can extend measurements to the low energy range.

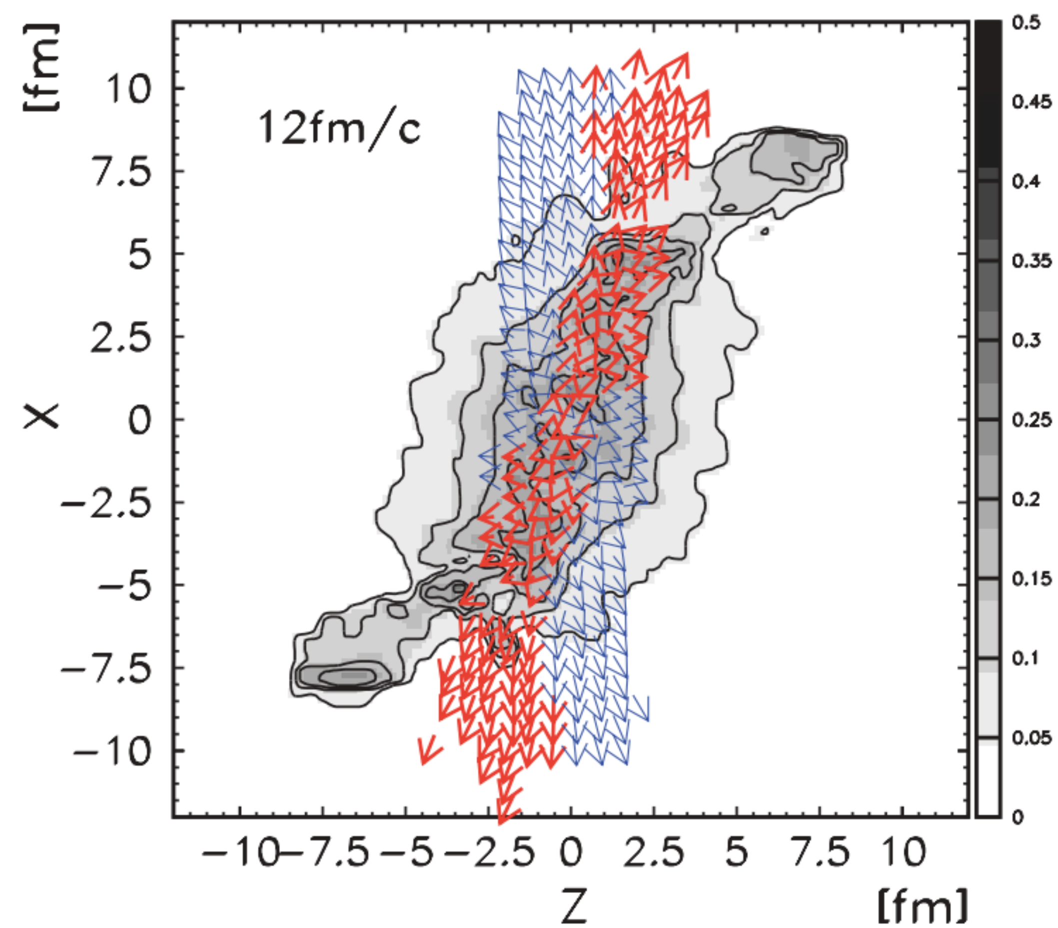
Directed flow

Directed flow is … $v_1 = \langle \cos(\phi - \Psi) \rangle$

- ✓ **Evaluated by the coefficients of the 1st harmonic in the Fourier expansion.**
- ✓ **Generated by the interaction between participants and spectators.**
- ✓ **Observable signature that was suggested to be sensitive to the first-order phase transition. (softest point)**
- ✓ **Possible probe of search for the QGP signature. (anti-flow)**

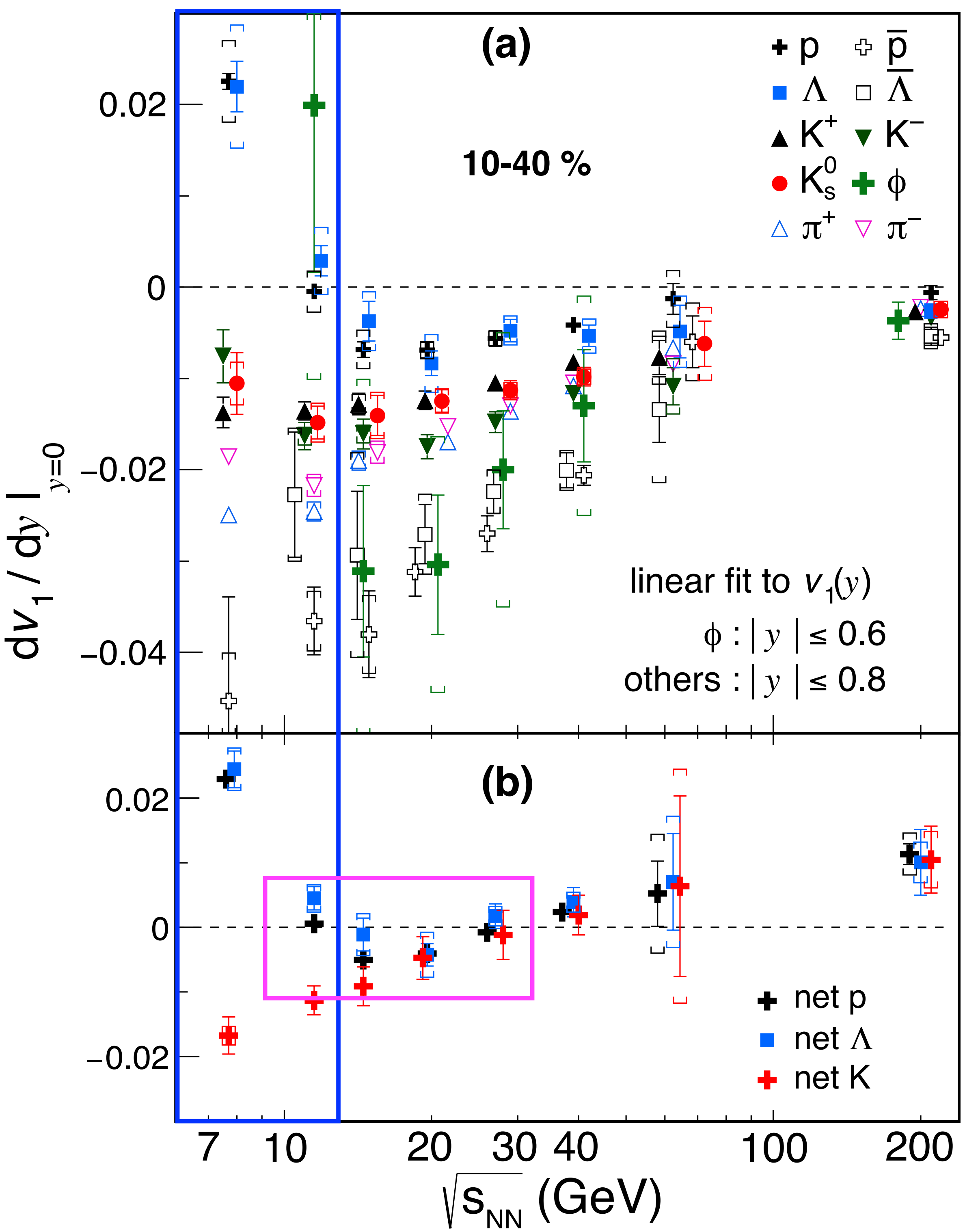


H. Stocker NPA750, 121-147(2005)



J. Brachmann et al. PRC 61, 024909 (2000)

Directed flow analysis



STAR PRL 120 (2018) 062301

- ✓ Opposite sign of dv_1/dy at midrapidity is observed for baryons and mesons at low energies.
- ✓ Minimum at $\sqrt{s_{NN}}$=10-20 GeV for net baryon is observed. This is called "softest point" and may be a possible sign of the first-order phase transition.
- ✓ Models cannot explain energy dependence of the directed flow
  - ➡ experiment:minimum at 10-20 GeV model:minimum at 4 GeV

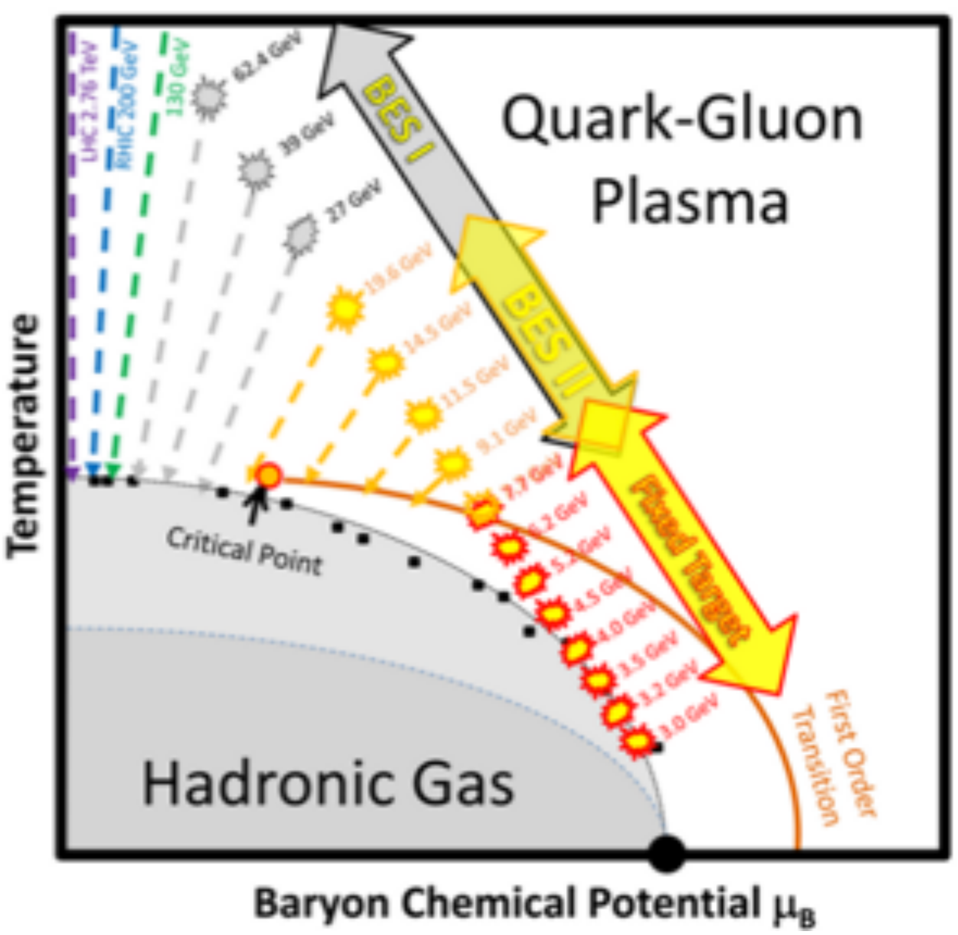
H. Stocker NPA750, 121-147(2005)

Motivation

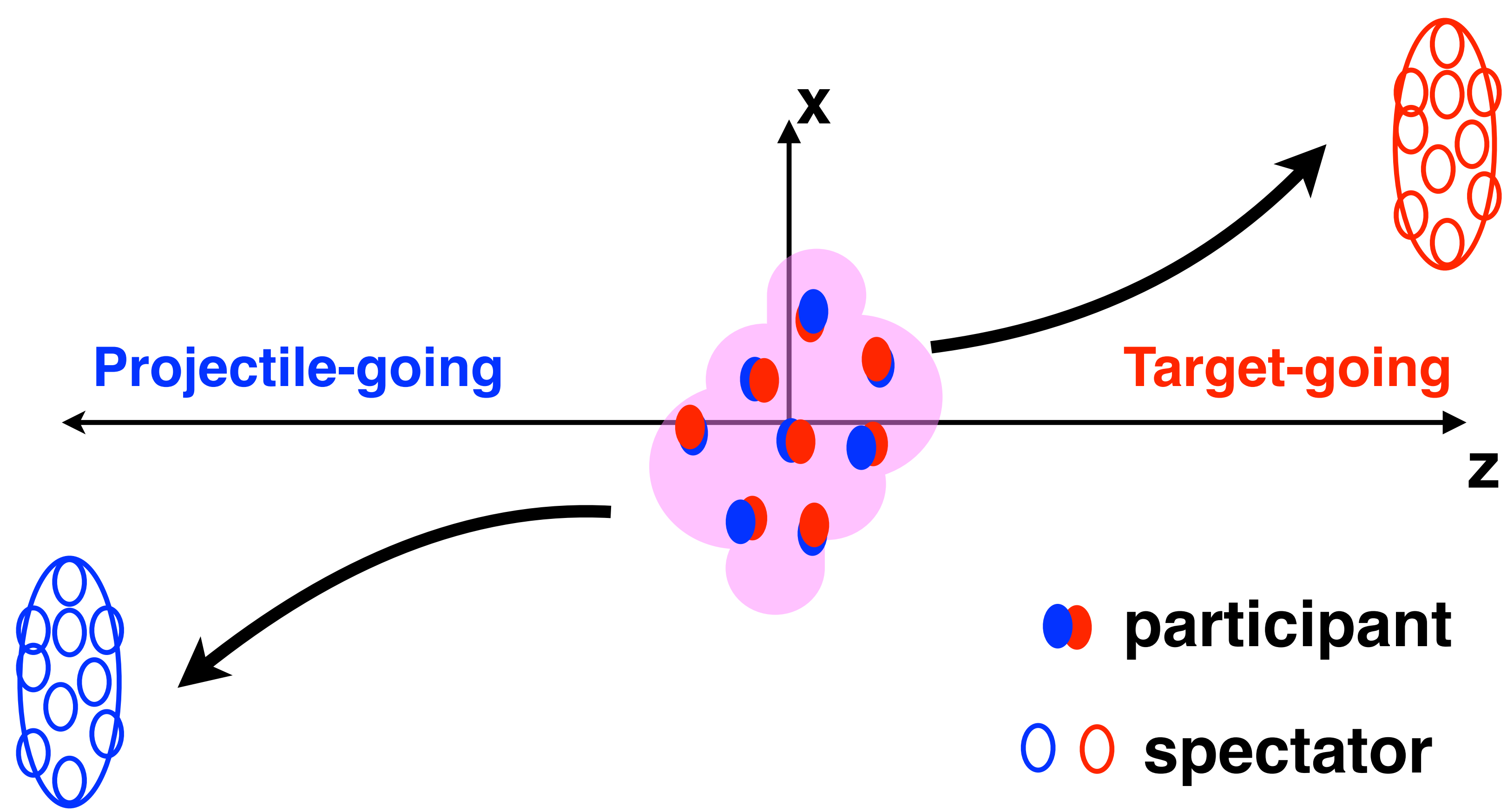
✓ The directed flow is an observable probe which suggested to be sensitive to the first-order phase transition.

