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

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U.S. DEPARTMENT OF ENERGY

STAR

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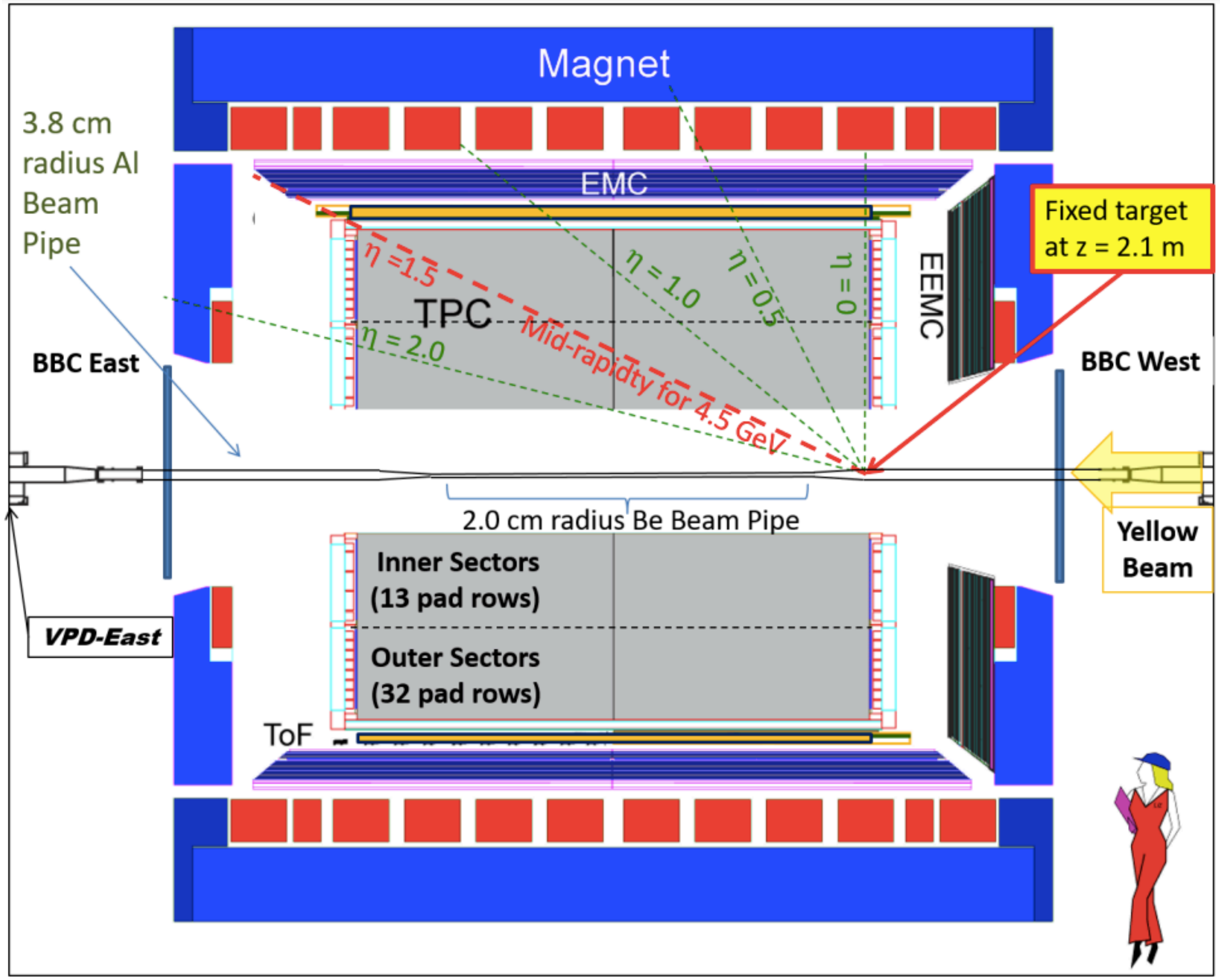
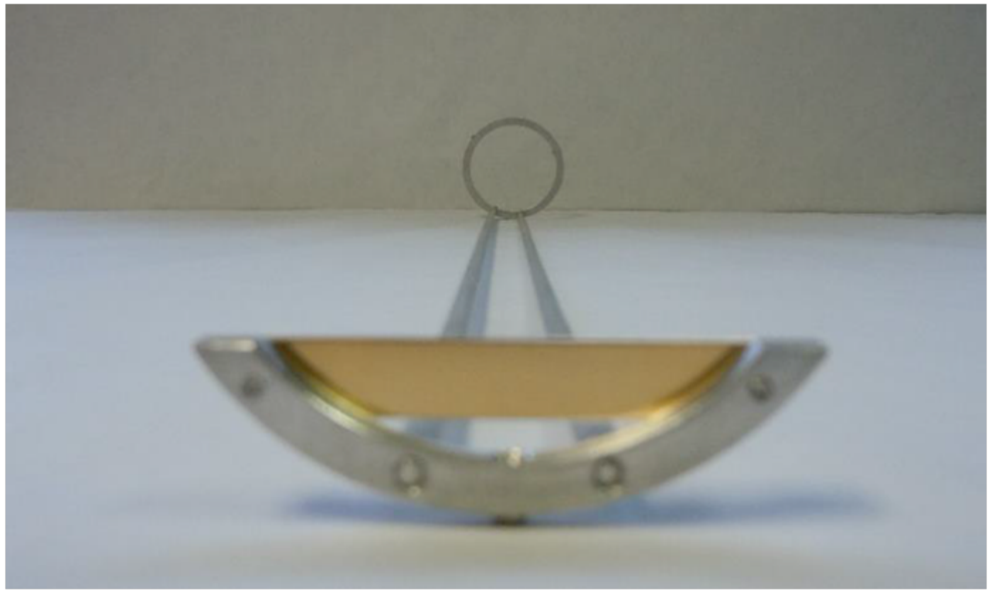
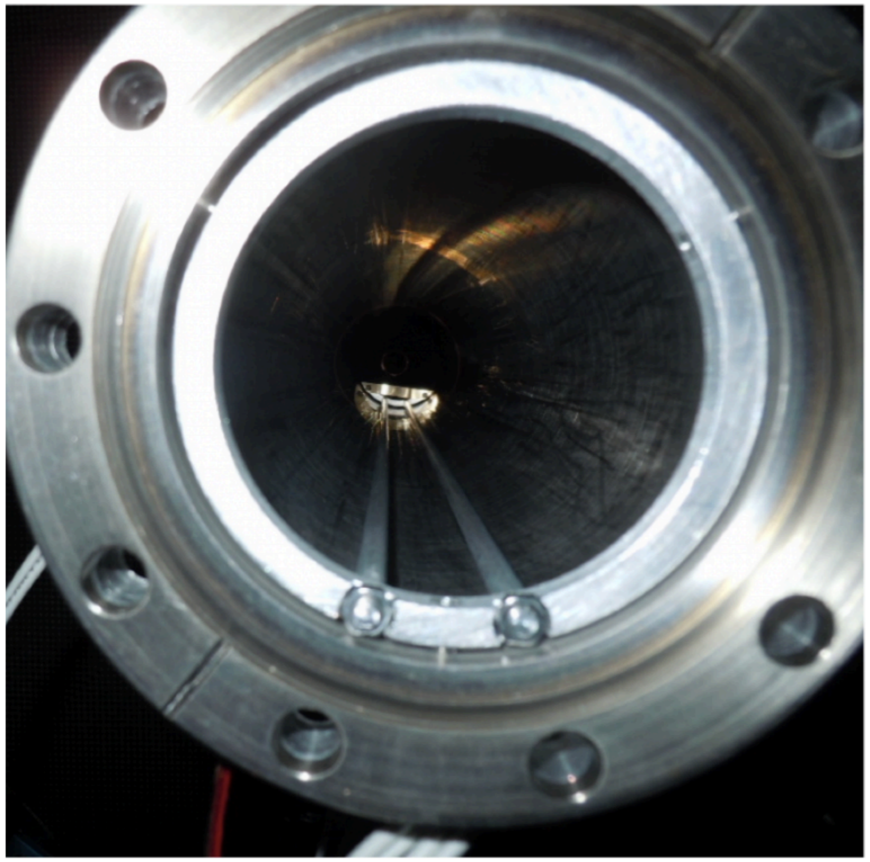
Outline

- ✓ 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

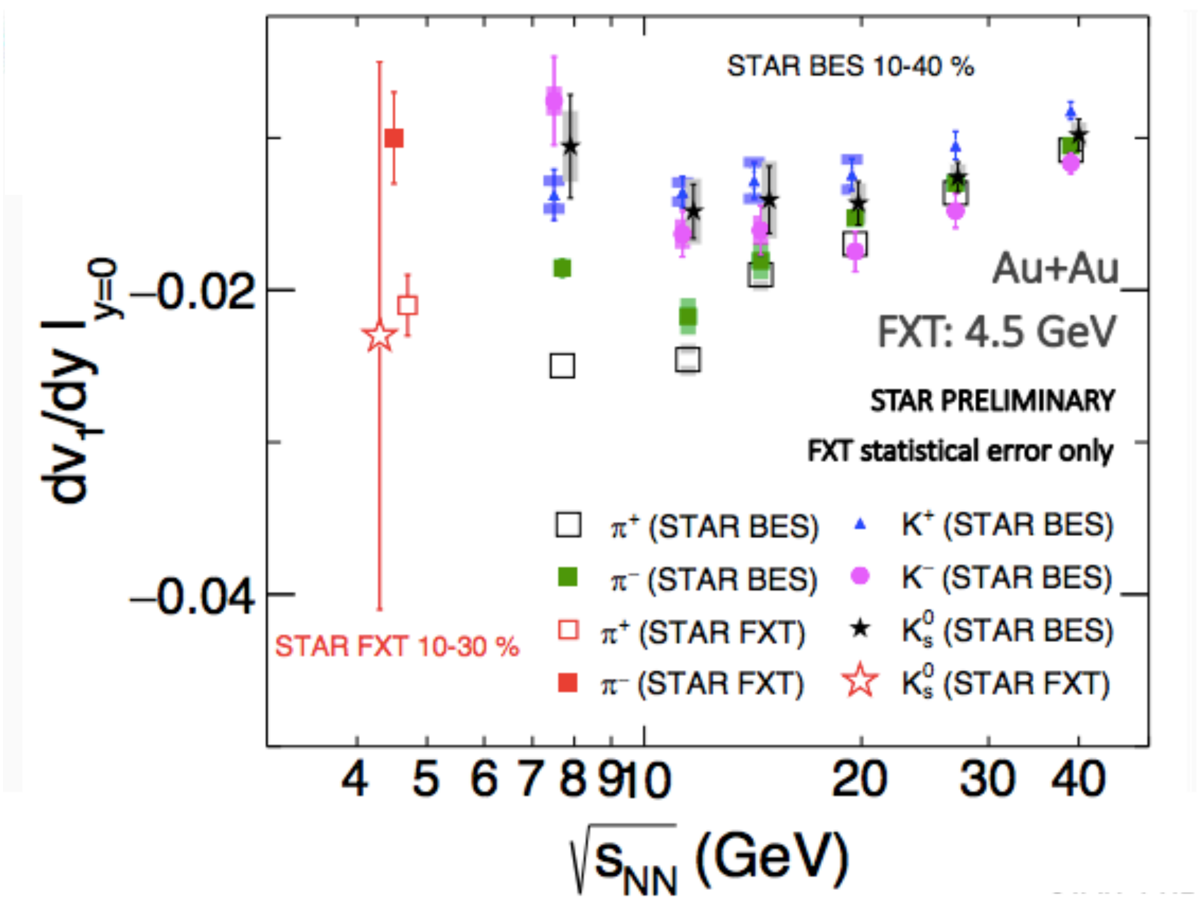
top 30% central trigger.