✓ The fixed-target program extends the RHIC BES to higher μ_B.

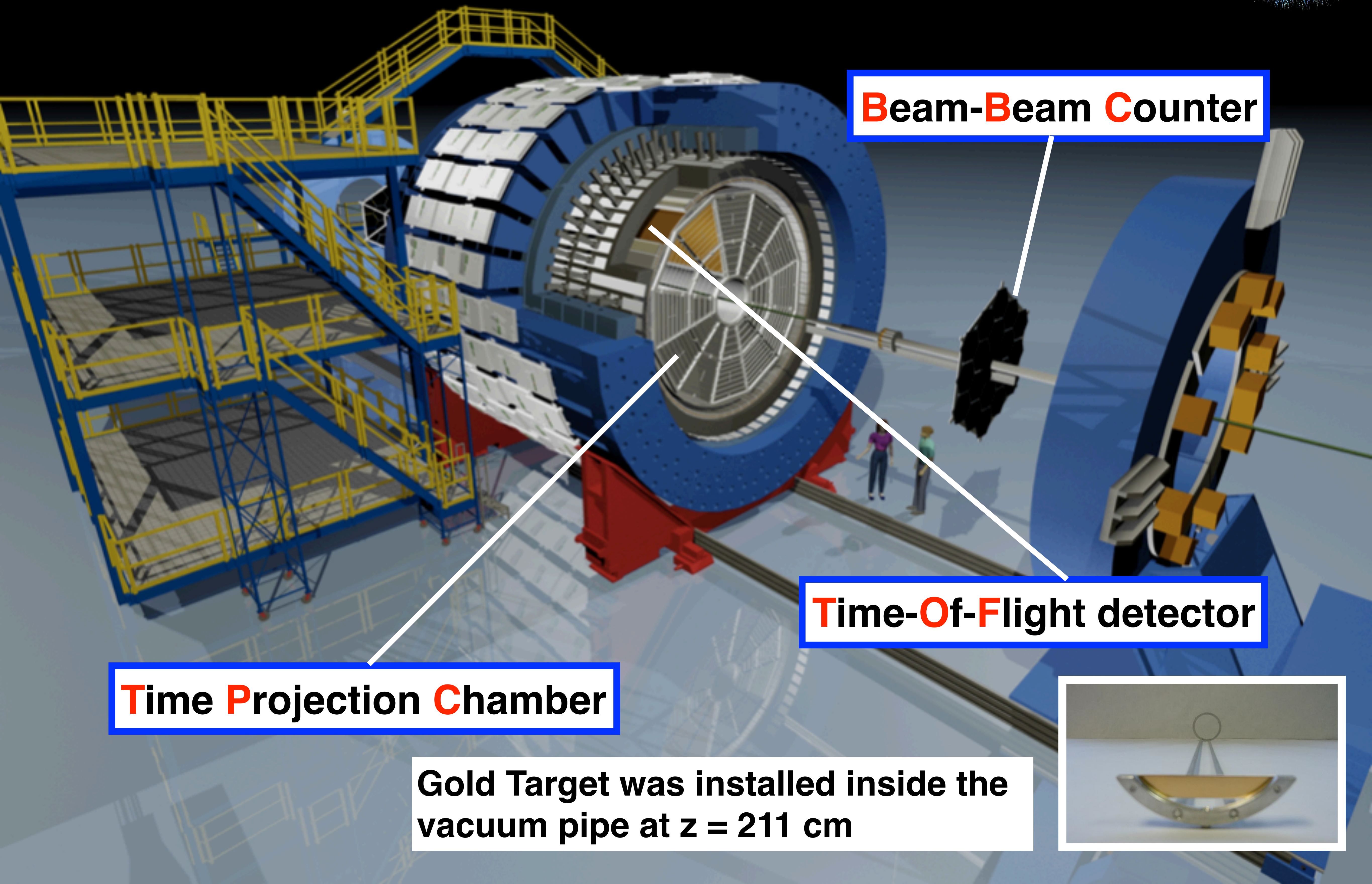
To clarify the structure of the first-order phase transition, study the characteristics of directed flow at low energies is important.



NPA (2017) 06.007
STAR,QM2017 proceeding

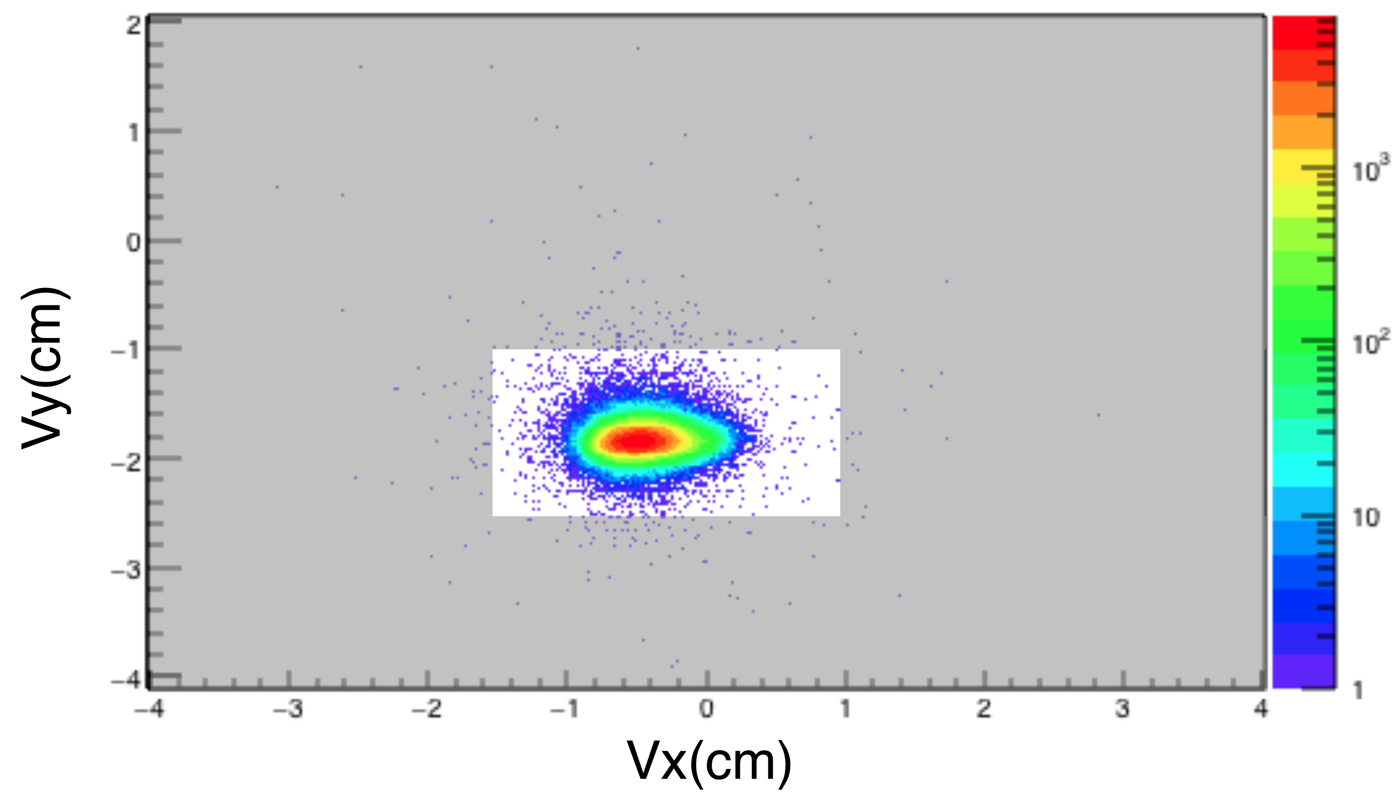


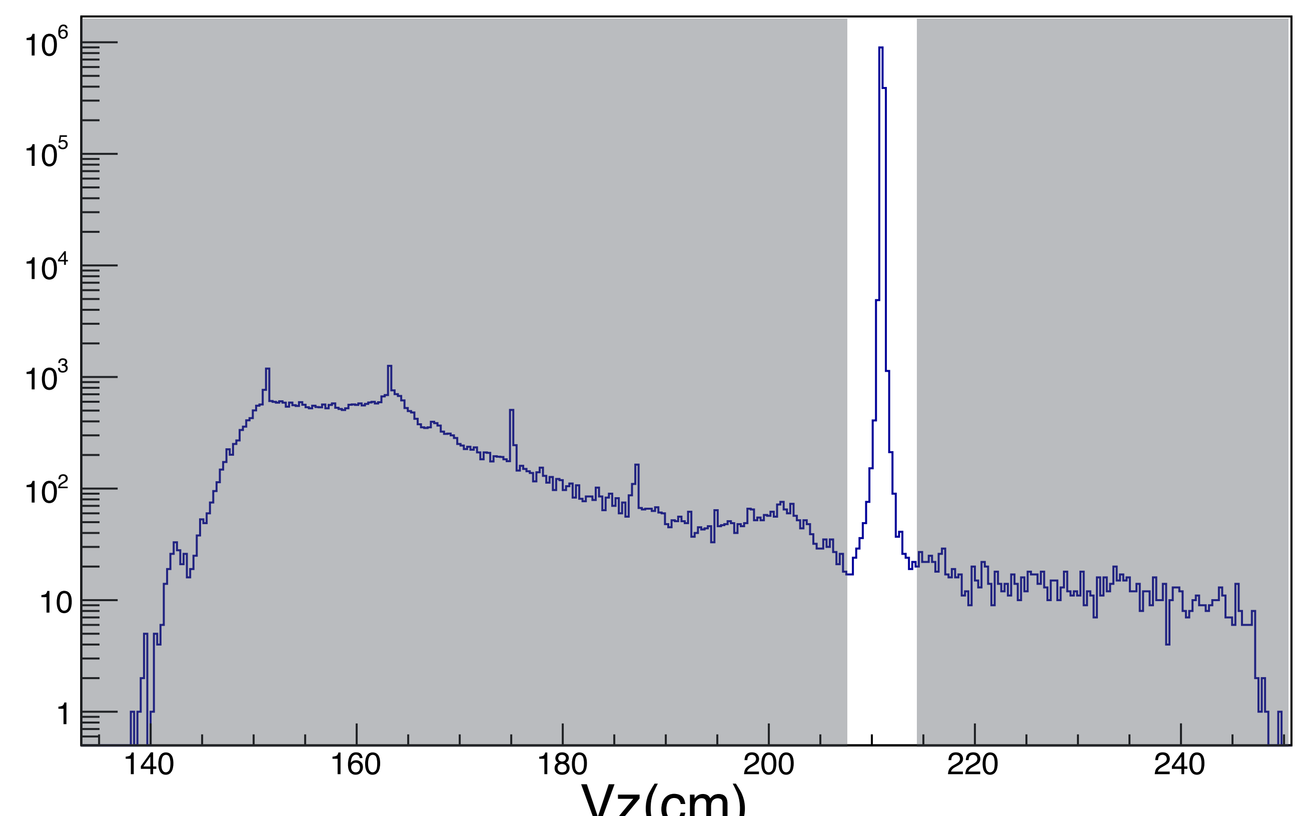
The Solenoidal Tracker At RHIC



Data selection

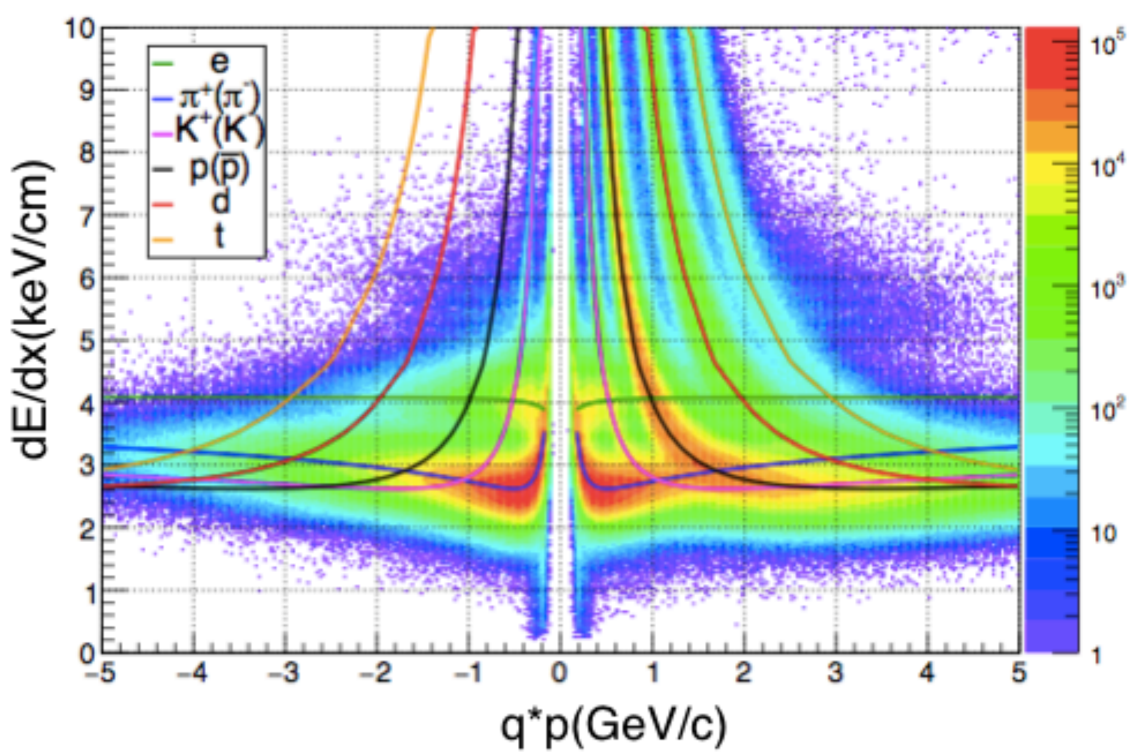
- **Data Set**
  - ✓ Au+Au : $\sqrt{s_{NN}}$=4.5 GeV
  - ✓ Test run conducted in 2015
  - ✓ 1.3 central million events
  - ✓ Midrapidity : -1.52
- **Event Selection**
  - ✓ Vertex X = -1.5 to 1.0 cm
  - ✓ Vertex Y = -2.5 to -1.0 cm
  - ✓ Vertex Z = 210 to 212 cm
- **Track Selection**
  - ✓ nHitsFit > 20
  - ✓ nHitFit/nHitsPoss > 0.52