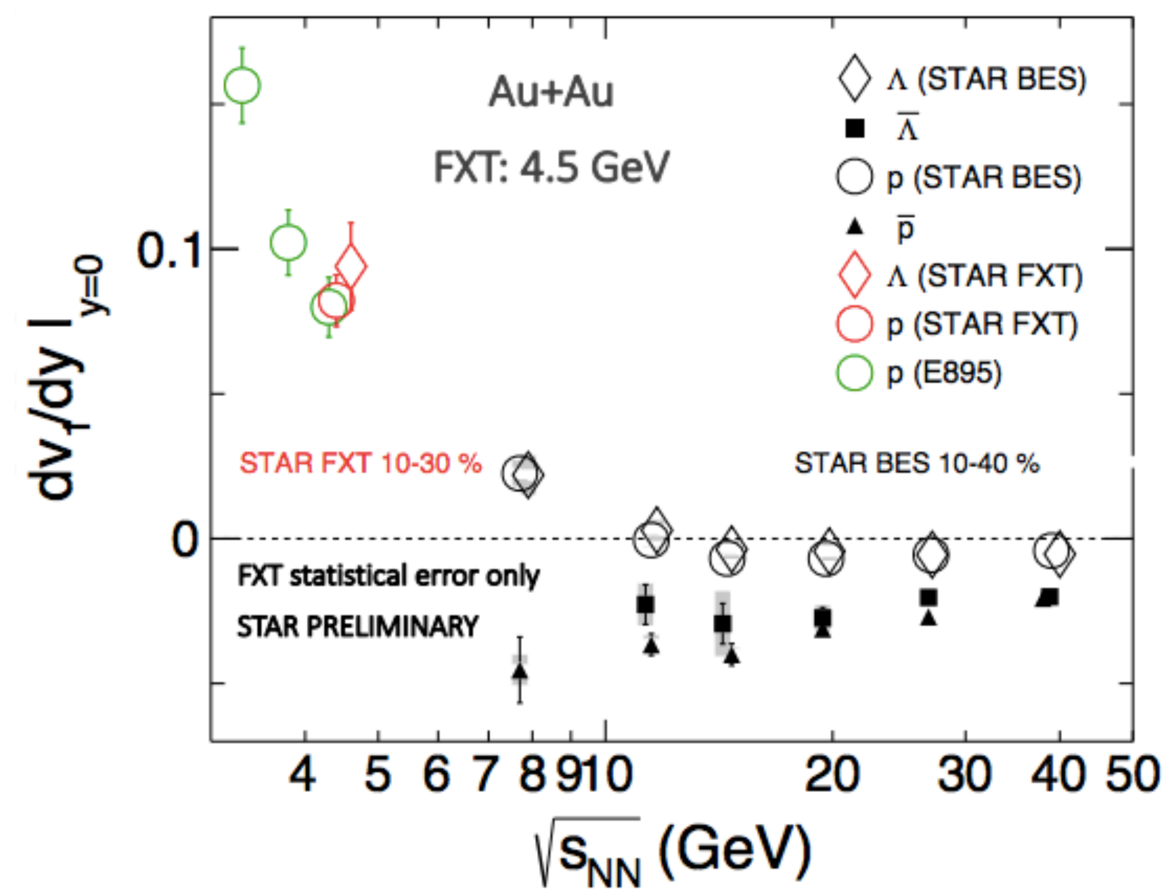
Au+Au $\sqrt{s_{NN}}$=4.5 GeV

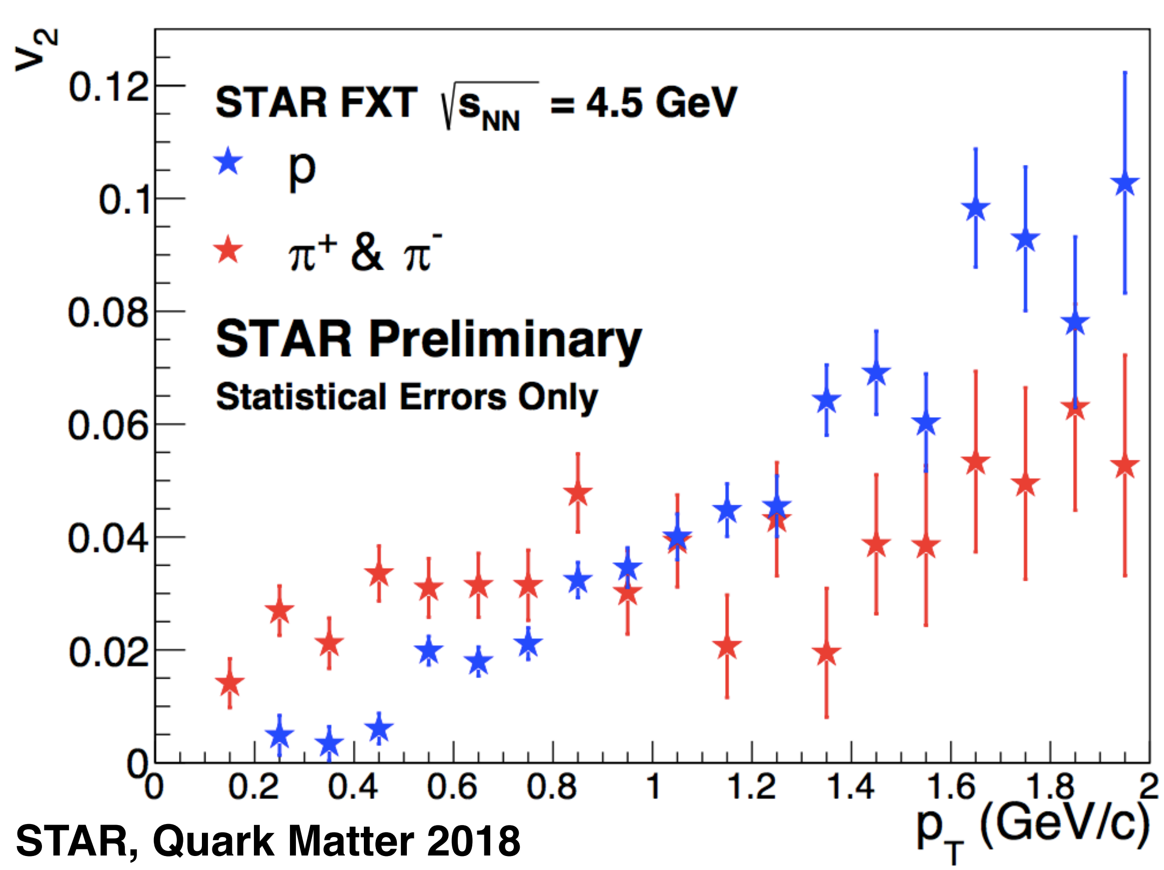
Previous flow results from FXT

E895 PRL 84(2000) 5488

STAR PRL 112(2014) 162301







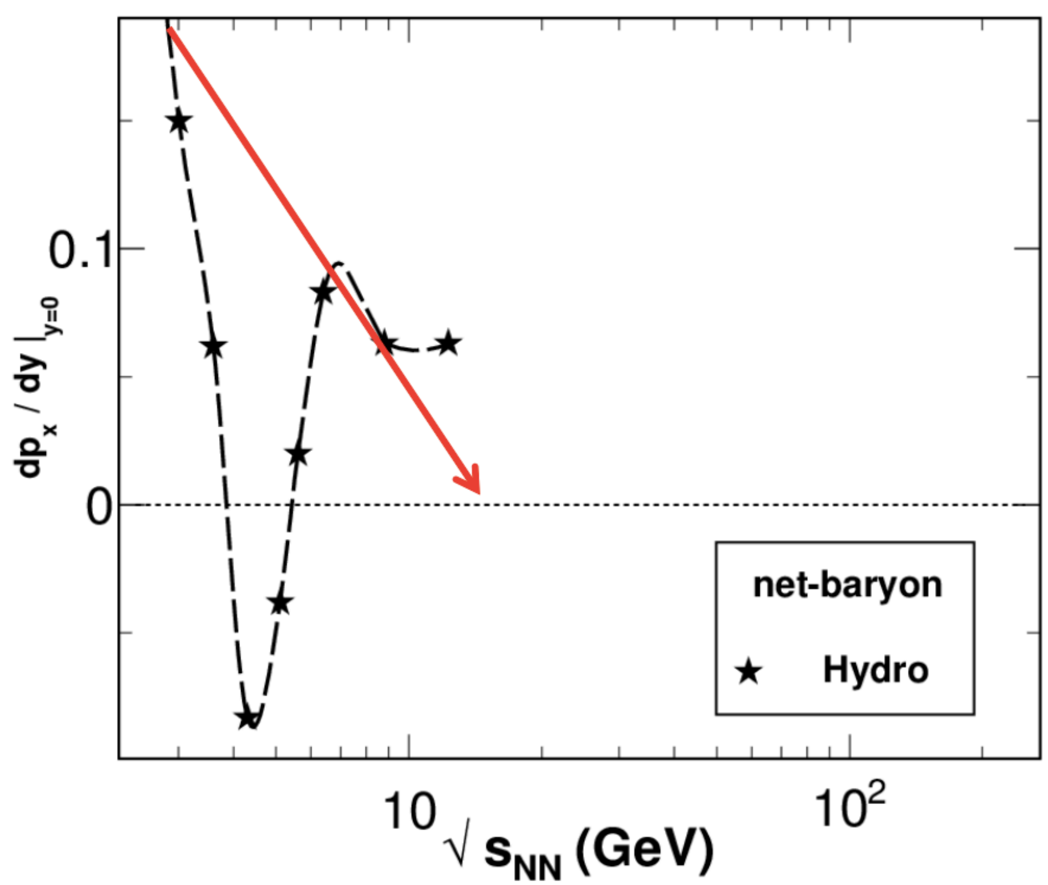
STAR, Quark Matter 2018

- ✓ 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.

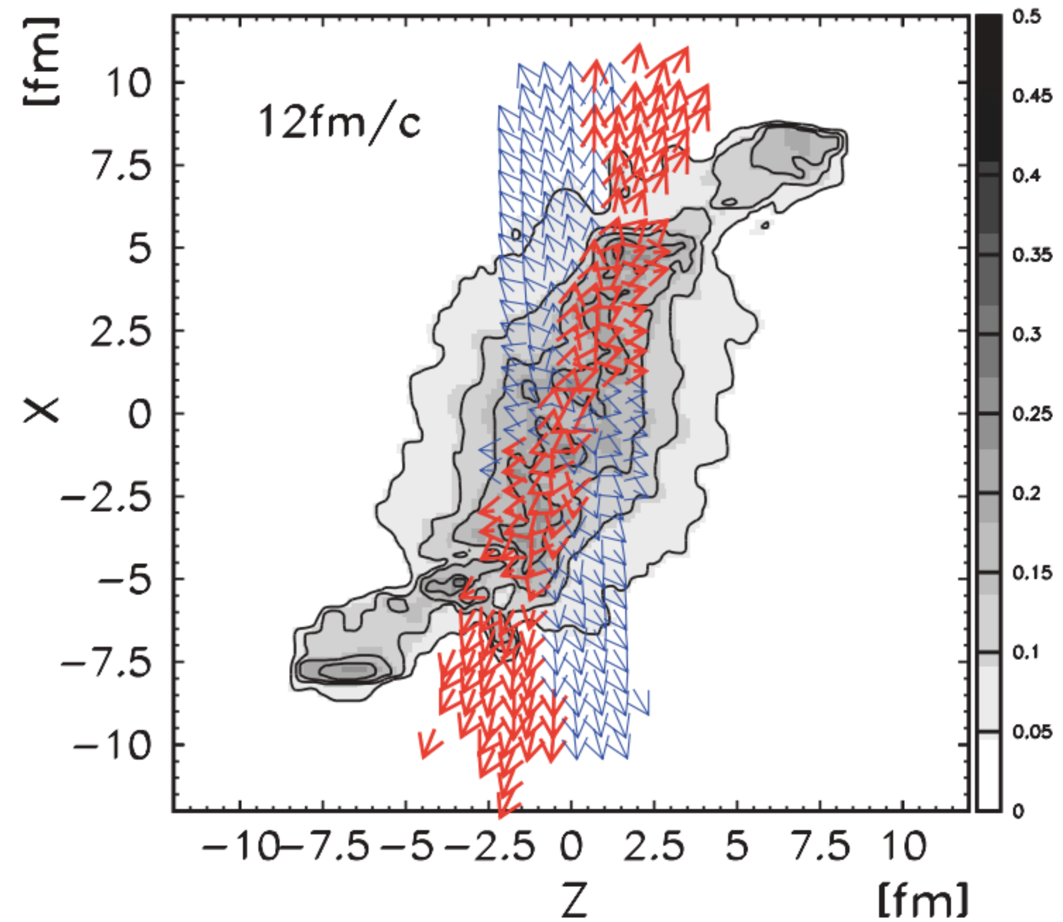
Directed flow

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)**

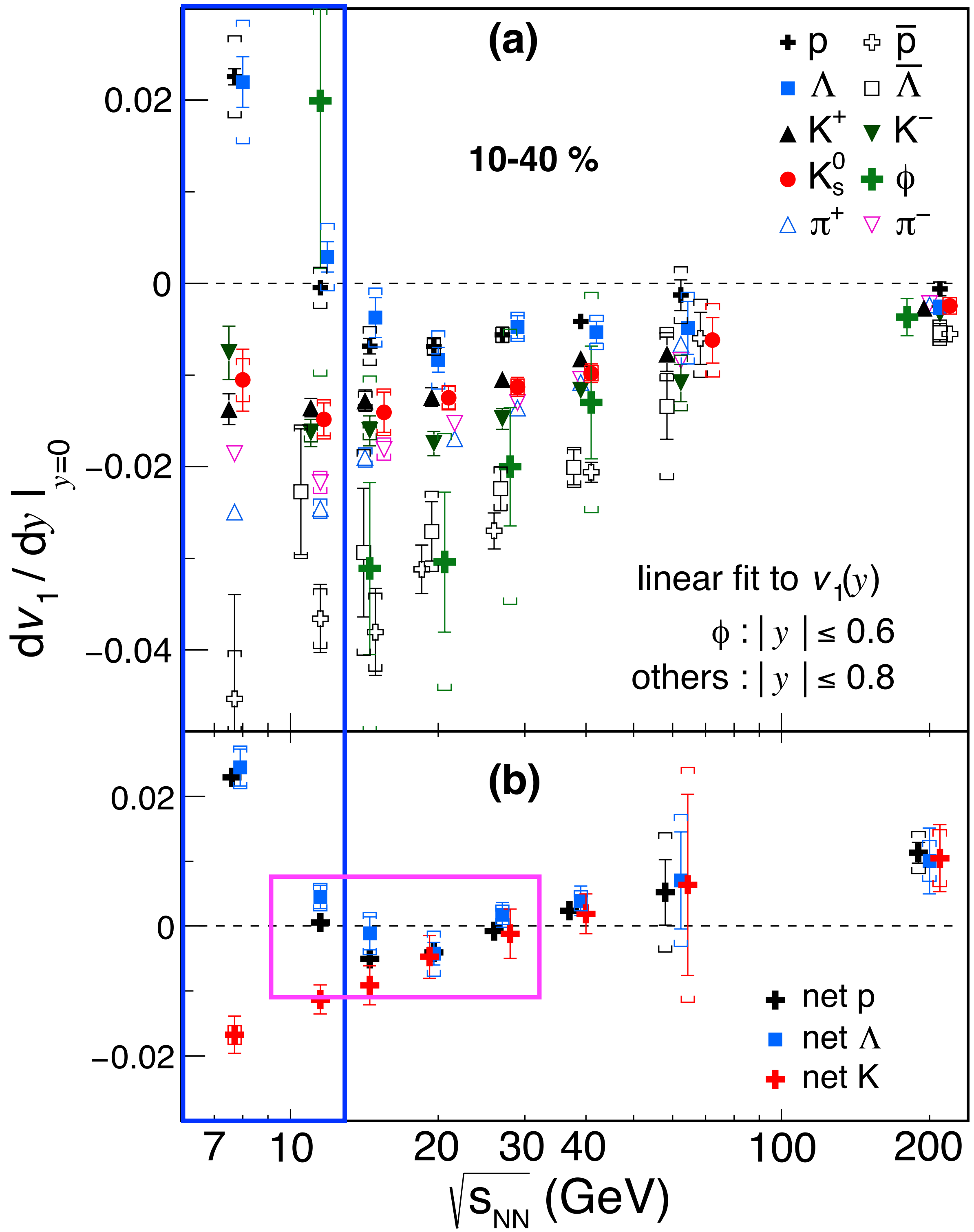


H. Stocker NPA750, 121-147(2005)



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

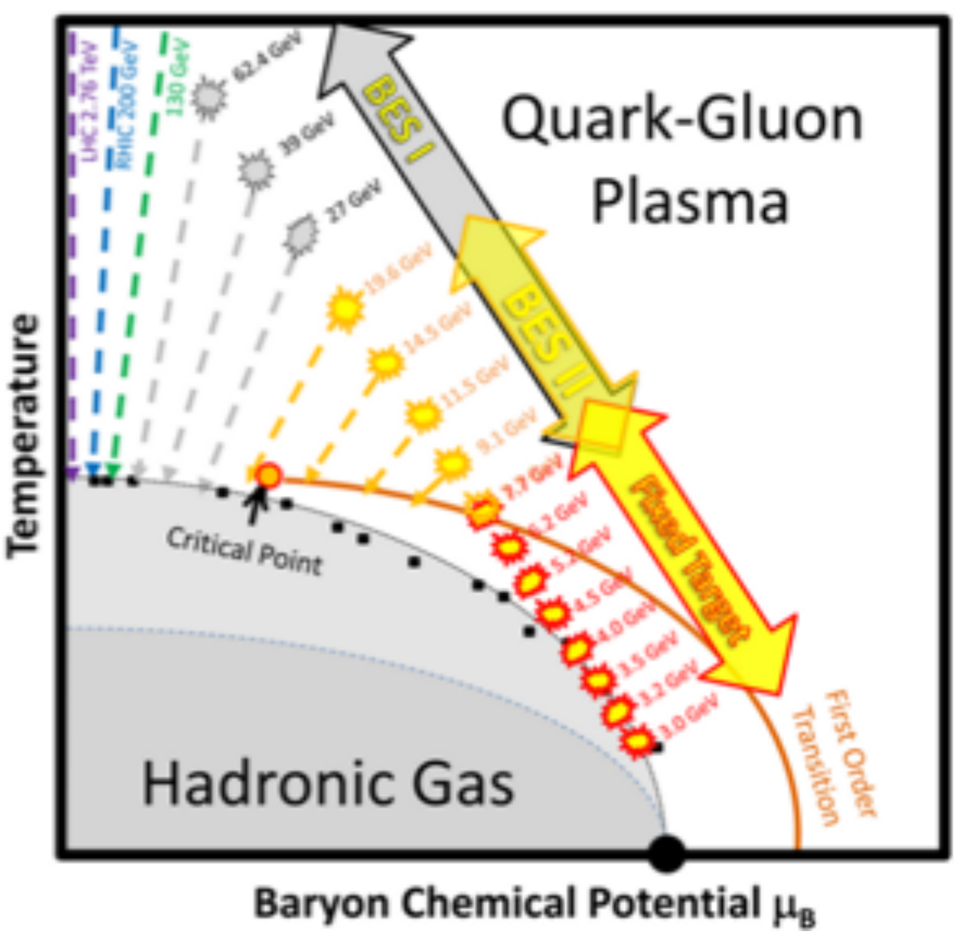
➡ experiment:minimum at 10-20 GeV
model:minimum at 4 GeV

H. Stocker NPA750, 121-147(2005)

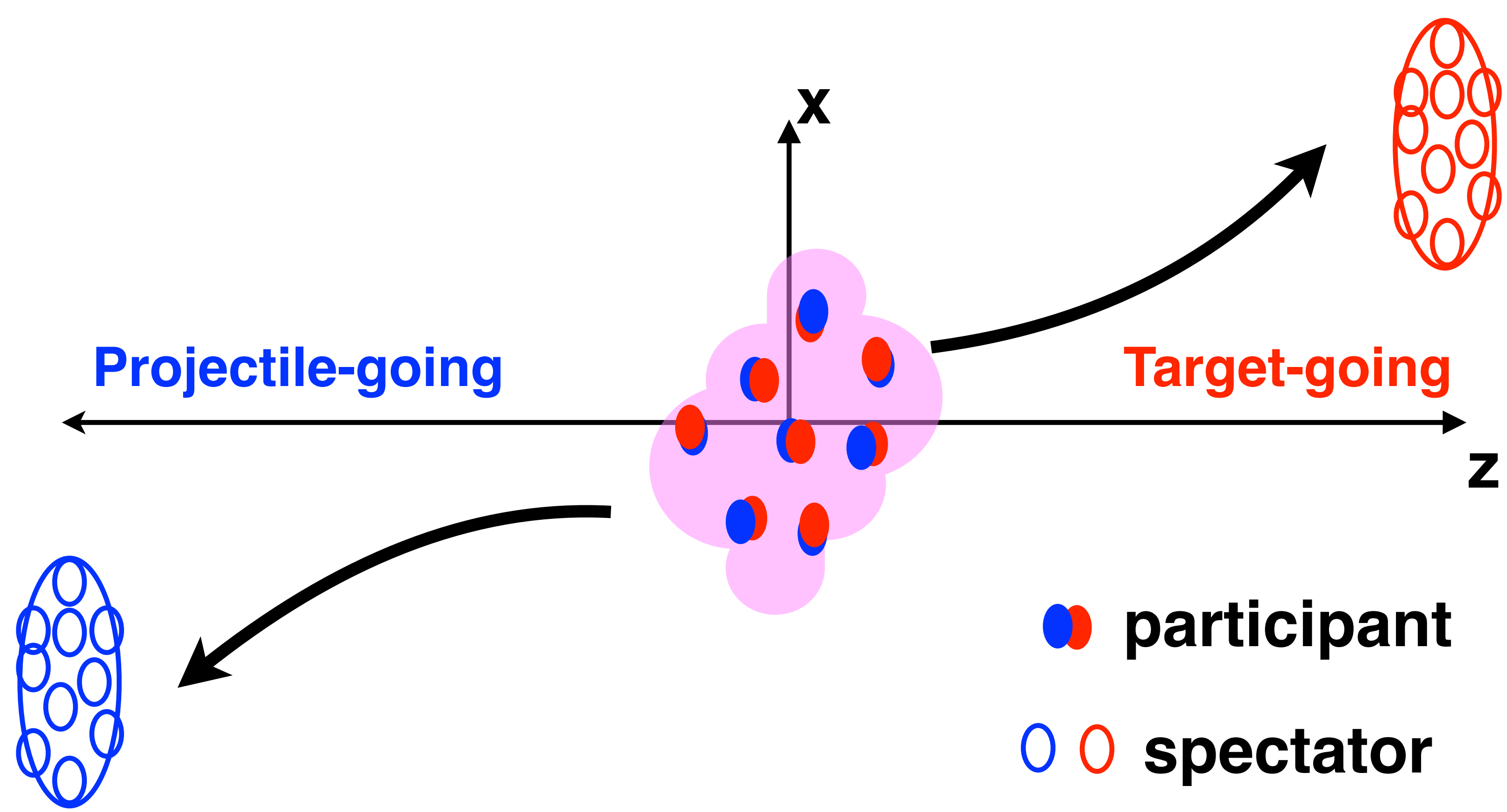
Motivation

- ✓ 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.

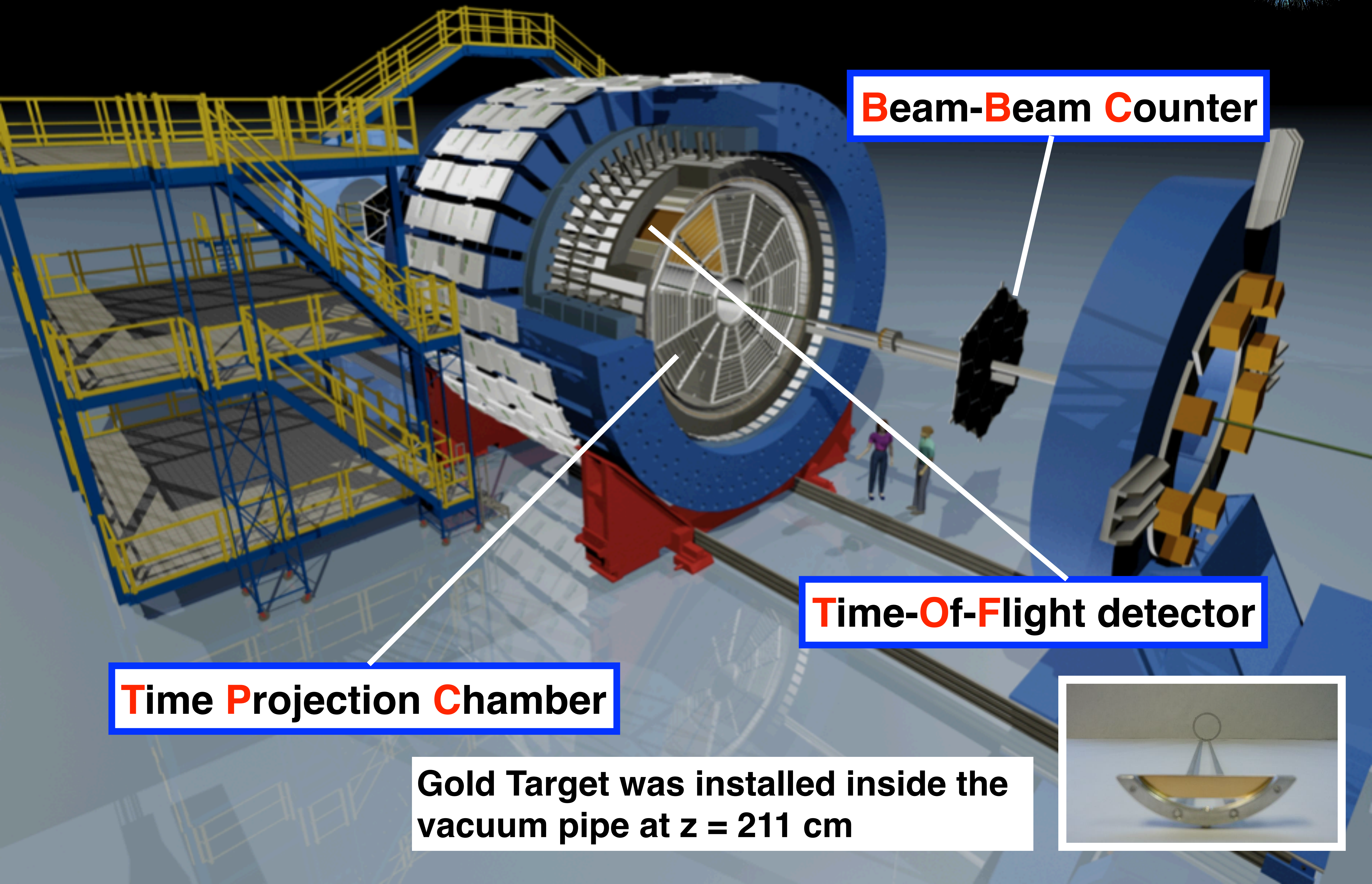
To clarify the structure of the first-order phase transition, study the characteristics of directed flow at low energies is important.