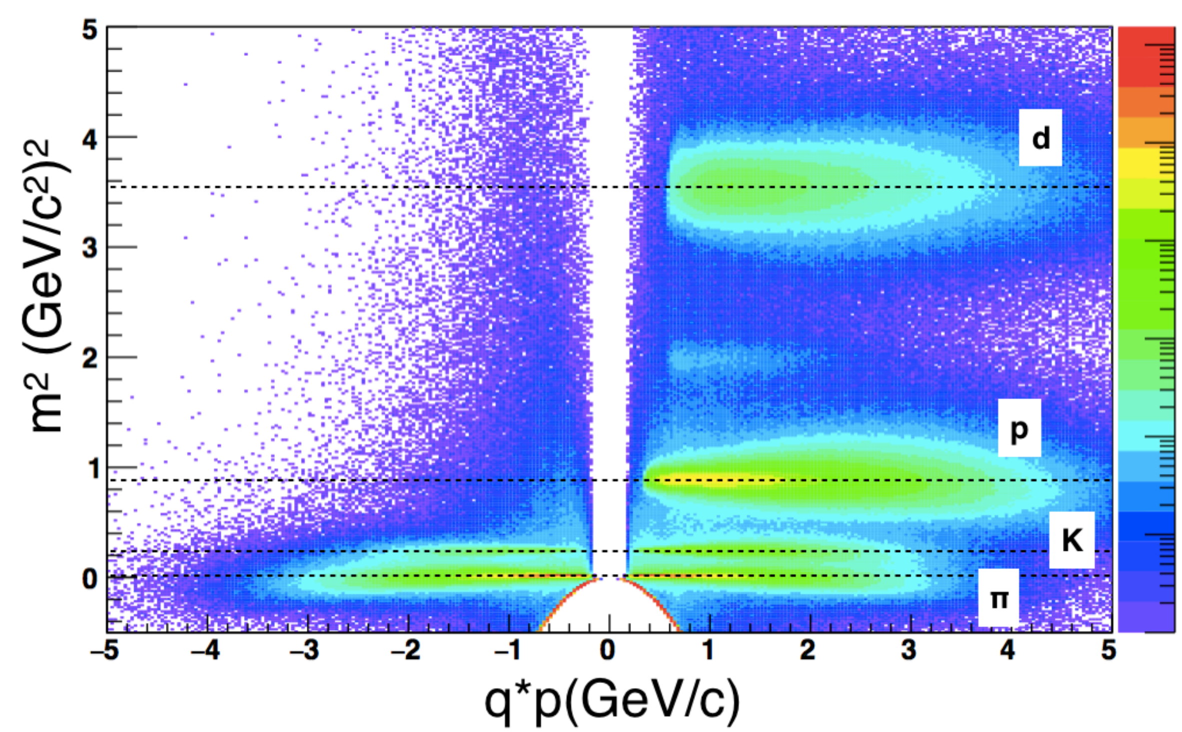




Particle identification

- π
  - ✓ $|n\sigma(\pi)| < 2$
  - ✓ $0.2 < p_T$ GeV/c
  - ✓ $p < 1.6$ GeV/c
  - ✓ $-0.15 < m^2 < 0.14$ $(GeV/c^2)^2$ (If TOF available)
- K
  - ✓ $|n\sigma(K)| < 2$
  - ✓ $p_T < 2.0$ GeV/c
  - ✓ $0.14 < m^2 < 0.4$ $(GeV/c^2)^2$ (If TOF available)
- P
  - ✓ $|n\sigma(p)| < 2$
  - ✓ $0.4 < p_T < 2.0$ GeV/c
  - ✓ $0.4 < m^2 < 1.4$ $(GeV/c^2)^2$ (If TOF available)
  - ✓ If no hit in TOF, but satisfying other selection criteria, track is kept as a proton candidate.





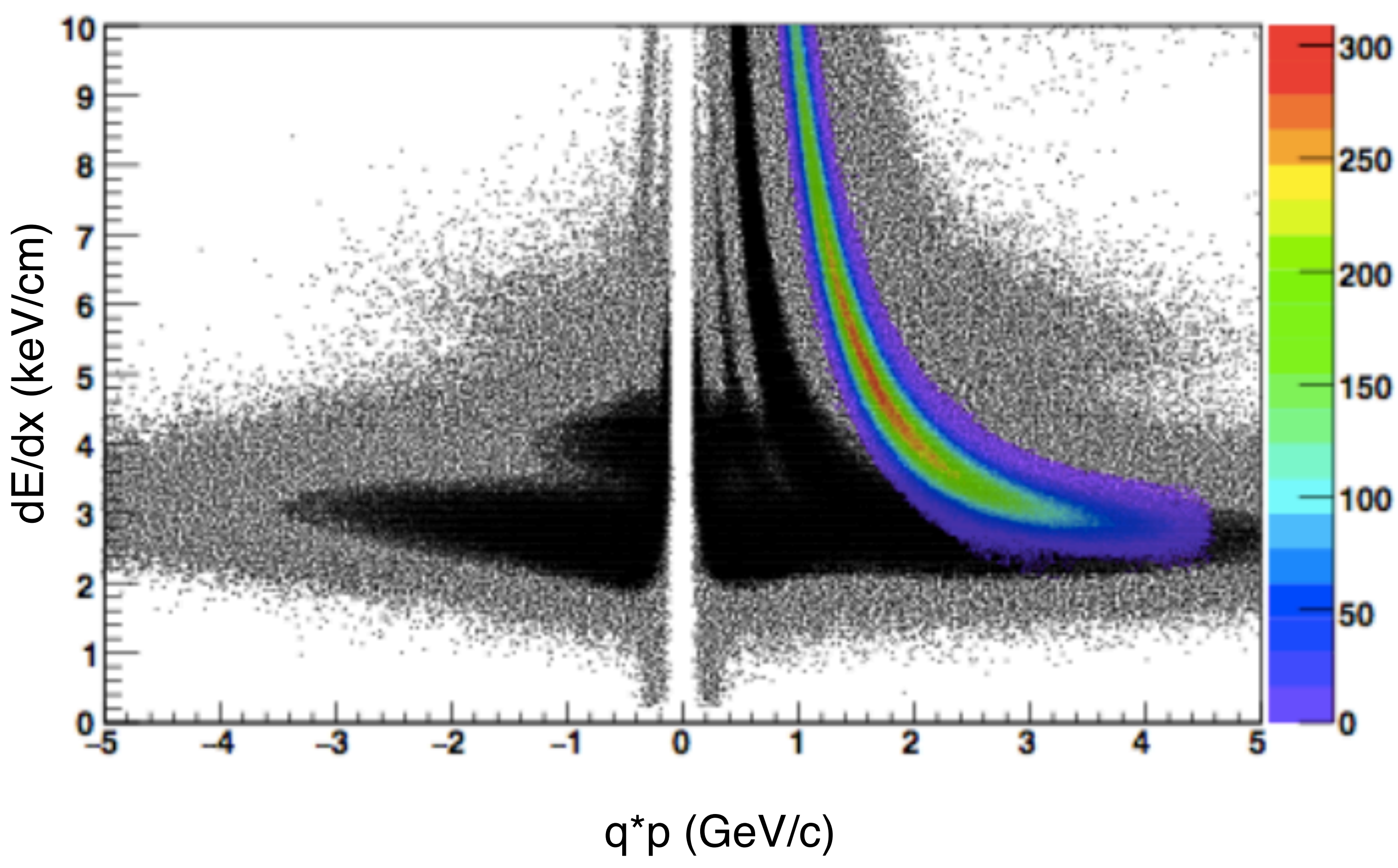
Deuteron identification

- **Deuteron**
  - ✓ $2.8 < m^2 < 4.5\ (GeV/c^2)^2$
  - ✓ $|n\sigma(d)| < 3\sigma_1$

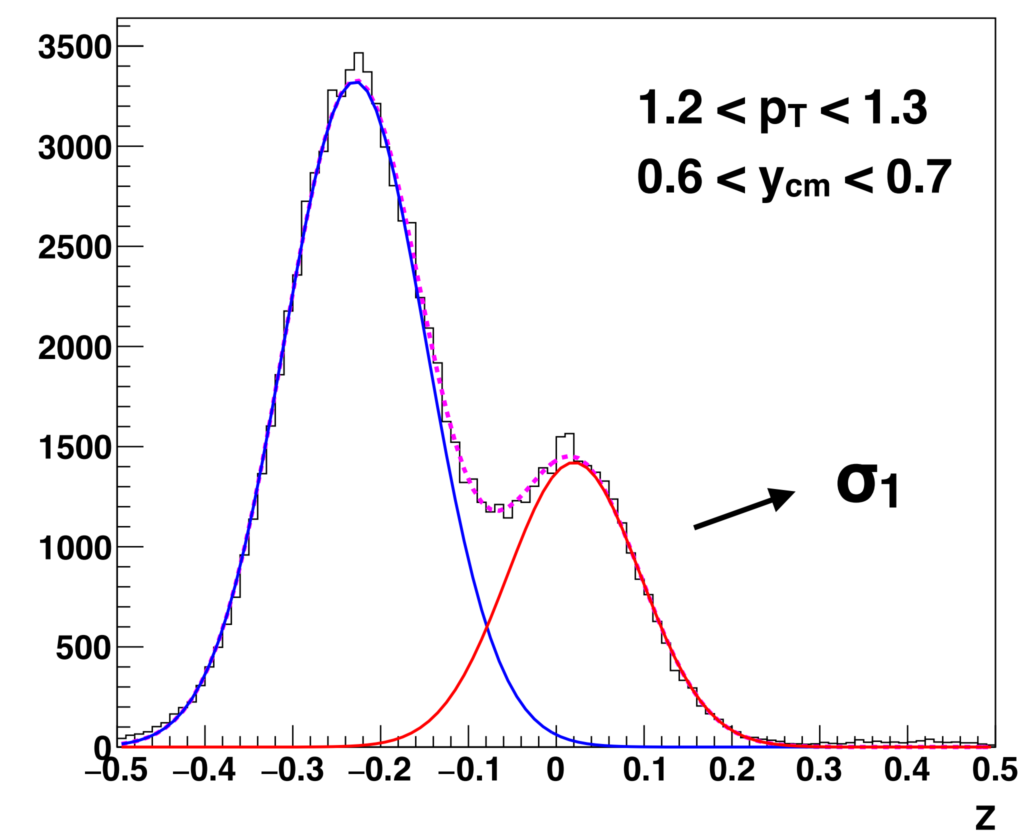
"$n\sigma(d)$" can be obtained by Gaussian fitting of Z.

"Z" is ratio of the measured ionization energy loss to theoretical value.

Evaluate and fit Z distribution for each p_T and y_{cm} region



$$Z = log((dE/dx)|_{exp}/(dE/dx)|_{th})$$



EP method

1. Define event plane from the direction in which the generated particles are emitted.

$$\Psi_1 = \tan^{-1}\left(\frac{\Sigma w_i \sin\phi_i}{\Sigma w_i \cos\phi_i}\right)$$

2. Event plane distortion from detector non-uniformity and/or beam offset are corrected using the recentering and flattening methods.

3. Perform the Fourier expansion of the angular distribution of particles.

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

→

$$v_1 = \langle \cos(\phi - \Psi) \rangle$$

4. Measured v_n include the effect of the finite detector resolution that can be corrected using so-called event plane resolution correction.

I. Selyuzhenkov and S. Voloshin, PRC 77 (2008), 034904
A.M.Poskanzer, S.A.Voloshin,PRC 58 (1998), 1671-1678

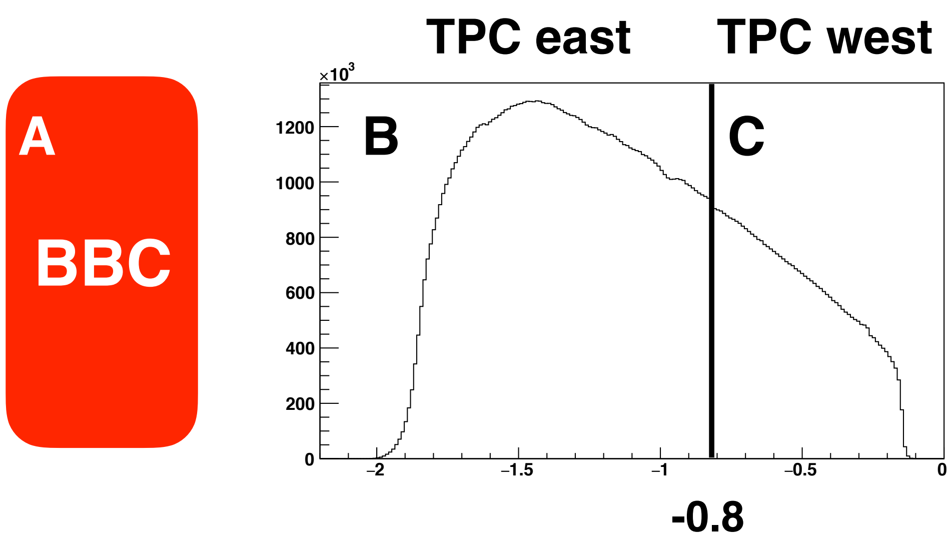
Event plane method : 2 or 3 subevents

2 subevents

Divide into 2 groups using random number (group A and B)

➡Because A and B are essentially the same, we calculate resolution using 2 subevents.

3 subevents



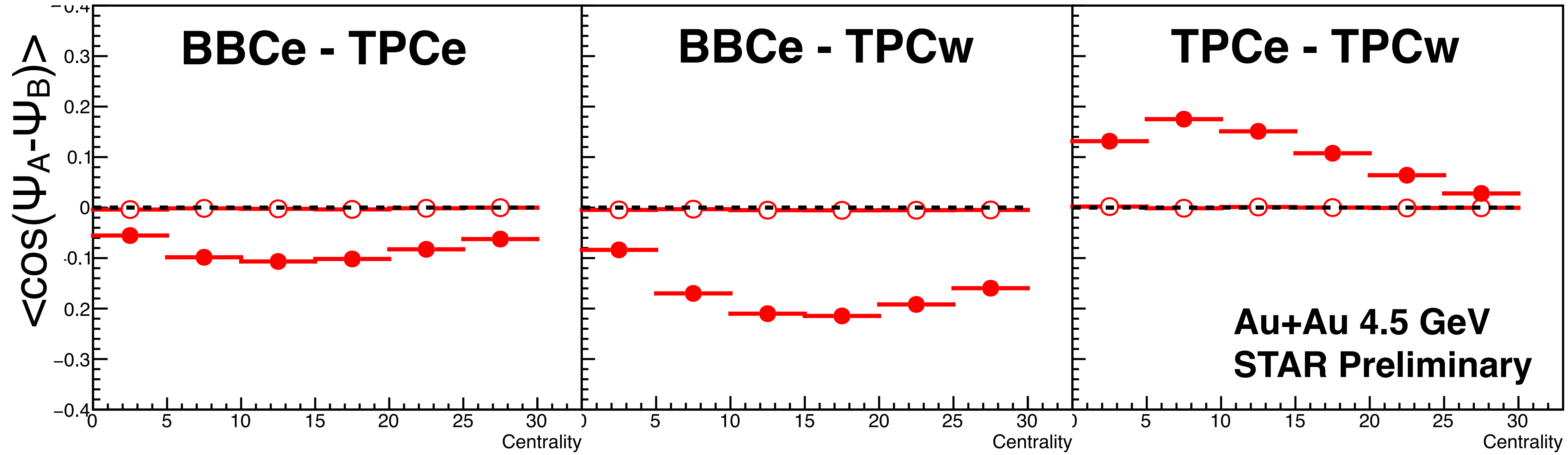
$$
\begin{aligned}
< cos(n[\Psi_n^A - \Psi_n^B]) > &= < cos(n[\Psi_n^A - \Psi_n^{true}]) >< cos(n[\Psi_n^{true} - \Psi_n^B]) > \\
&= \sigma_n^A \sigma_n^B \\
< cos(n[\Psi_n^A - \Psi_n^C]) > &= < cos(n[\Psi_n^A - \Psi_n^{true}]) >< cos(n[\Psi_n^{true} - \Psi_n^C]) > \\
&= \sigma_n^A \sigma_n^C \\
< cos(n[\Psi_n^B - \Psi_n^C]) > &= < cos(n[\Psi_n^B - \Psi_n^{true}]) >< cos(n[\Psi_n^{true} - \Psi_n^C]) > \\
&= \sigma_n^B \sigma_n^C
\end{aligned}
$$

Assuming a true event plane, calculate the resolution by taking correlations for each two of three regions.

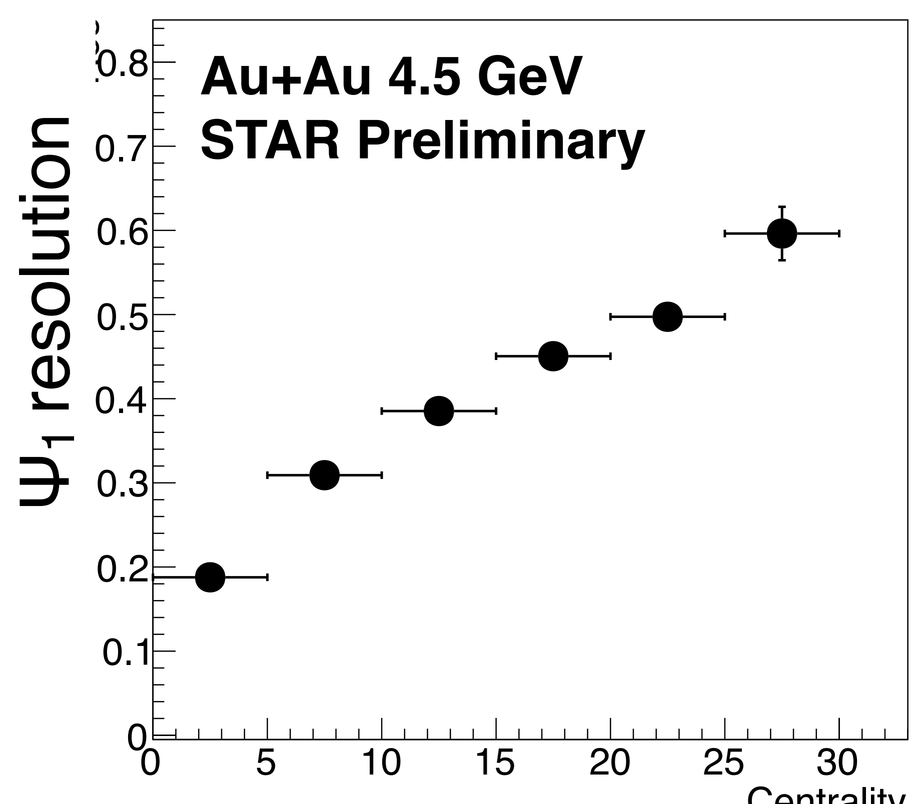
$$
Res_A = \sqrt{\frac{\sigma_{AB} \cdot \sigma_{AC}}{\sigma_{BC}}}
$$

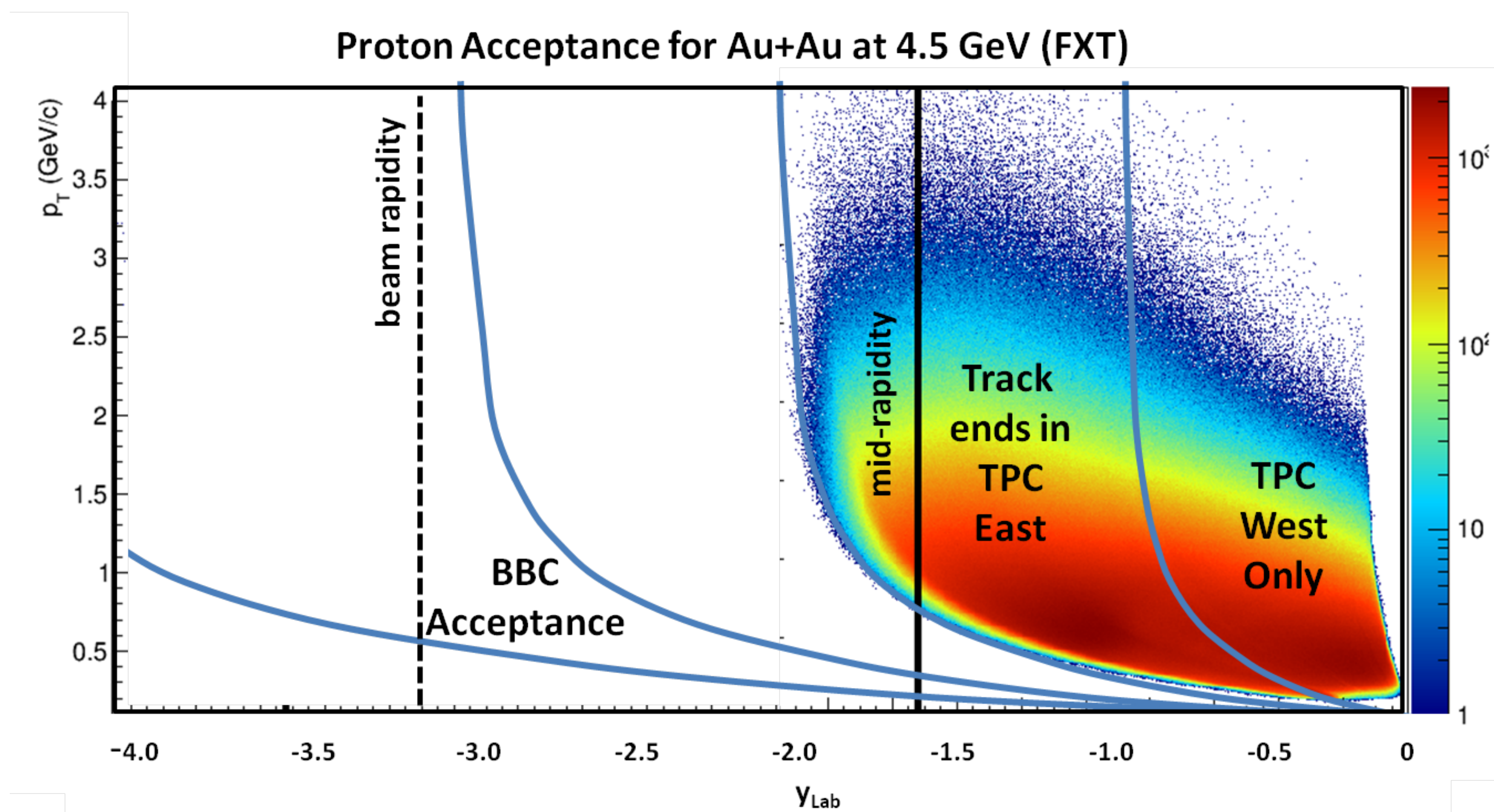
EP correlation and resolution

EP Correlation



EP Resolution (BBCe)





Systematic uncertainty

1. 2 TPC subevent planes divided at y = -0.8, and BBC east.
2. Randomly assigning particles to subevent A or B. Use charged particles.
3. Randomly assigning particles to subevent A or B. Use not protons.
4. Randomly assigning particles to subevent A or B. Use protons only.

3 subevents

$$Res_A = \sqrt{\frac{\sigma_{AB} \cdot \sigma_{AC}}{\sigma_{BC}}}$$

Systematic uncertainty from EP definition difference.

2 subevents

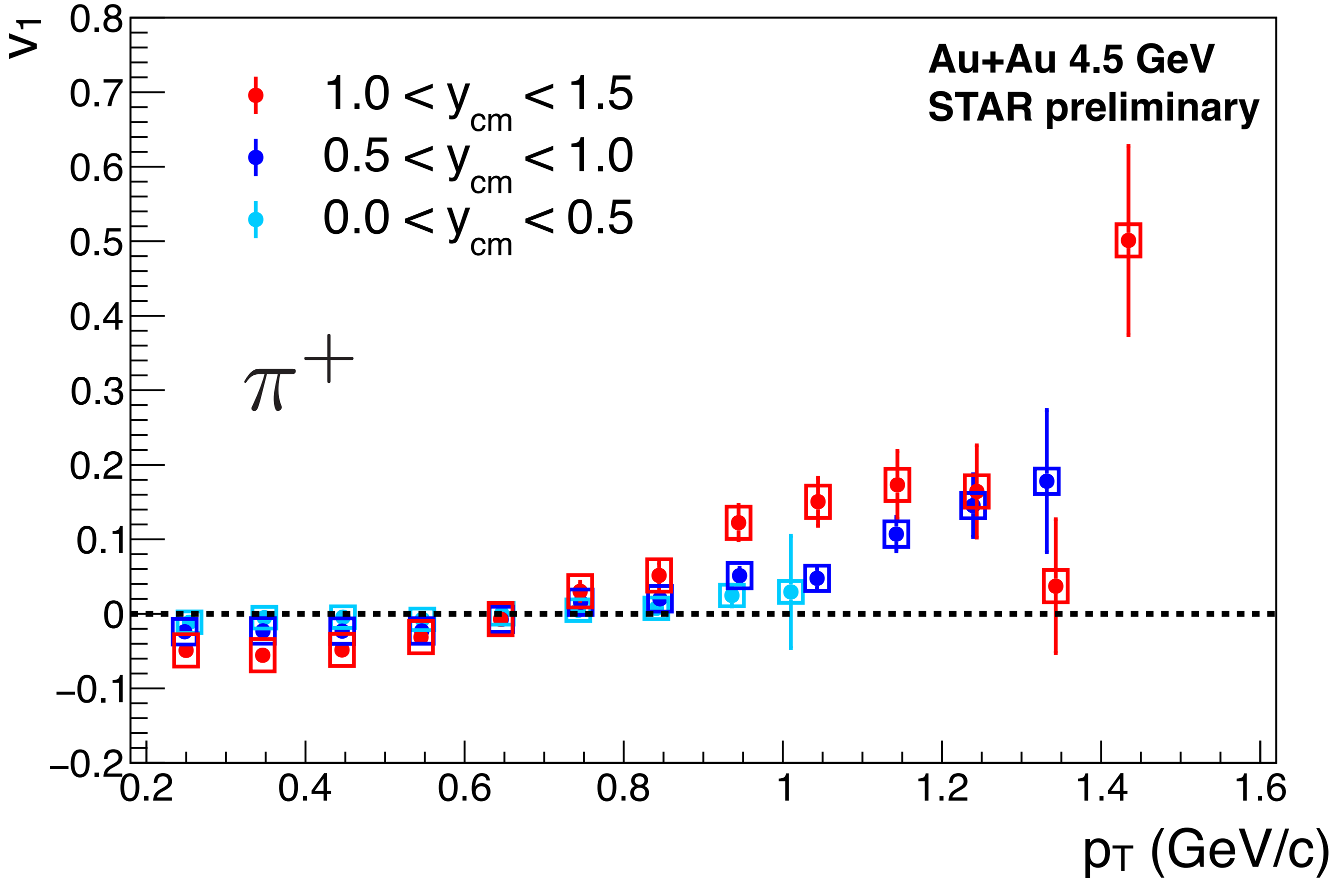
$$Res_A = Res_B = \sqrt{\langle cos(\Psi_A - \Psi_B)\rangle}$$