NPA (2017) 06.007
STAR,QM2017 proceeding



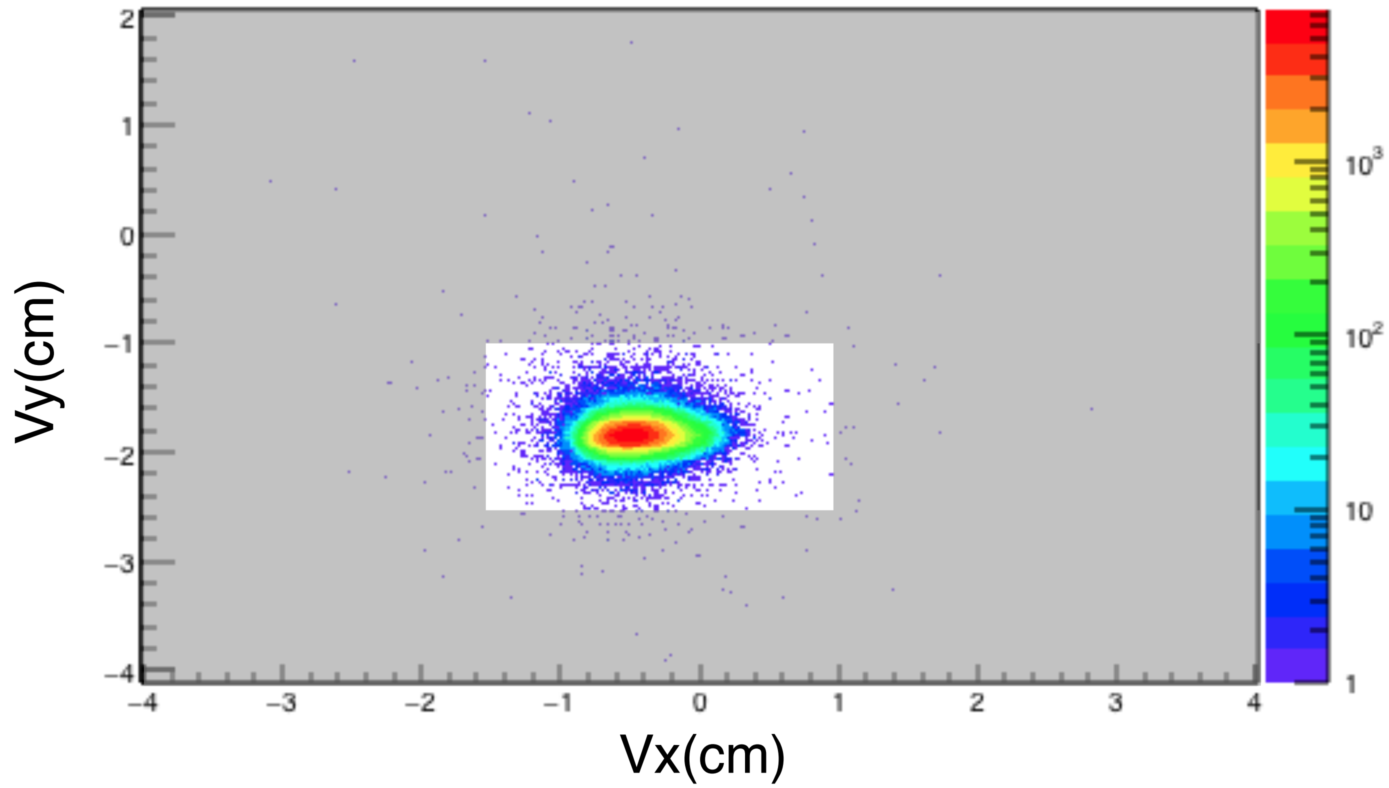
The Solenoidal Tracker At RHIC

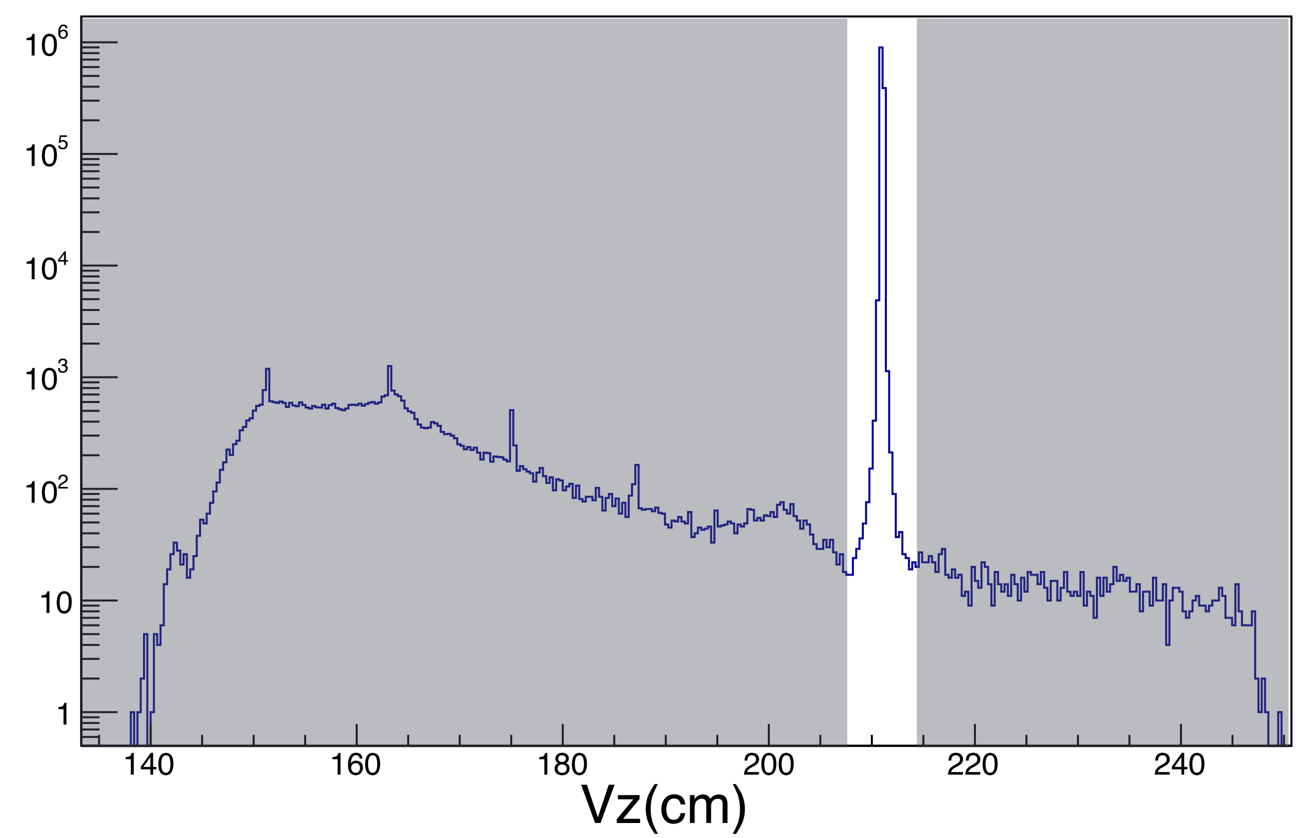


Gold Target was installed inside the vacuum pipe at z = 211 cm

Data selection

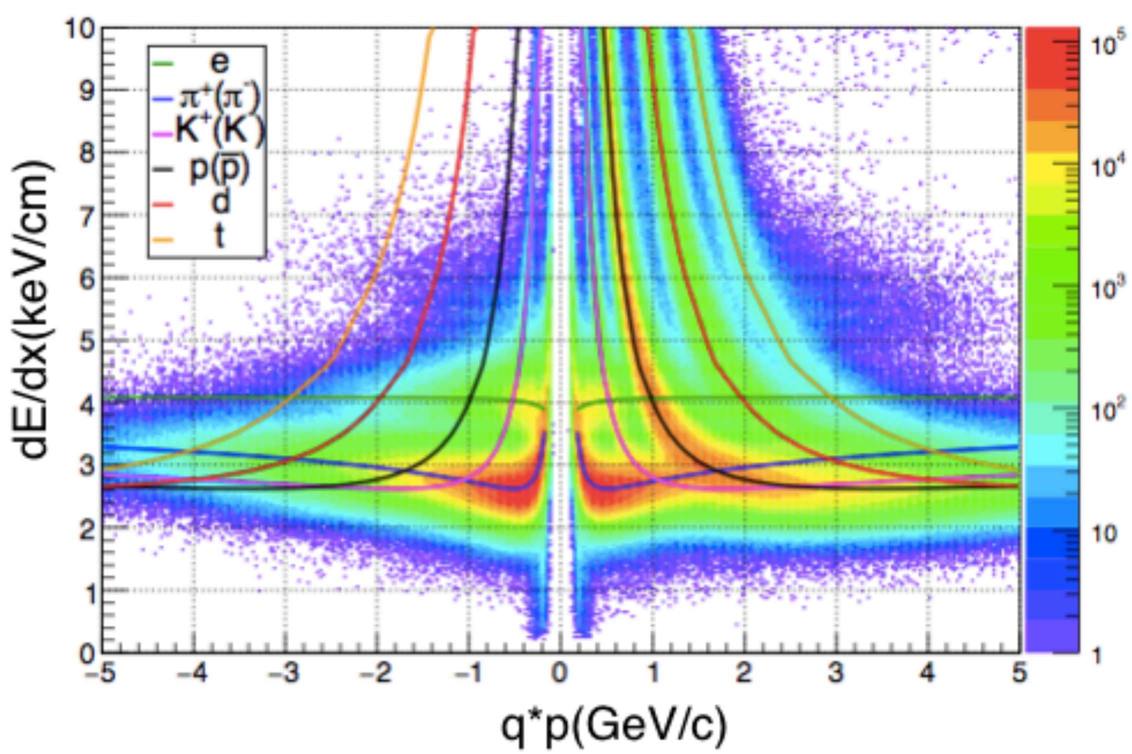
- **Data Set**
  - ✓ Au+Au : $\sqrt{s_{NN}}$=4.5 GeV
  - ✓ Test run conducted in 2015
  - ✓ 1.3 central million events
  - ✓ Midrapidity : -1.52
- **Event Selection**
  - ✓ Vertex X = -1.5 to 1.0 cm
  - ✓ Vertex Y = -2.5 to -1.0 cm
  - ✓ Vertex Z = 210 to 212 cm
- **Track Selection**
  - ✓ nHitsFit >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

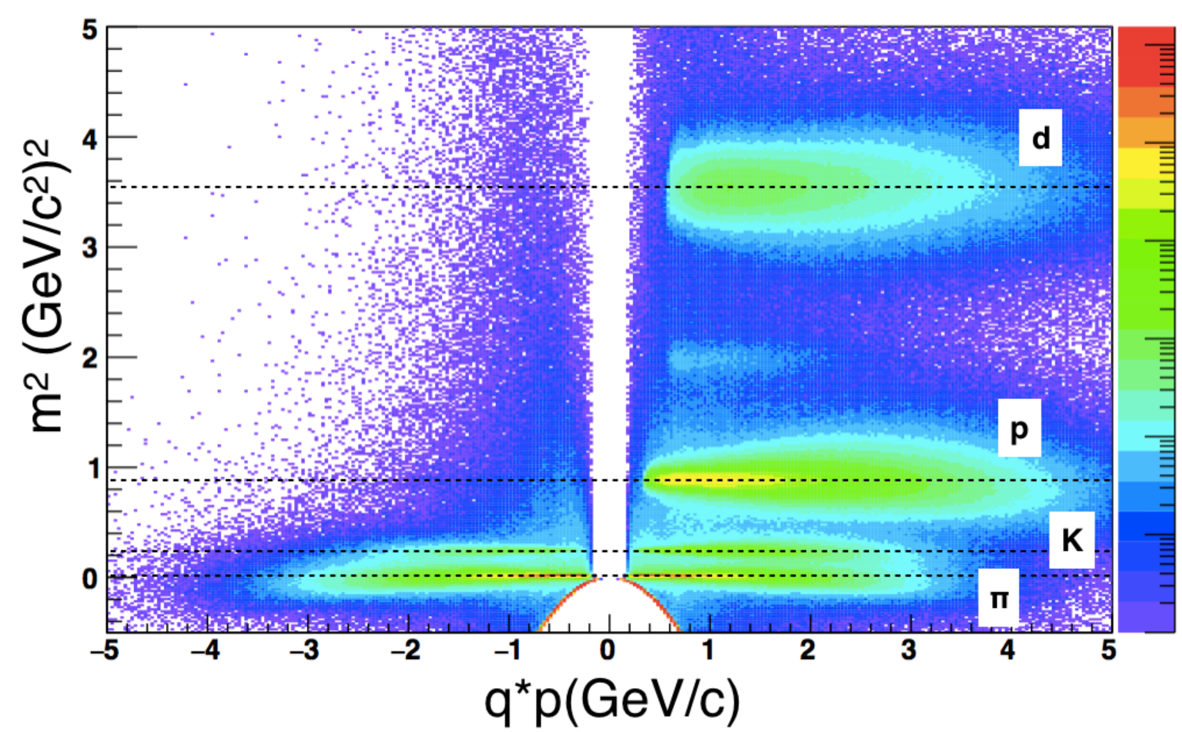




Particle identification

- 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.