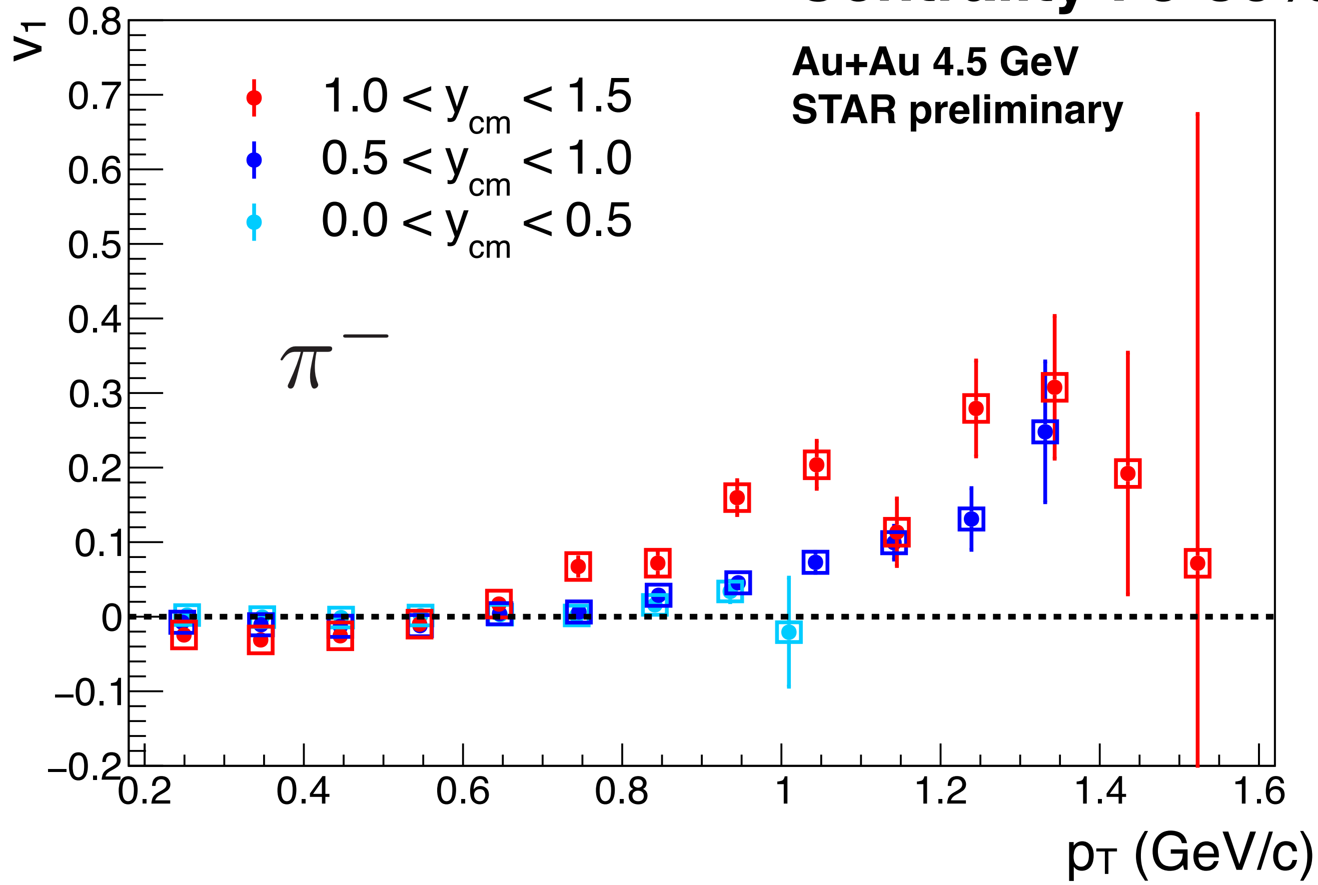
Systematic uncertainty

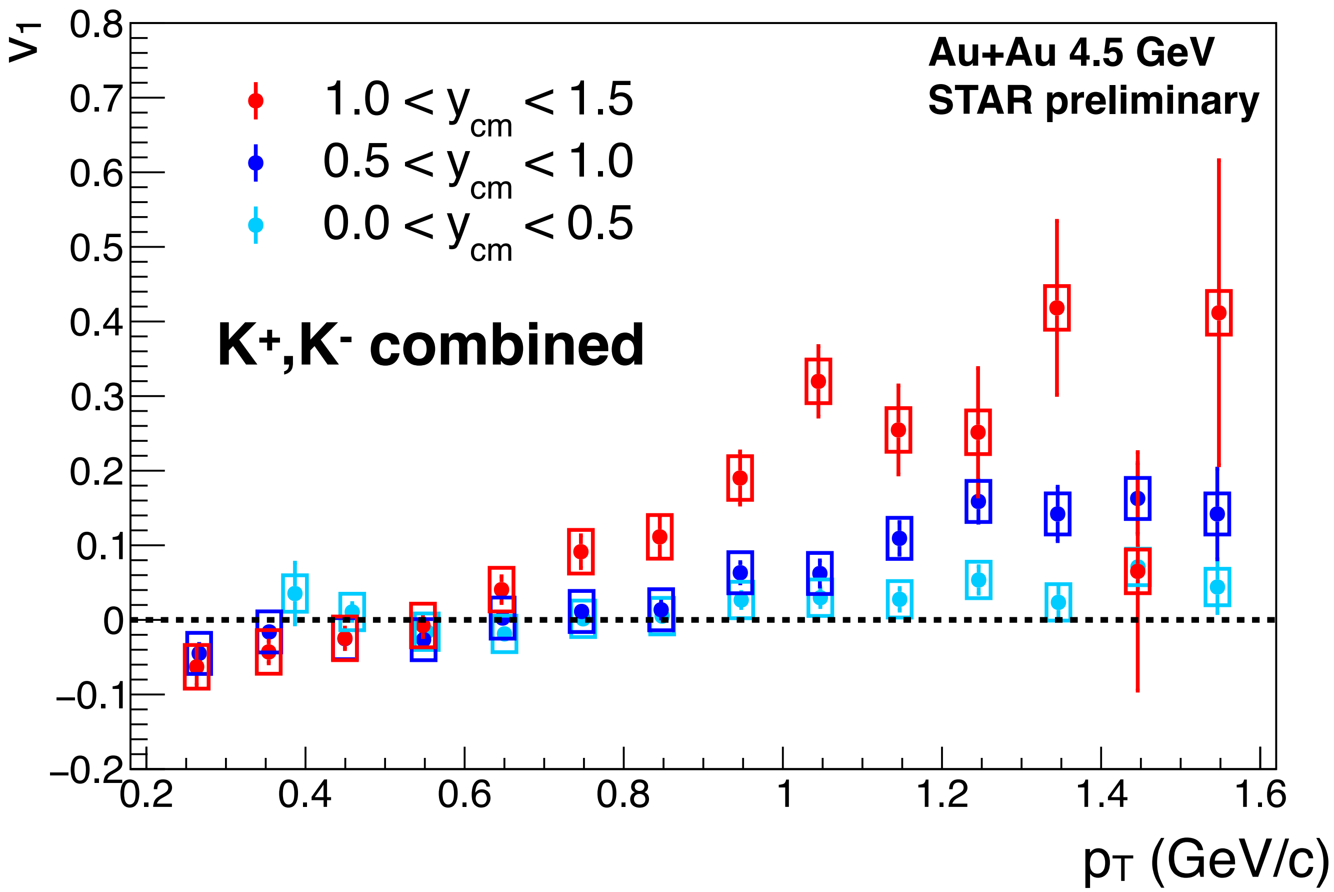
$$Err_{sys}^2 = \frac{\sum_{n=1}^{N}(x_i - x_{ave})^2}{N}$$

p_T dependence of v_1 (π, K)

Centrality : 5-30%





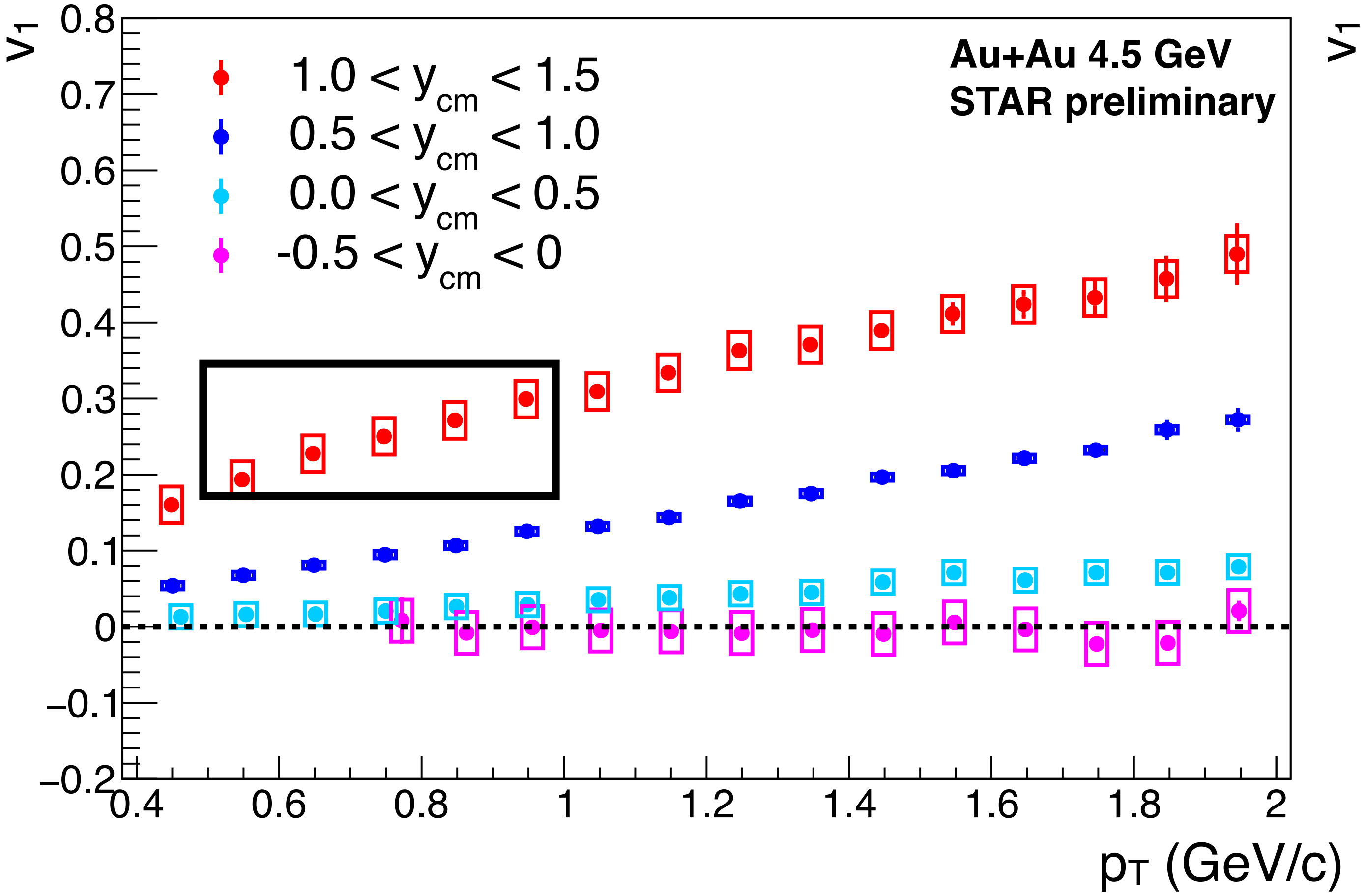


- ✓ **All particle species have similar p_T dependence.**
- ✓ **v_1 changes sign at $p_T \approx 0.6$ GeV/c.**
- ✓ **v_1 may increase with increasing y_{cm}.**
- ✓ **Sys. uncertainty from EP determination.**

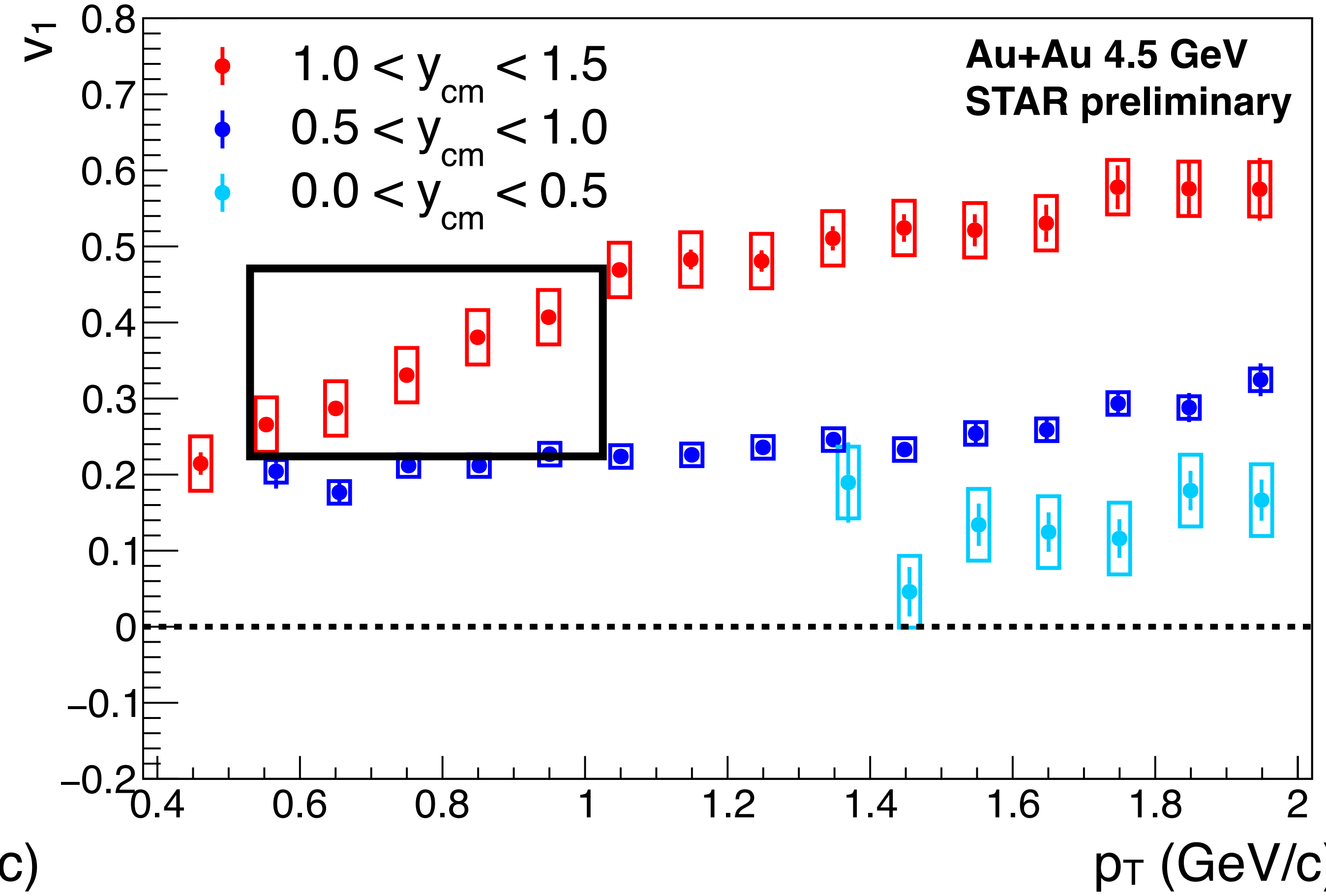
p_T dependence of v_1 (p, d)

Centrality : 5-30%

proton

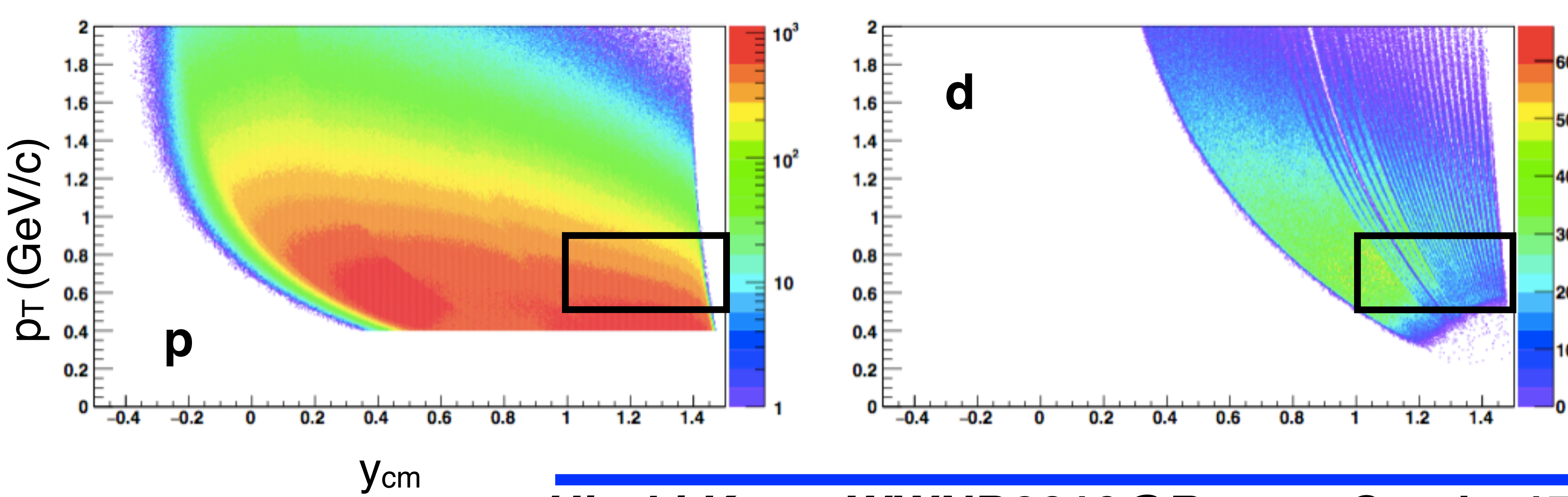


deuteron

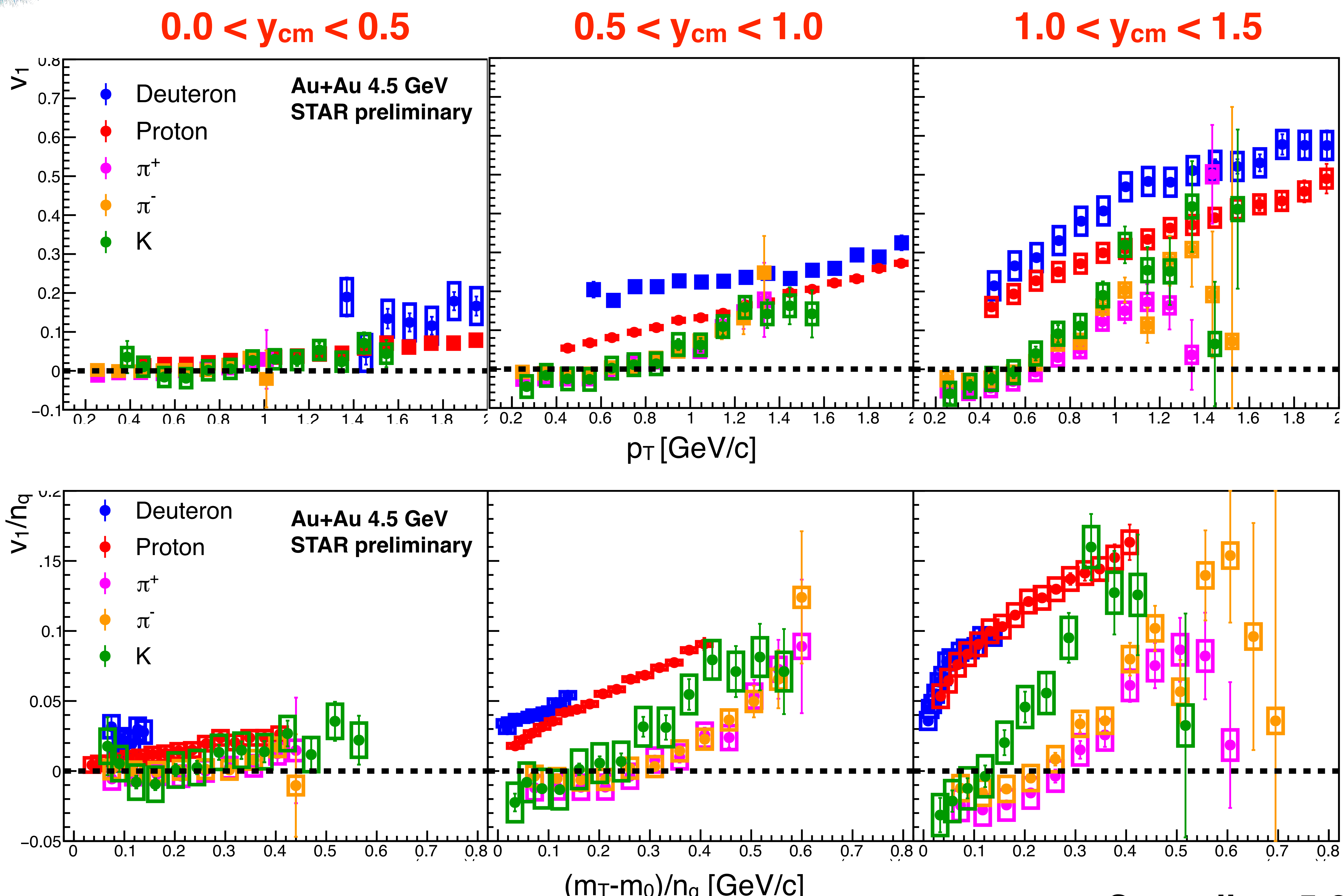


v_1 increases with increasing p_T at $1.0<y_{cm}<1.5$

Detector acceptance effects have been taken into account



Result of NCQ scaling (m_T-scaling)

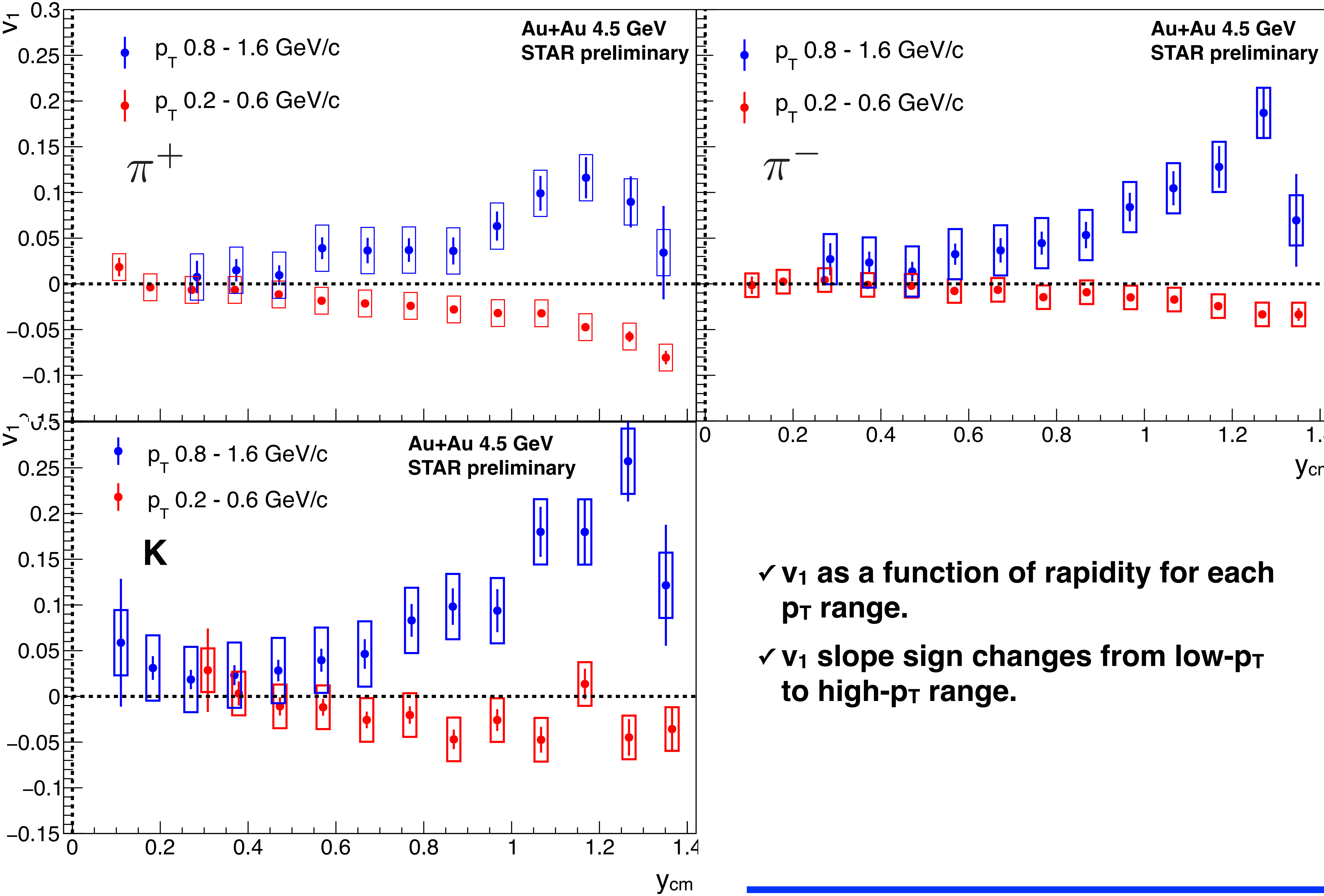


Centrality : 5-30%

✓ v_1 values of p and d become closer to each other after m_T-scaling is performed.

Rapidity dependence of v_1 (π, K)

centrality : 5-30%



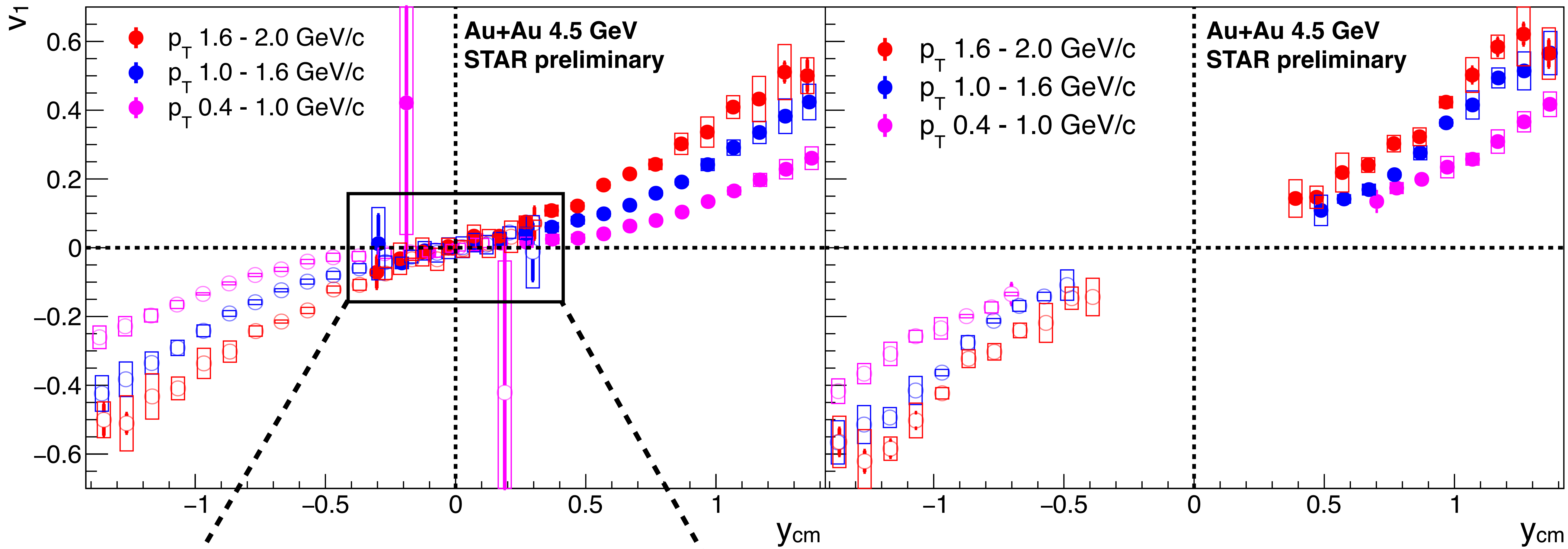
- ✓ v_1 as a function of rapidity for each p_T range.
- ✓ v_1 slope sign changes from low-p_T to high-p_T range.