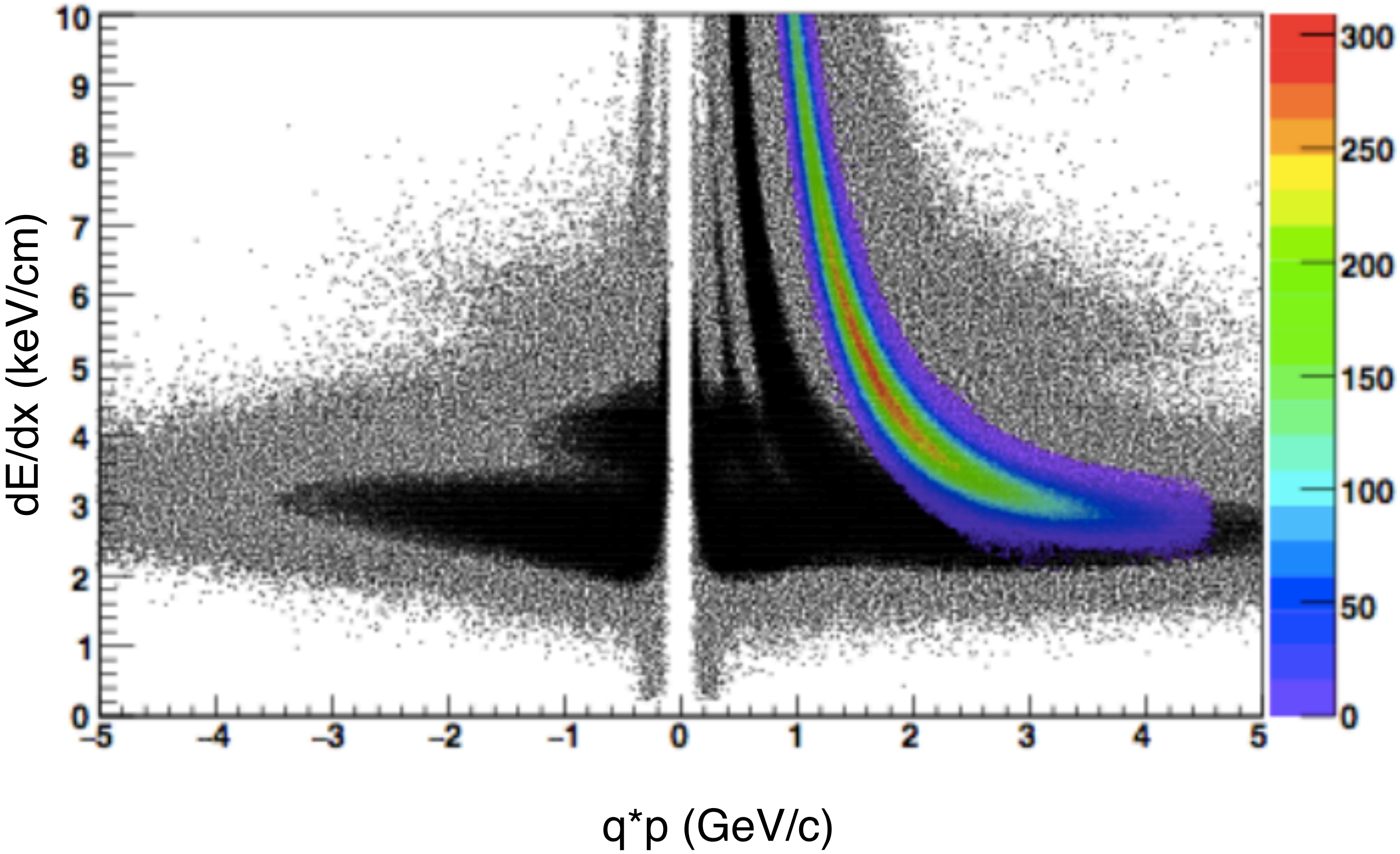
Deuteron identification

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

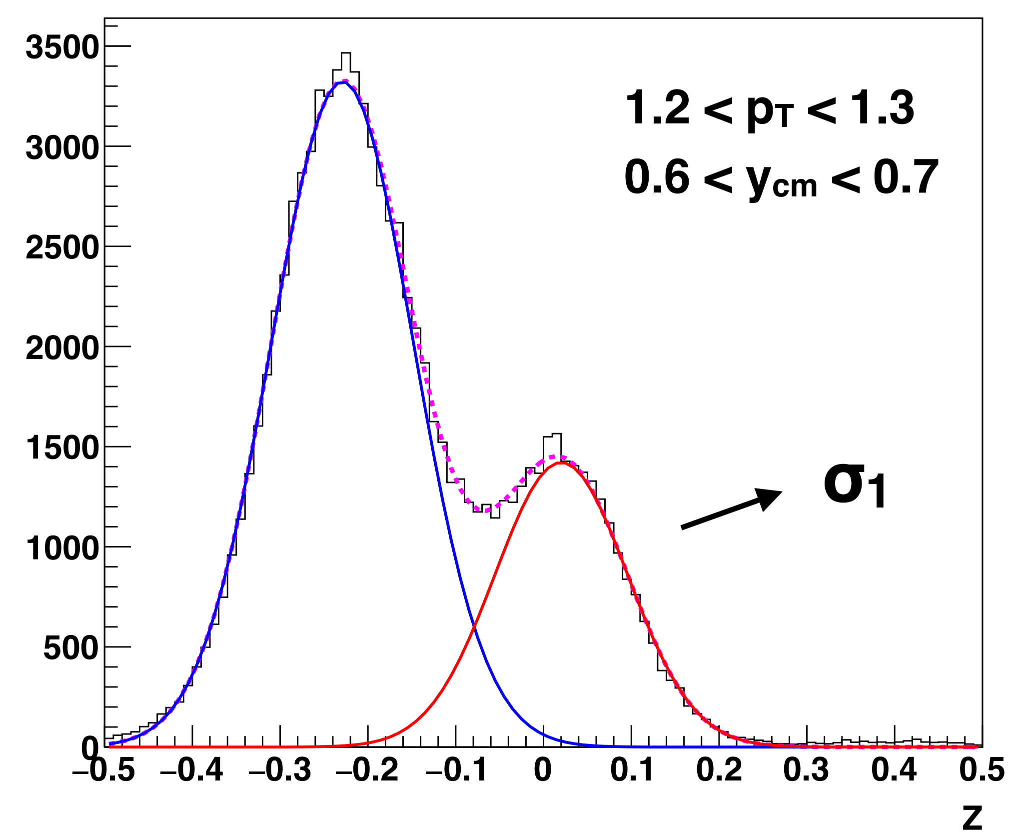
"nσ(d)" can be obtained by Gaussian fitting of Z.

"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

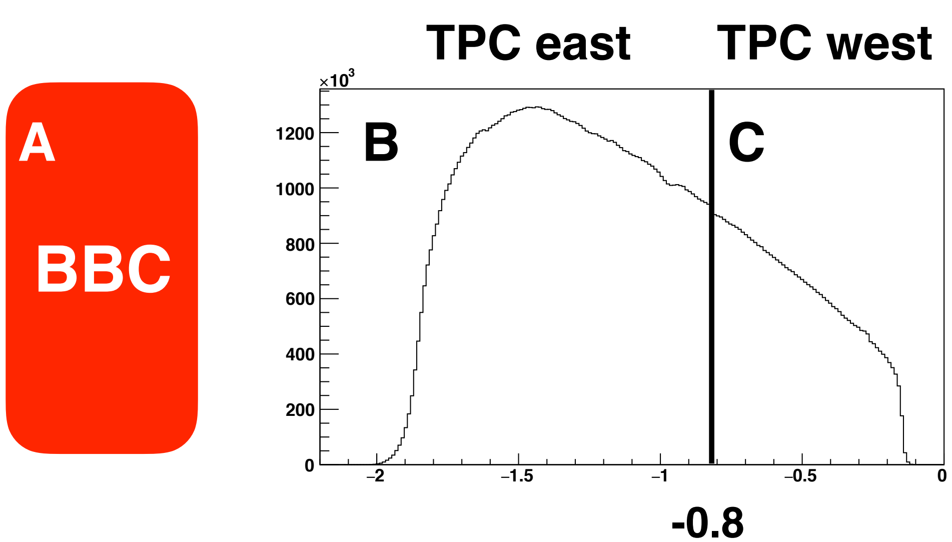
Event plane method : 2 or 3 subevents

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



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

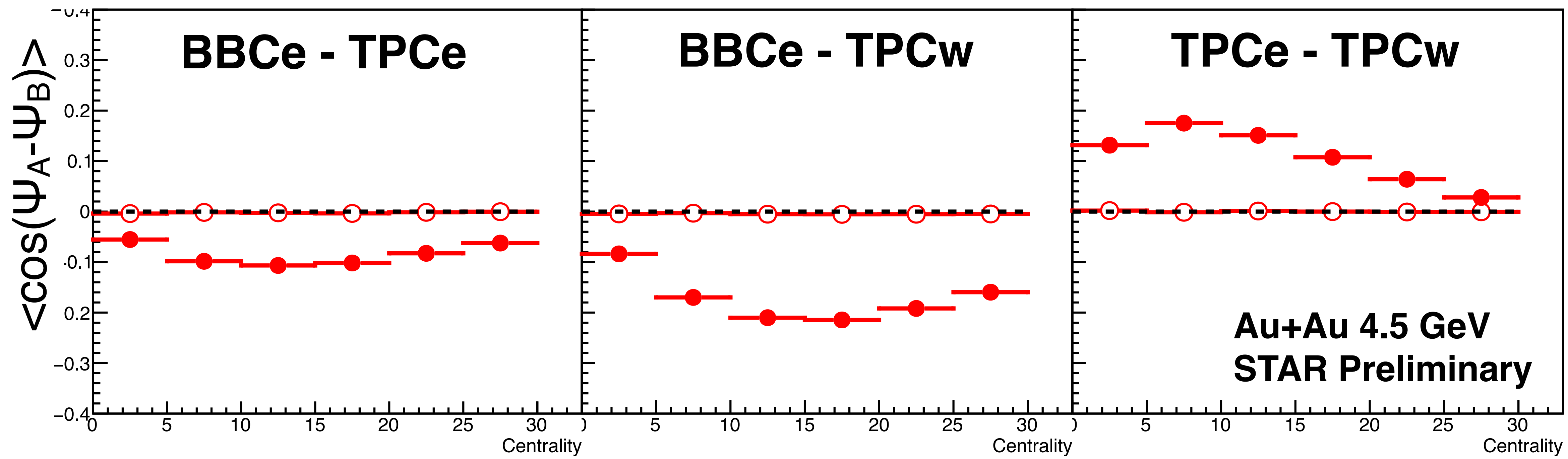
Assuming a true event plane, calculate the resolution by taking correlations for each two of three regions.

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

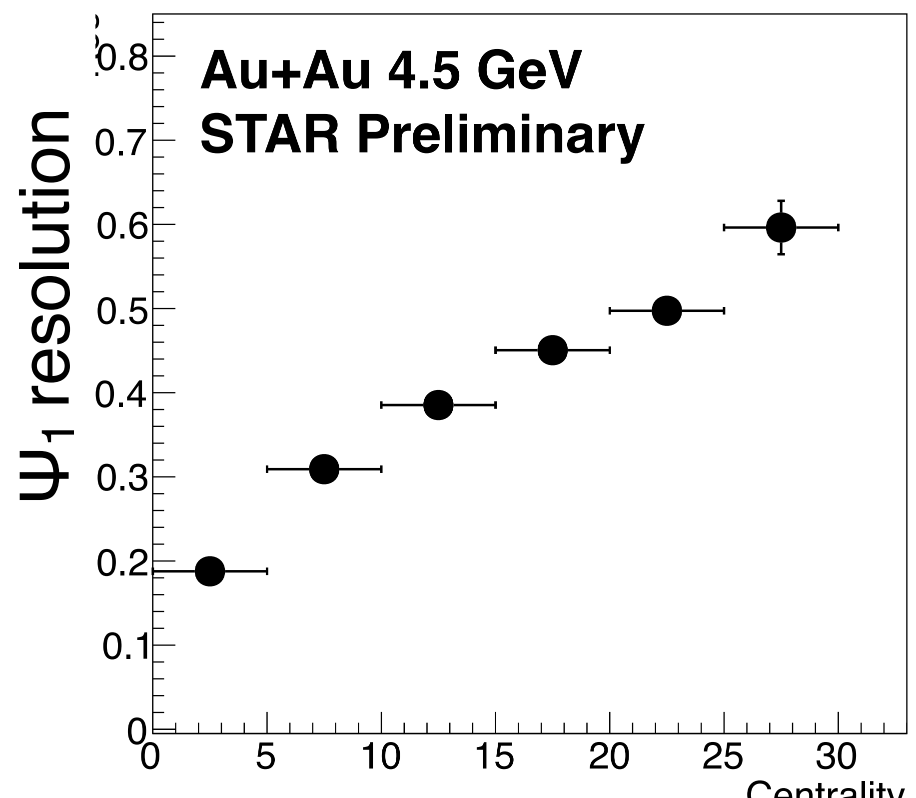
EP correlation and resolution

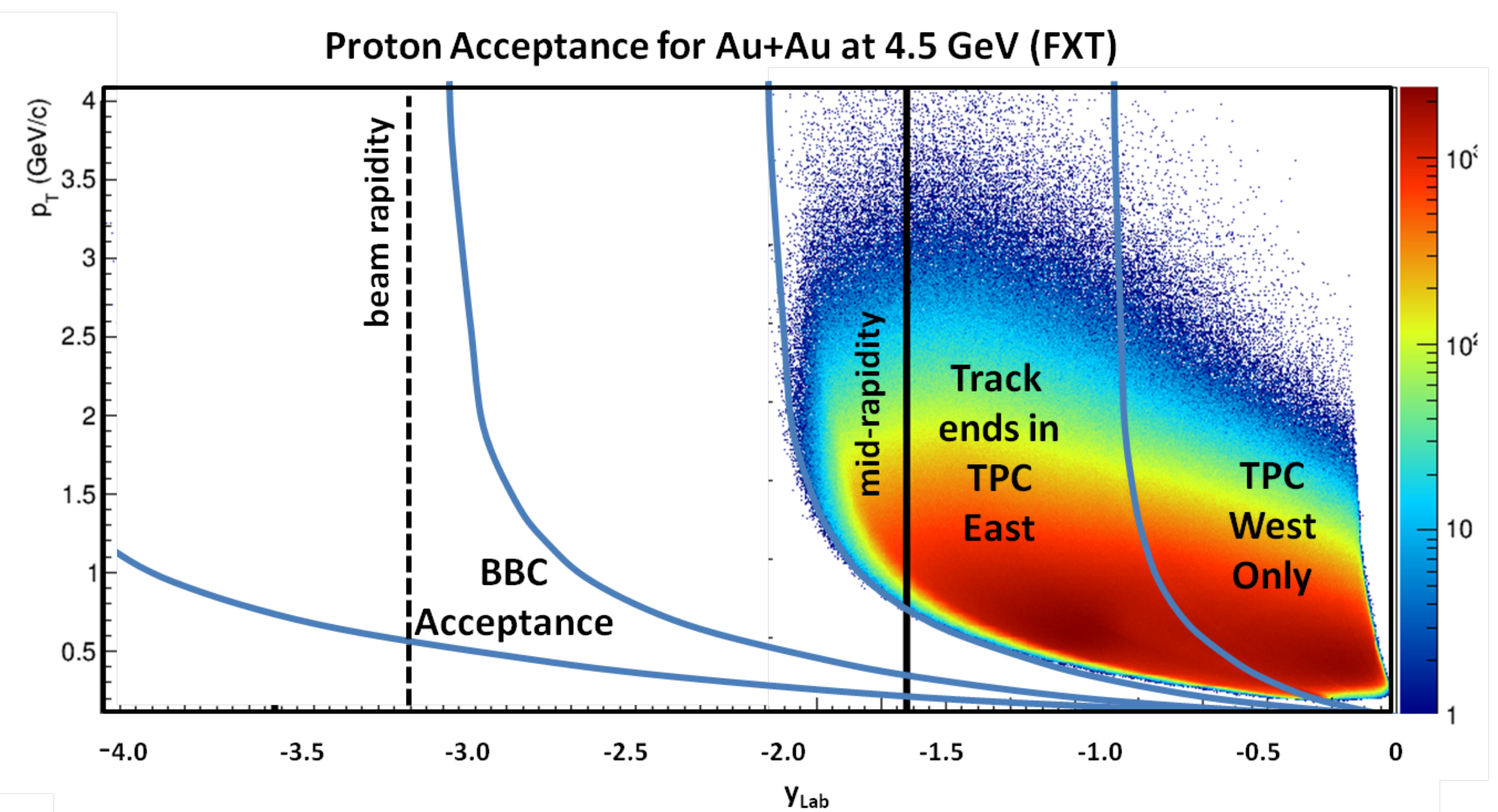
● $\langle\cos(\Psi_A - \Psi_B)\rangle$
○ $\langle\sin(\Psi_A - \Psi_B)\rangle$

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

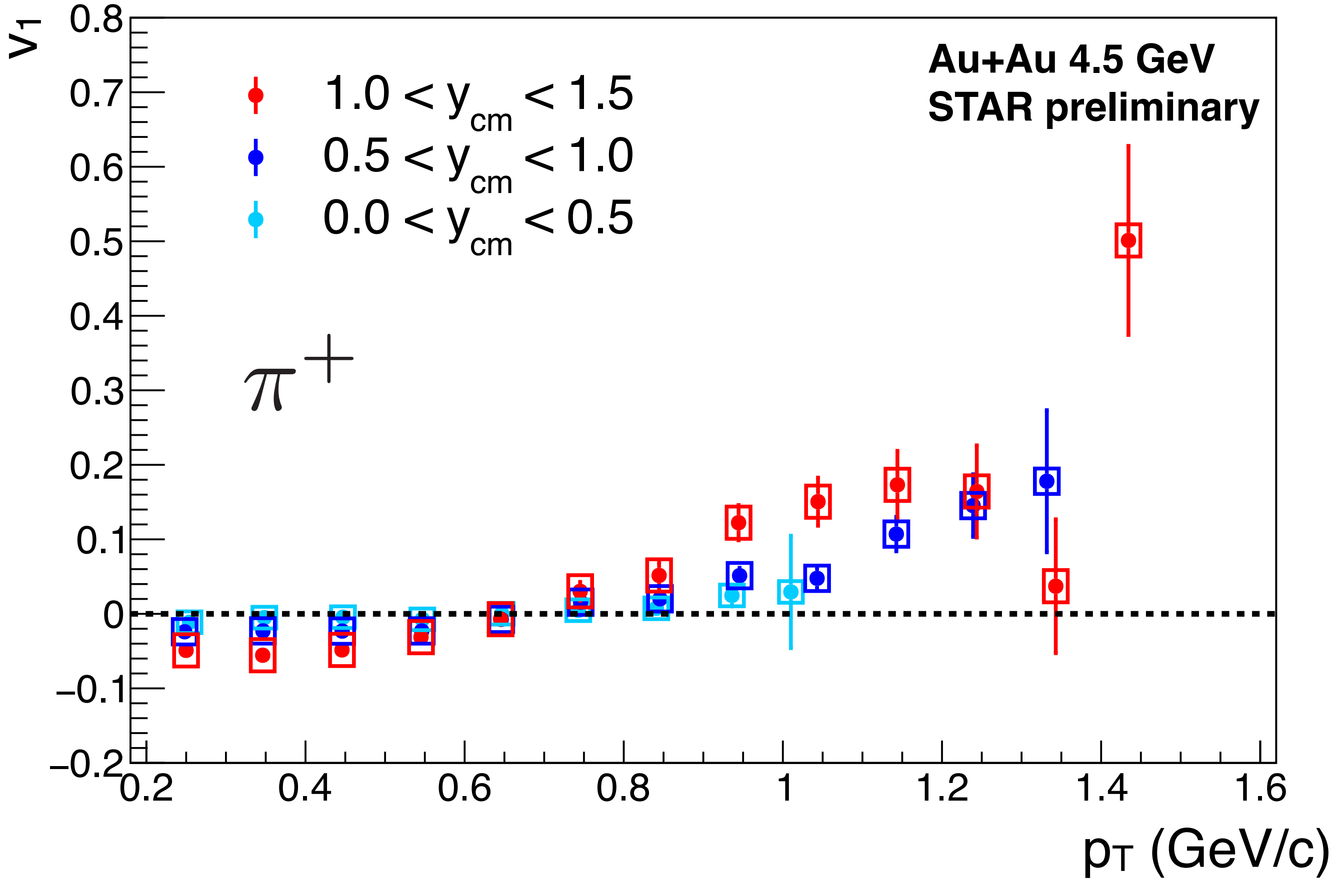
$$Res_A = Res_B = \sqrt{\langle cos(\Psi_A - \Psi_B)\rangle}$$

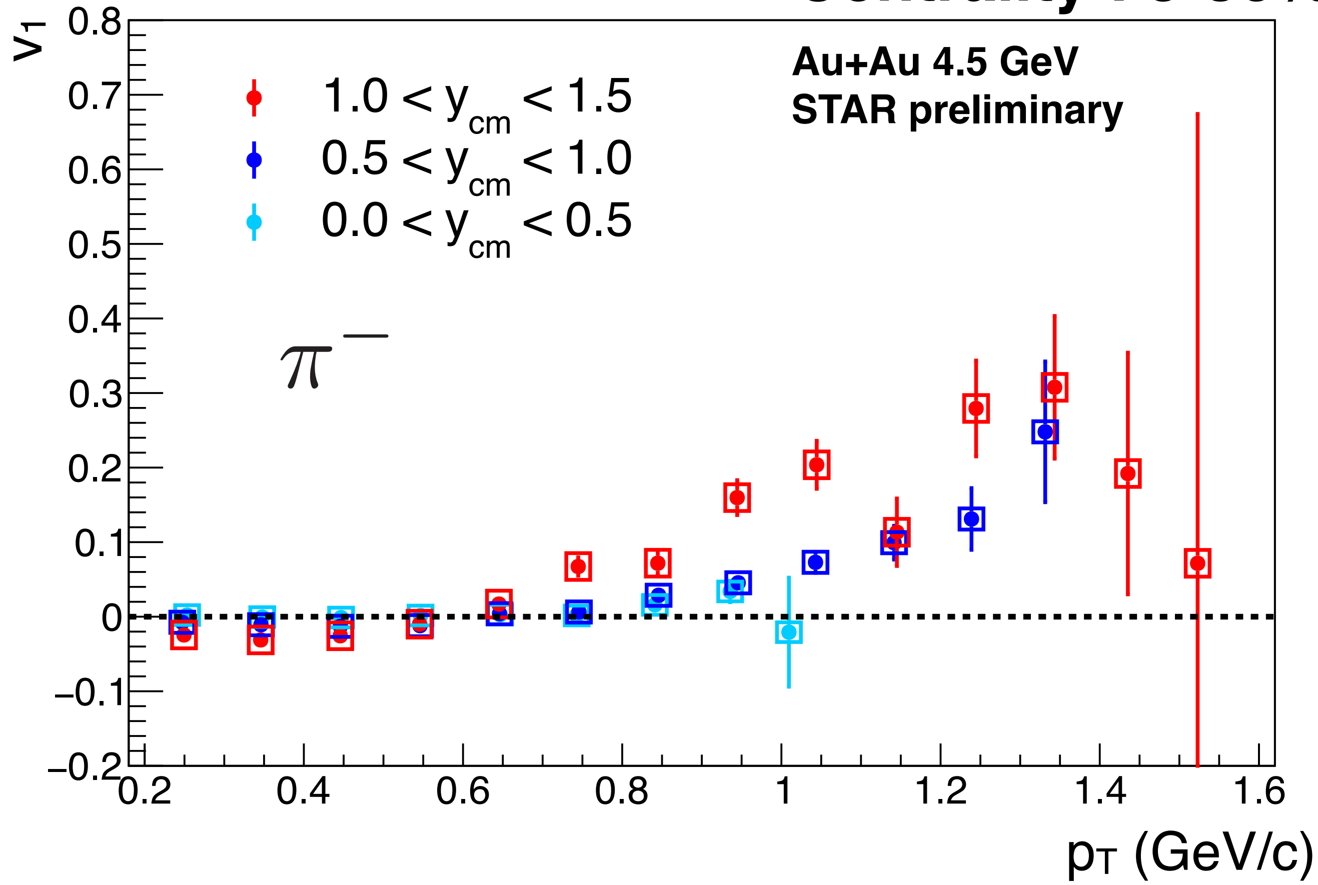
Systematic uncertainty

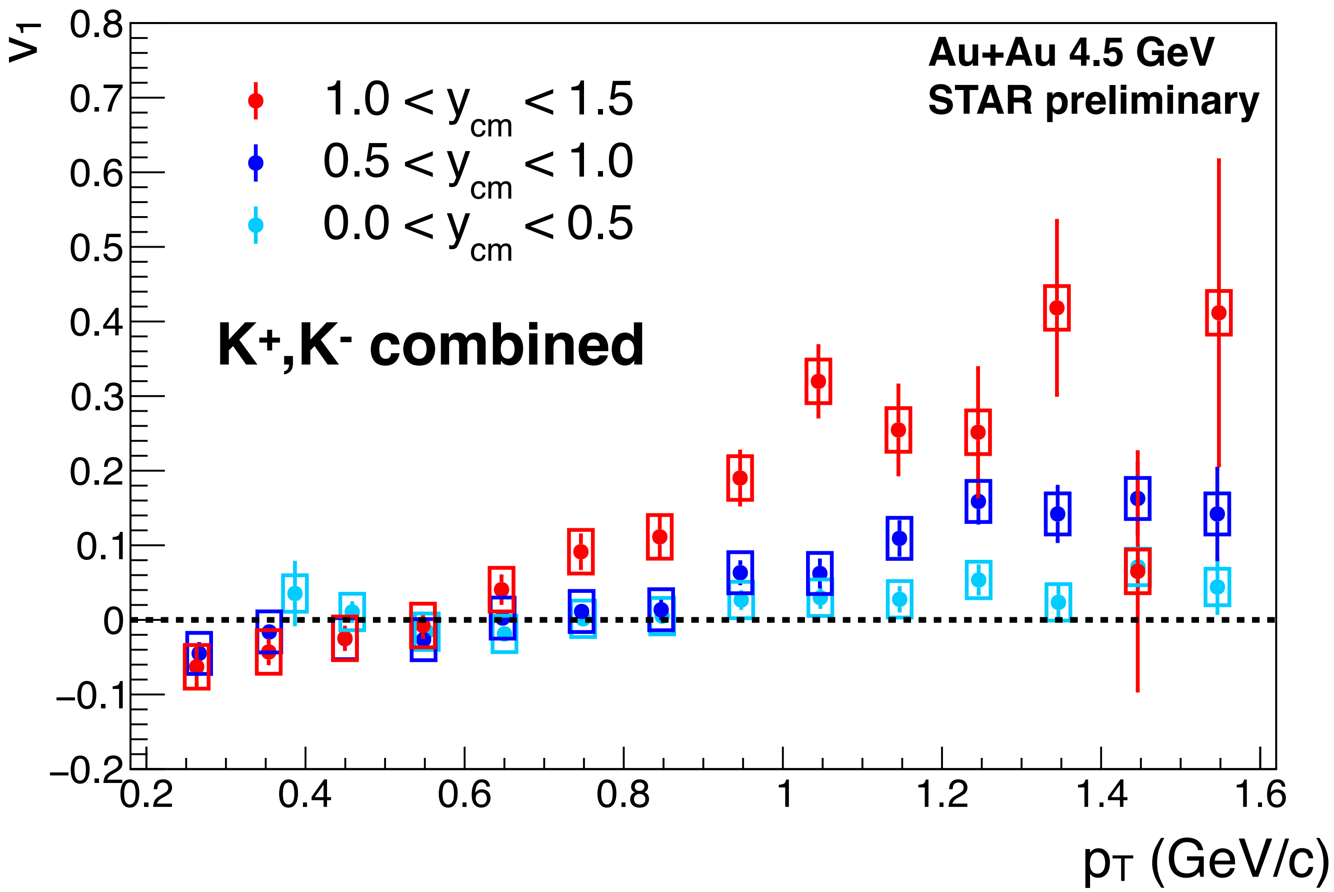
$$Err^2_{sys} = \frac{\sum_{n=1}^{N}(x_i - x_{ave})^2}{N}$$

p_T dependence of v_1 (π, K)

Centrality : 5-30%





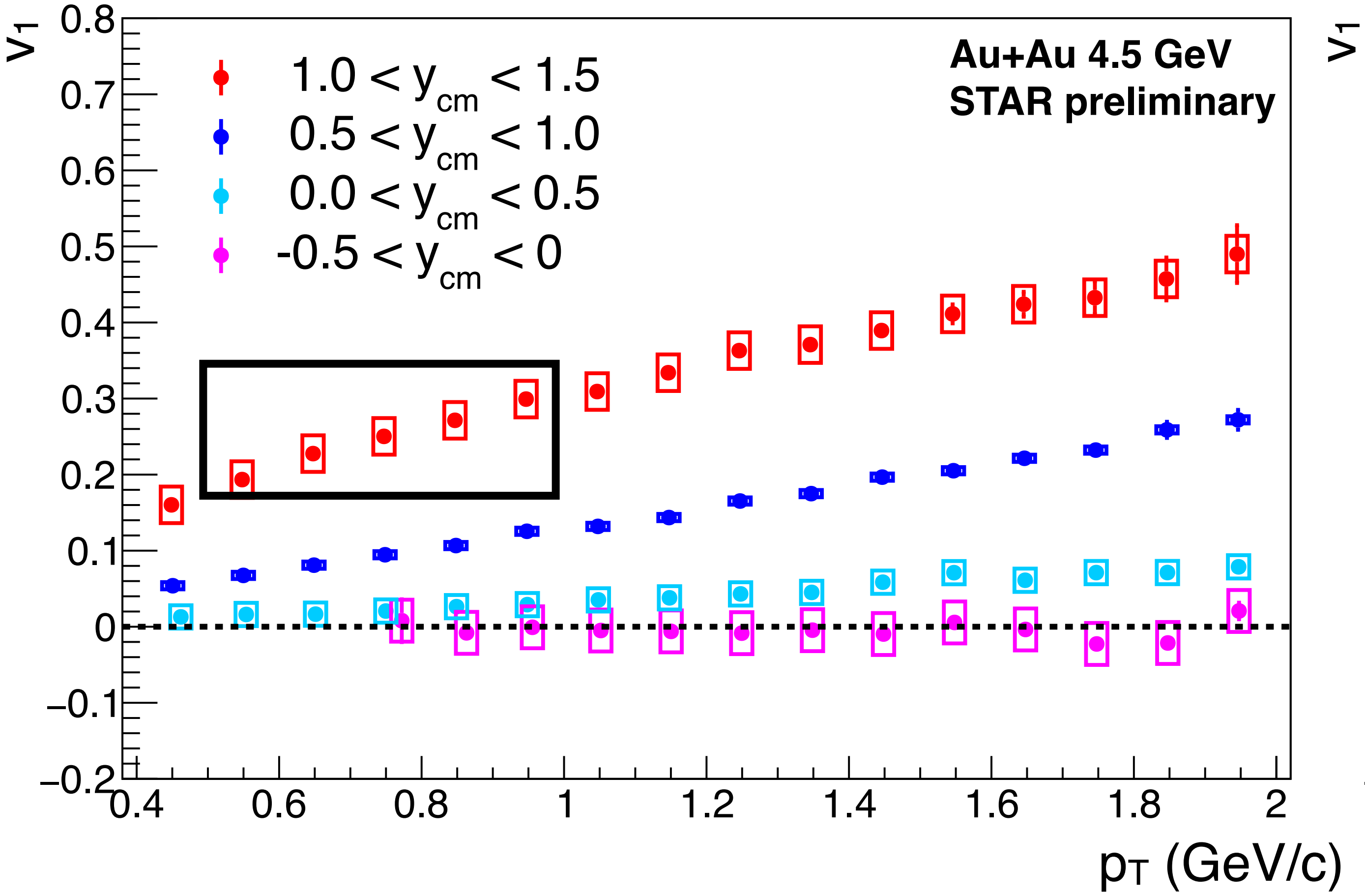


- ✓ **All particle species have similar p_T dependence.**
- ✓ **v_1 changes sign at $p_T \approx 0.6$ GeV/c.**
- ✓ **v_1 may increase with increasing y_{cm}.**
- ✓ **Sys. uncertainty from EP determination.**