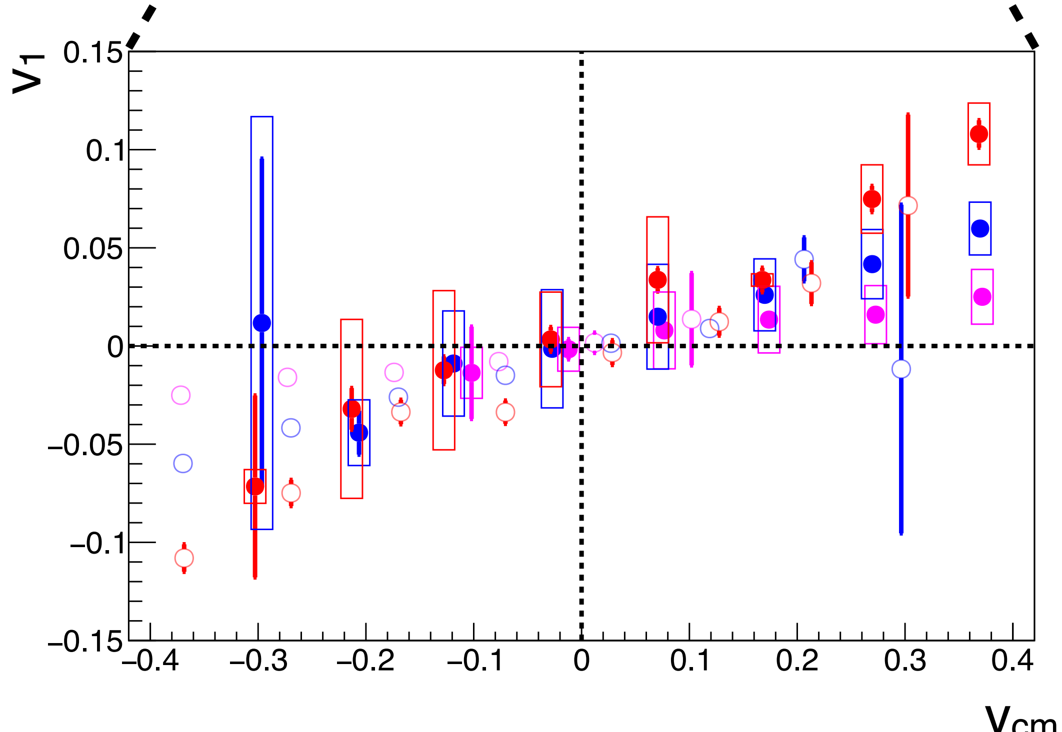
Rapidity dependence of v_1 (p, d)

centrality : 5-30%

Open marker is reflected

proton **deuteron**





reflected marker shown stat. err only

- ✓ v_1 as a function of rapidity for each p_T range.
- ✓ Data and reflected points are consistent within stat. and sys. uncertainty.
- ✓ Deuteron v_1 cannot be measured near midrapidity because of the detector acceptance.

Summary of v_1 analysis

π, K

✓v_1 sign is negative at low p_T, and is positive at high p_T.

✓p_T dependence is consistent for π^+, π^- and K.

p, d

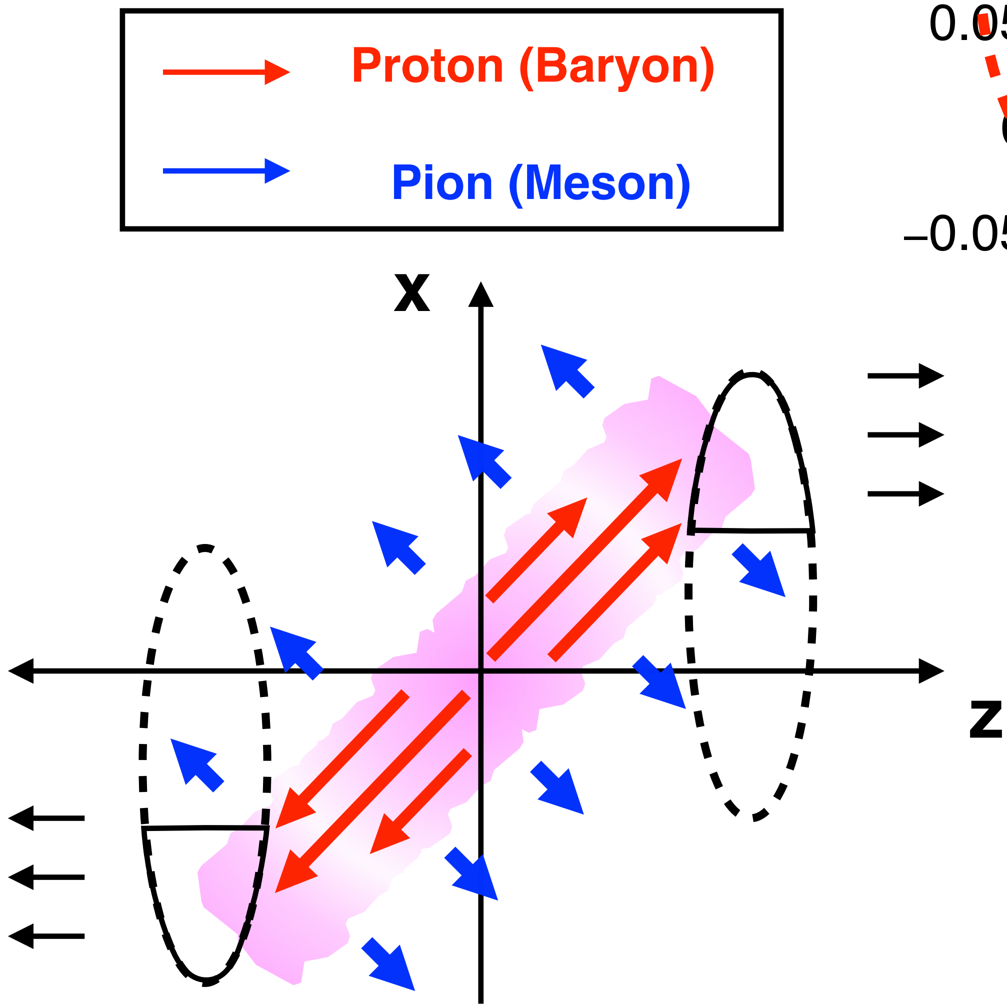
✓v_1 increases with increasing p_T.

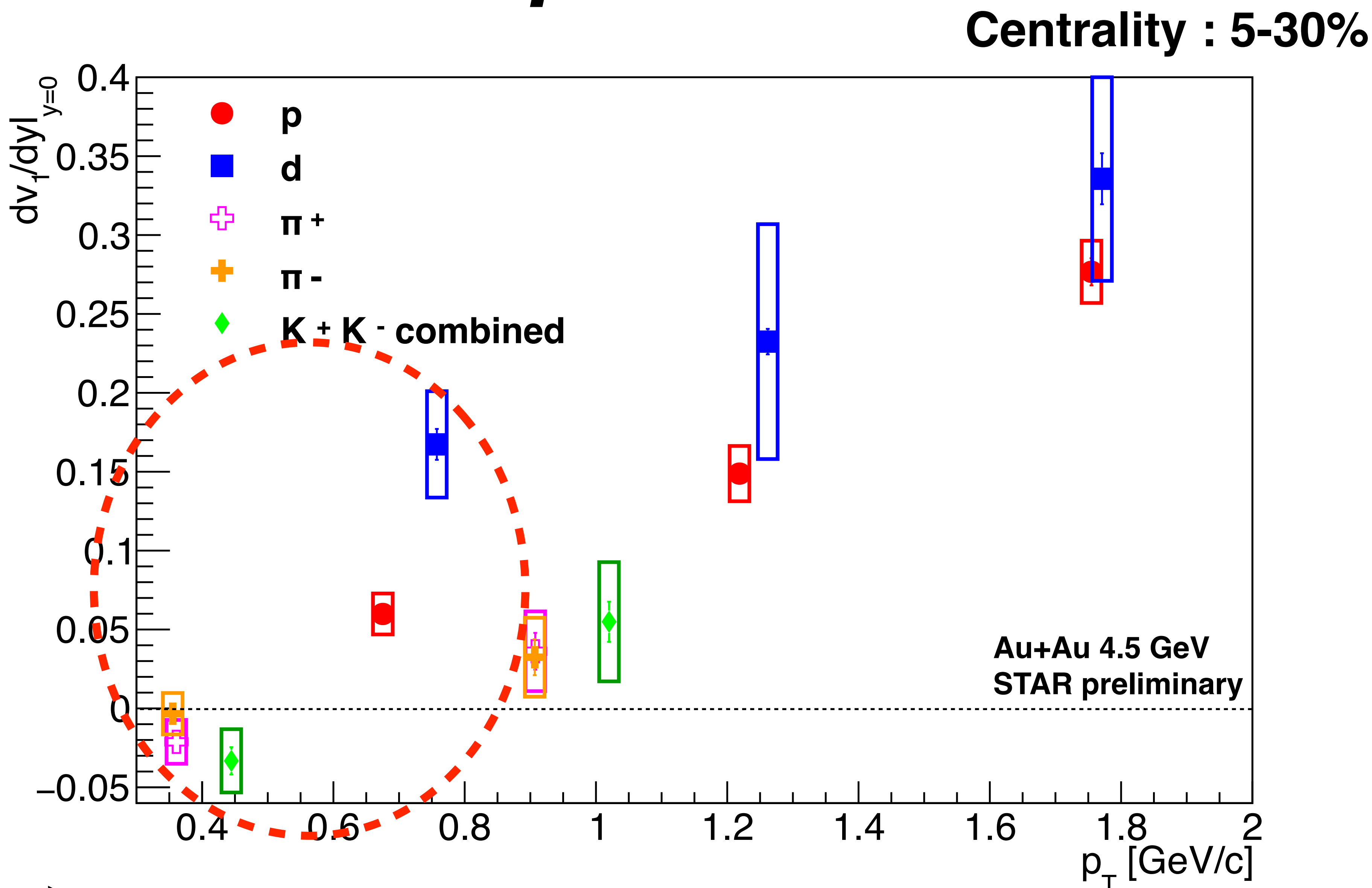
✓v_1 of p and d become closer after performing the m_T-scaling.

p_T dependence of v_1 slope

The 3 fit functions were used for $dv_1/dy|_{y=0}$ systematic uncertainty estimation:

$$Fy$$
$$Fy + F_3y^3$$
$$Fy + F_3y^3 + F_5y^5$$





Low-p_T region→Shadowing effect is dominant

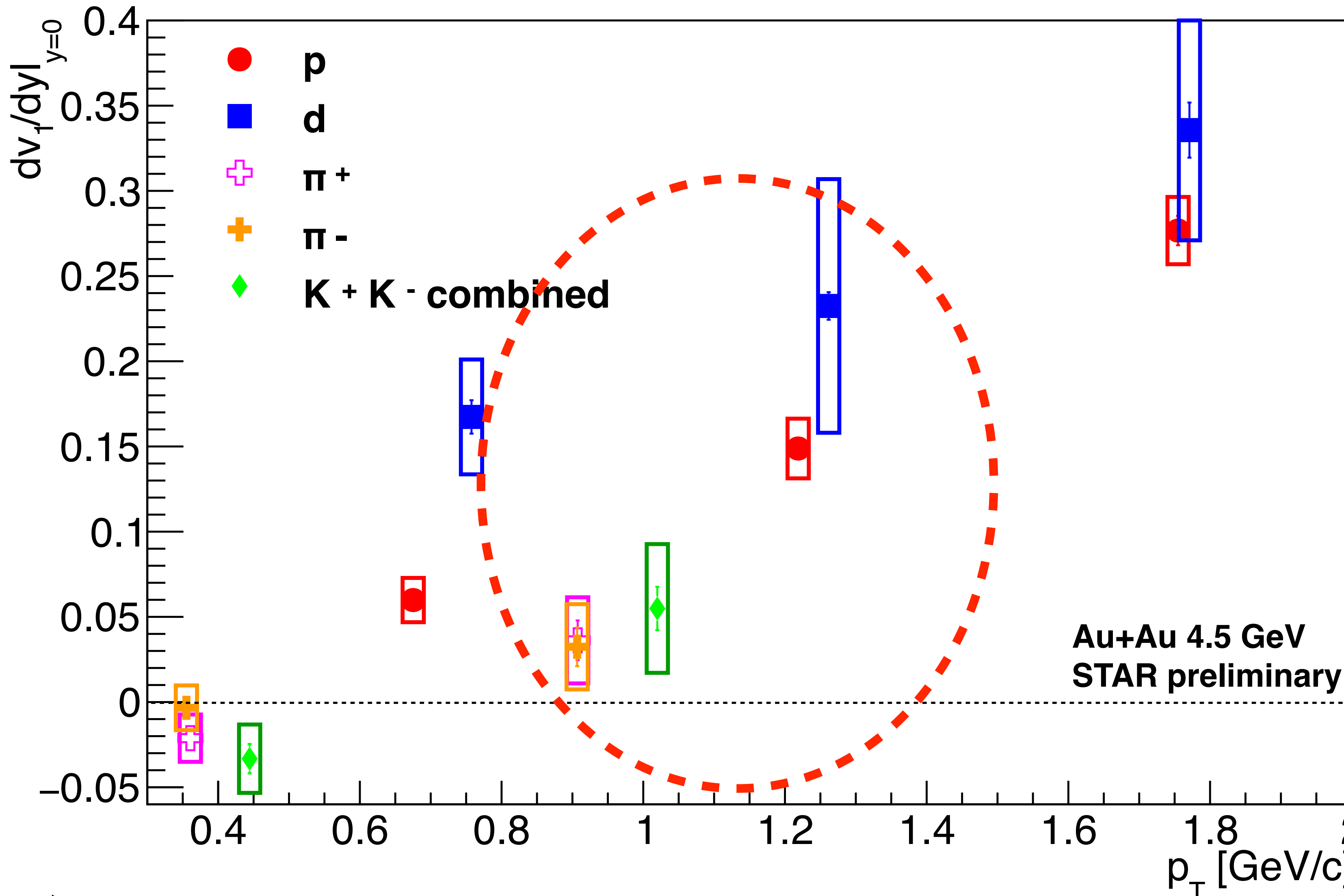
- ✓ Interaction between produced pions and kaons with the spectator nucleons. Shadowing due to the baryon-meson interactions.
- ✓ Proton (baryon) and pion/kaon (mesons) have the opposite direction of v_1 slope.

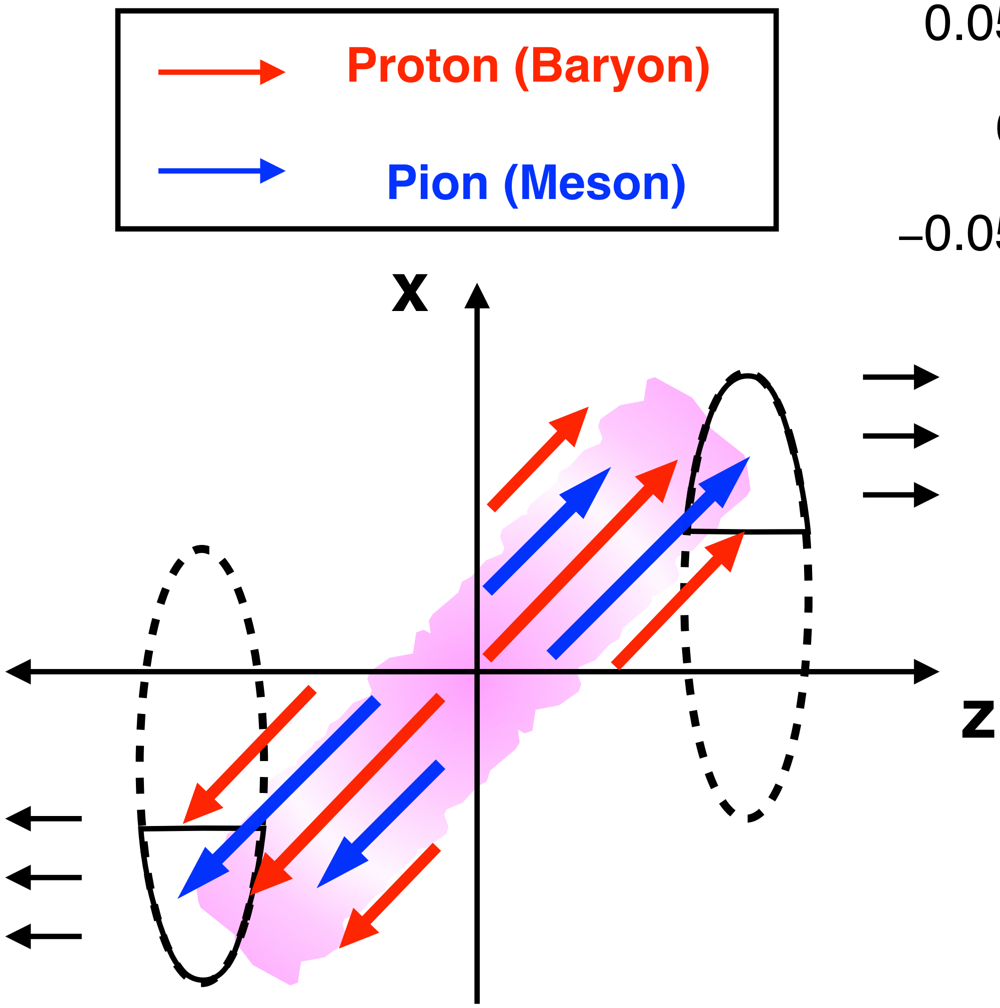
p_T dependence of v_1 slope

Centrality : 5-30%

The 3 fit functions were used for $dv_1/dy|_{y=0}$ systematic uncertainty estimation:

$$Fy$$
$$Fy + F_3y^3$$
$$Fy + F_3y^3 + F_5y^5$$





High-p_T region

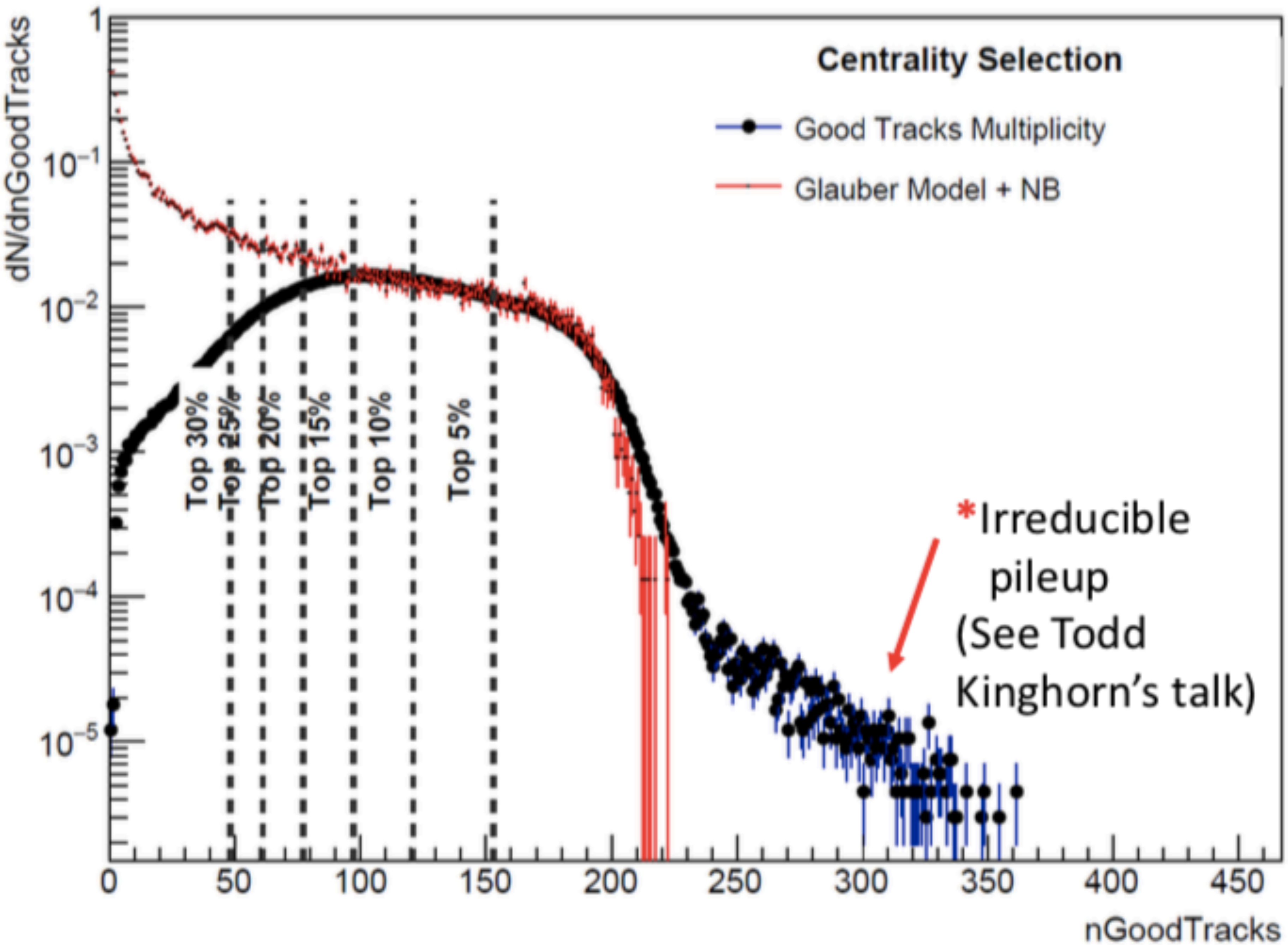
➡ collective flow influence is considered to be more dominant than the shadowing effect.

Summary and Outlook

- ✓ We presented the results of the identified particle directed flow at $\sqrt{s_{NN}}$ = 4.5 GeV in Au+Au fixed-target collisions as a function of p_T and rapidity.
- ✓ Baryon and meson dv_1/dy slopes indicate opposite sign due to the shadowing effect.
- ✓ v_1 of baryons and mesons have the same sign at high-p_T region (> 0.8 GeV/c), which is averaged out in the previous measurement.
- ✓ The STAR FXT physics program is now ongoing (>300 million event at 3.0 and 7.2 GeV in 2018, will acquire > 100 million events at series of energies from 3.2 to 7.7 GeV from 2019-2021). Higher statistics will allow a more definitive physics message.

Back up

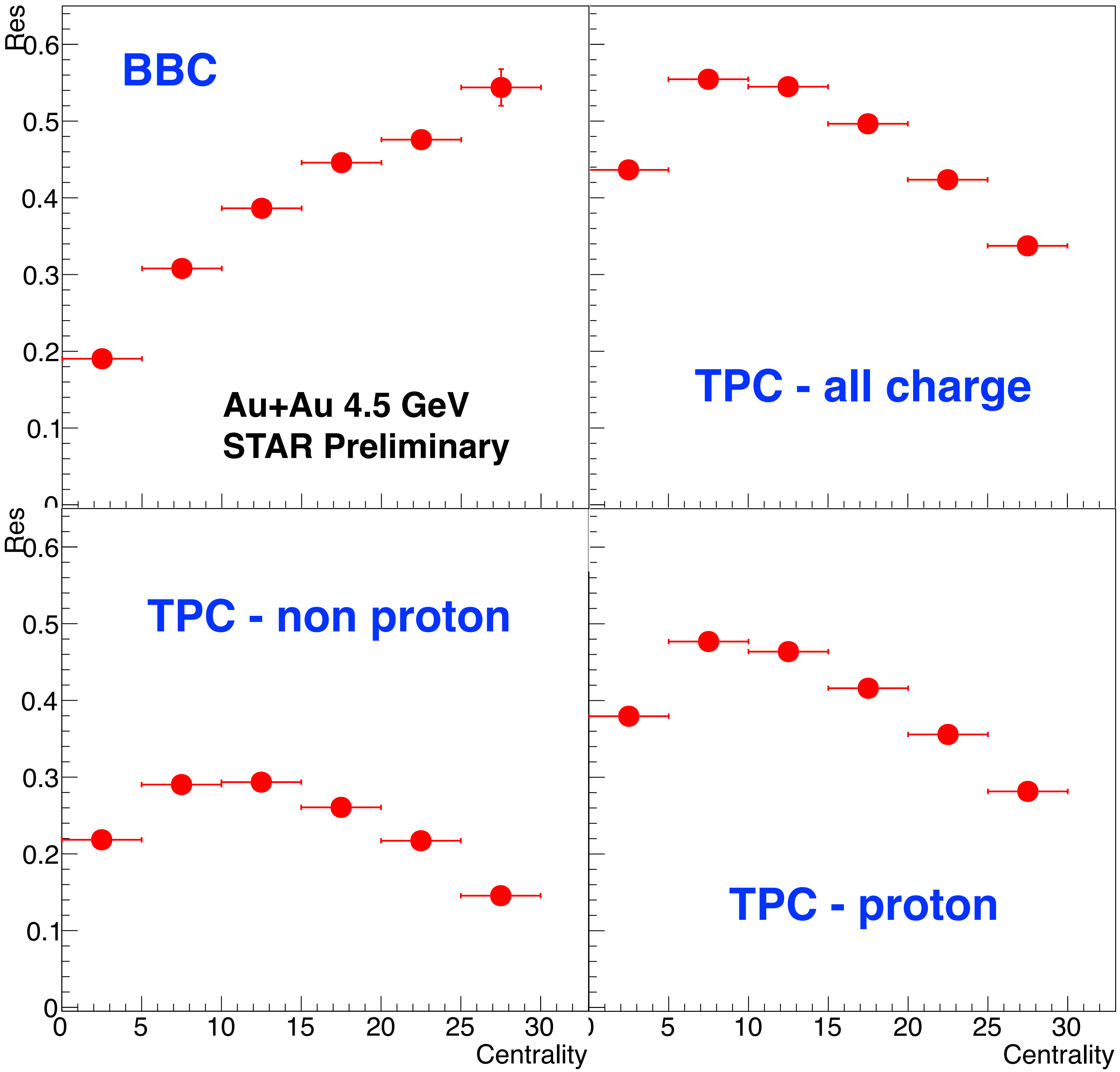
Centrality definition



Centrality Bin	Multiplicity cut
0~5%	153
5~10%	121
10~15%	97
15~20%	77
20~25%	61
25~30%	48

CBM-STAR joint Workshop
TU Darmstadt(Daniel Cebra)

EP resolution for each region



EP correction