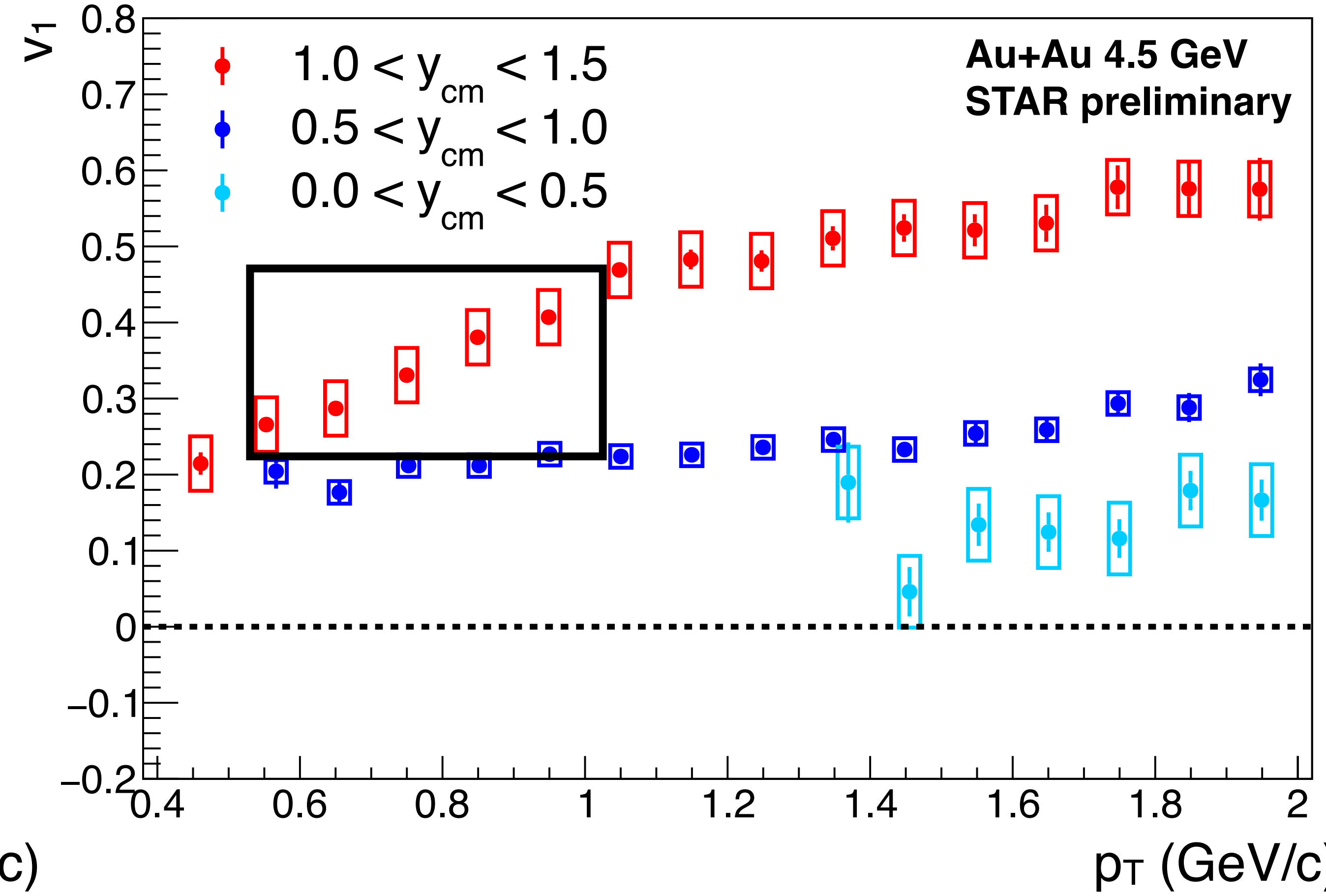
p_T dependence of v_1 (p, d)

Centrality : 5-30%

proton

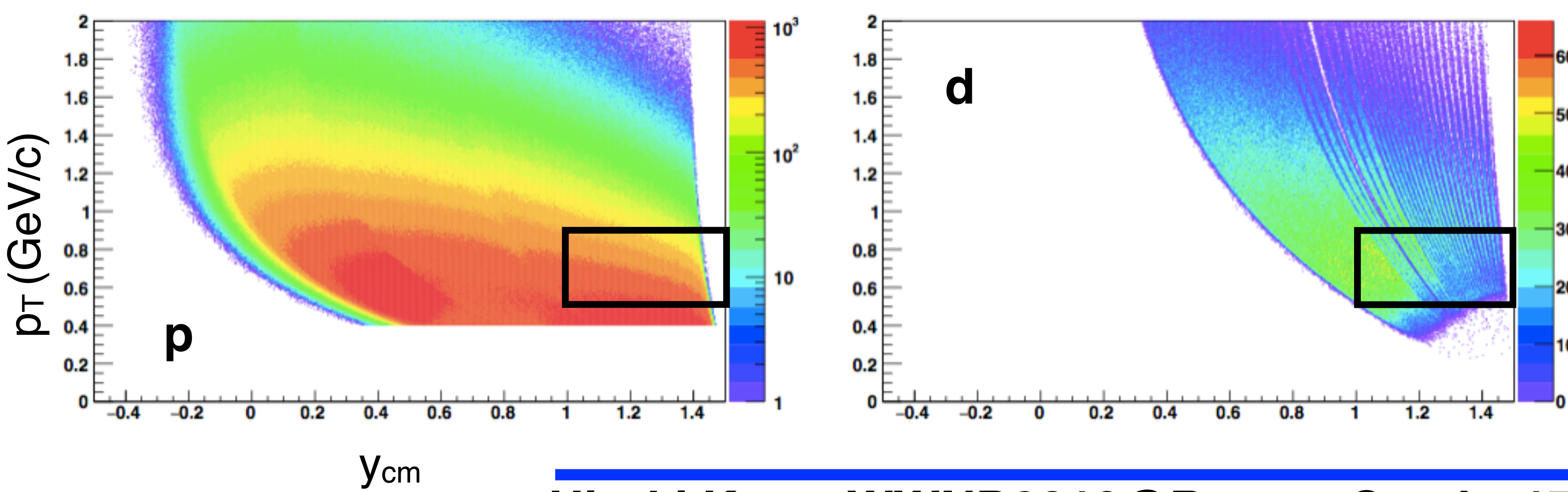


deuteron

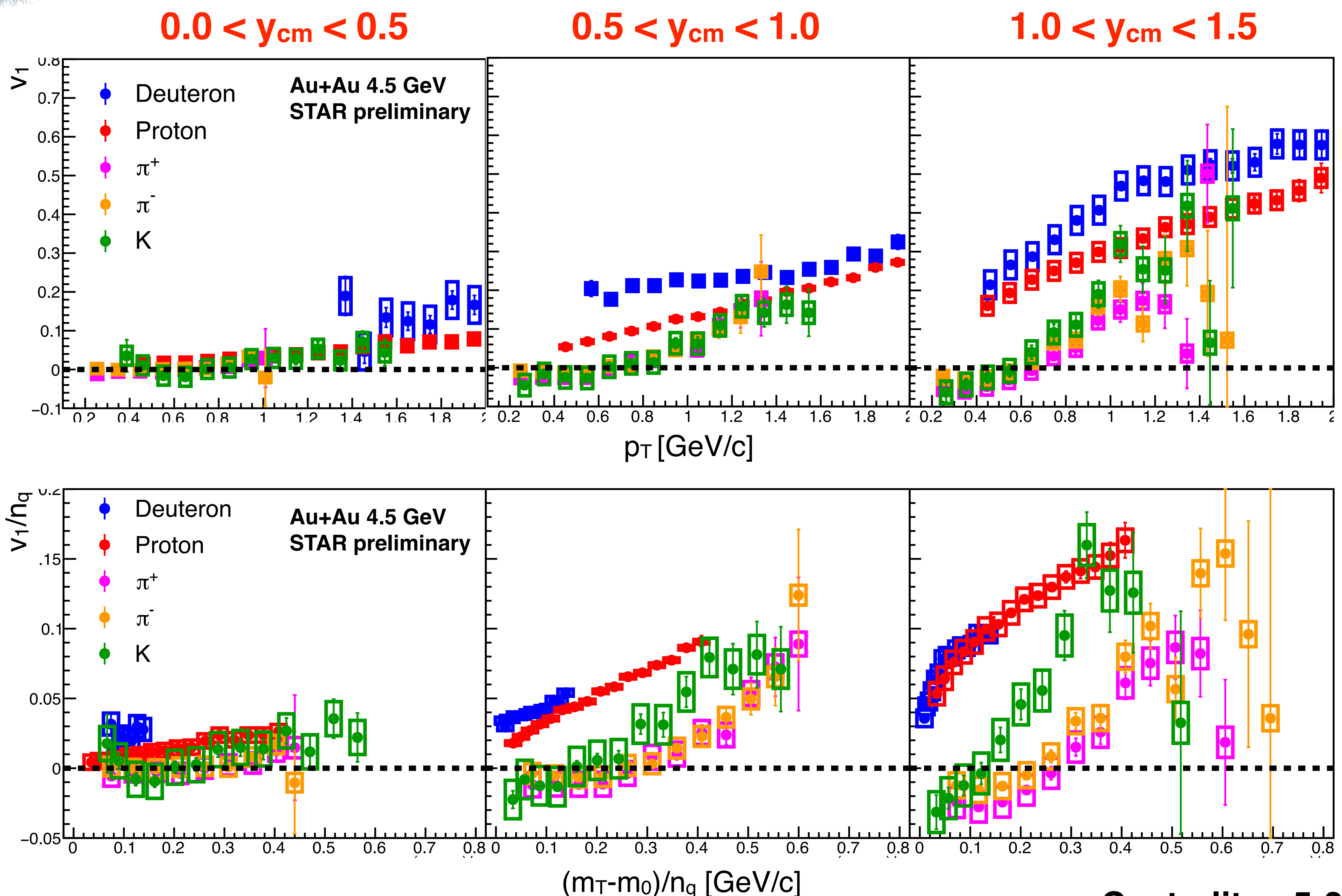


v_1 increases with increasing p_T at $1.0<y_{cm}<1.5$

Detector acceptance effects have been taken into account



Result of NCQ scaling (m_T-scaling)

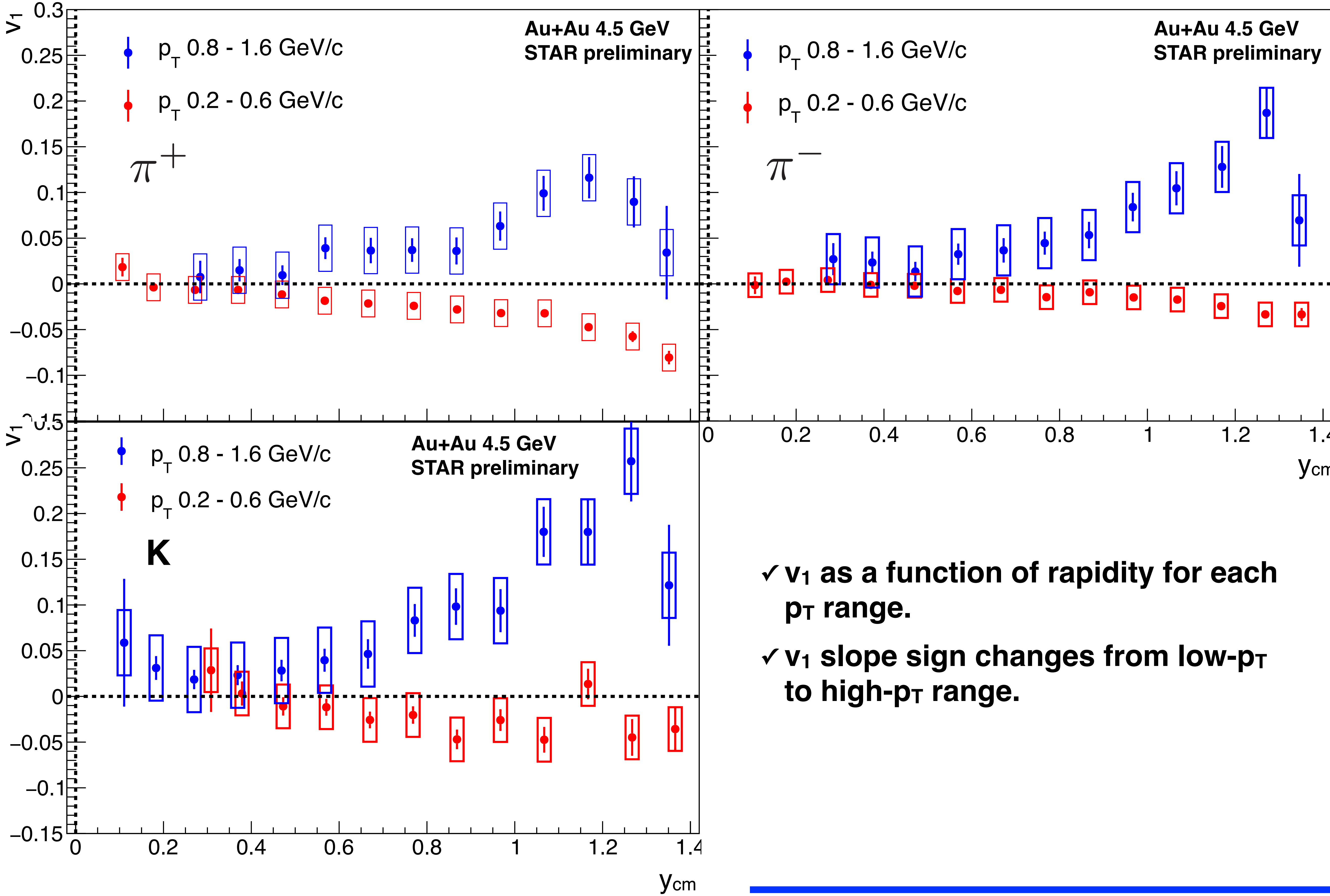


Centrality : 5-30%

✓ 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%

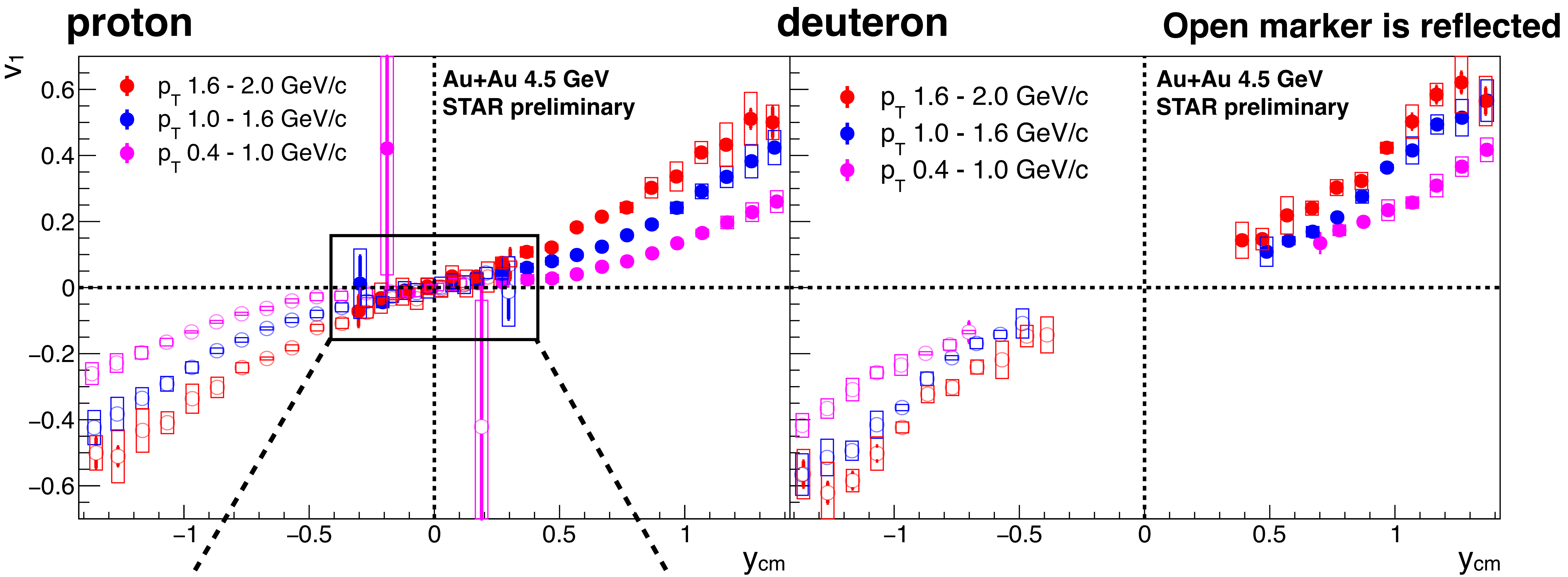


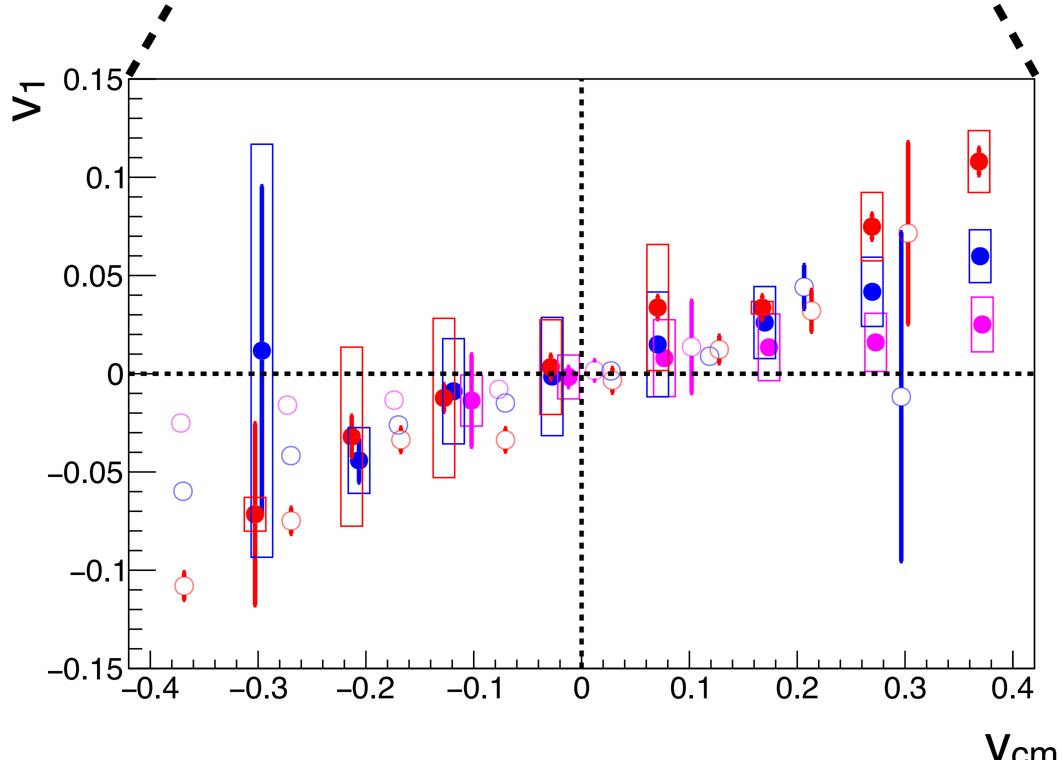
- ✓ v_1 as a function of rapidity for each p_T range.
- ✓ v_1 slope sign changes from low-p_T to high-p_T range.

Rapidity dependence of v_1 (p, d)

centrality : 5-30%

Open marker is reflected





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.

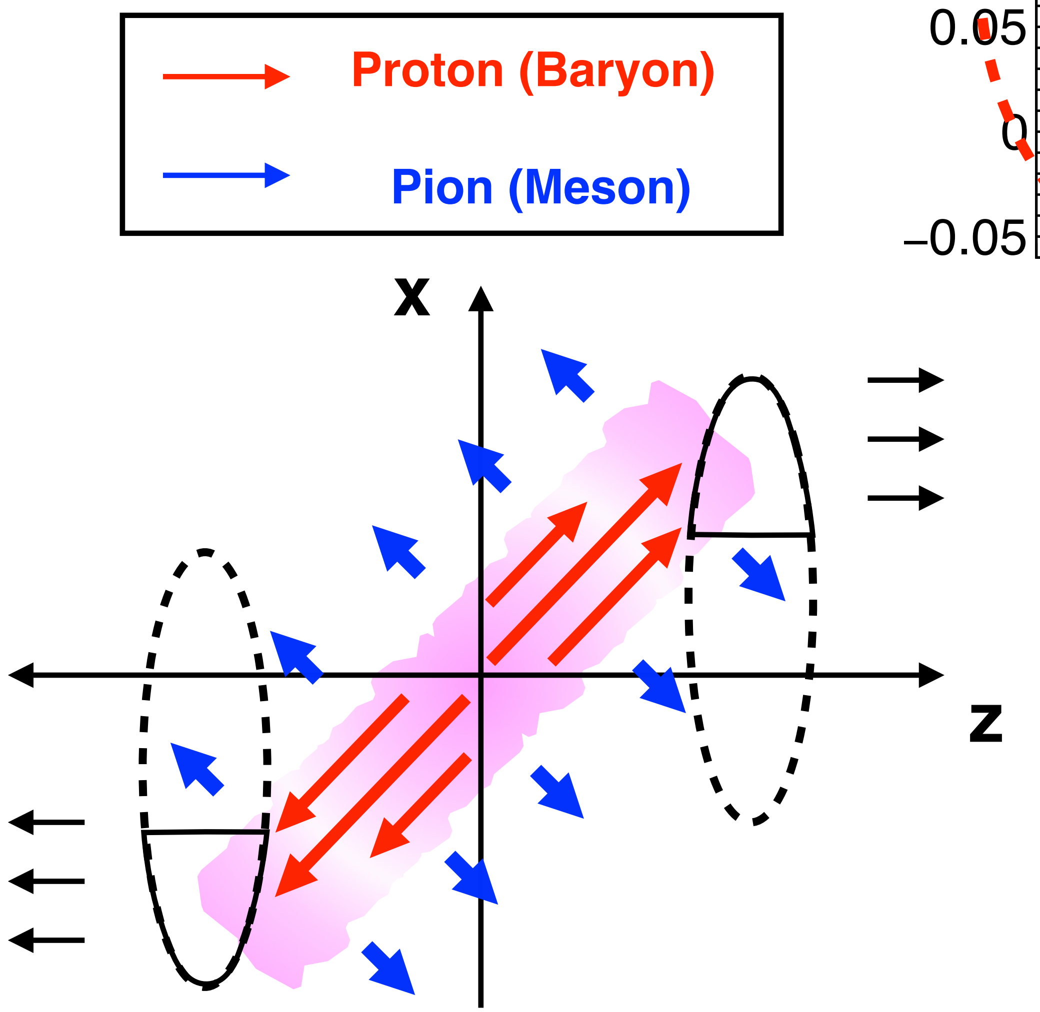
✓v_1 of p and d become closer after performing the m_T-scaling.

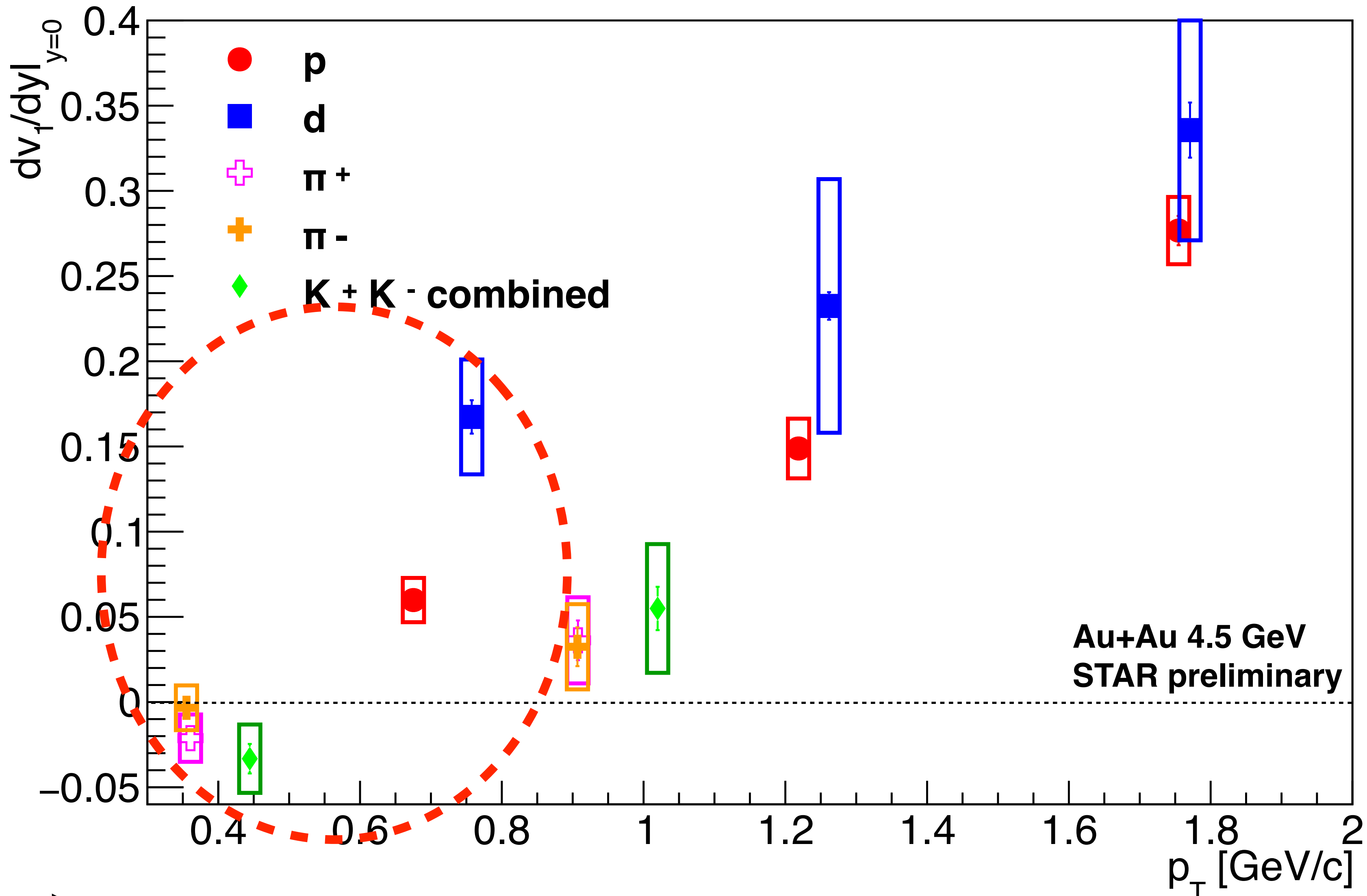
p_T dependence of v_1 slope

Centrality : 5-30%

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

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





Low-p_T region→Shadowing effect is dominant

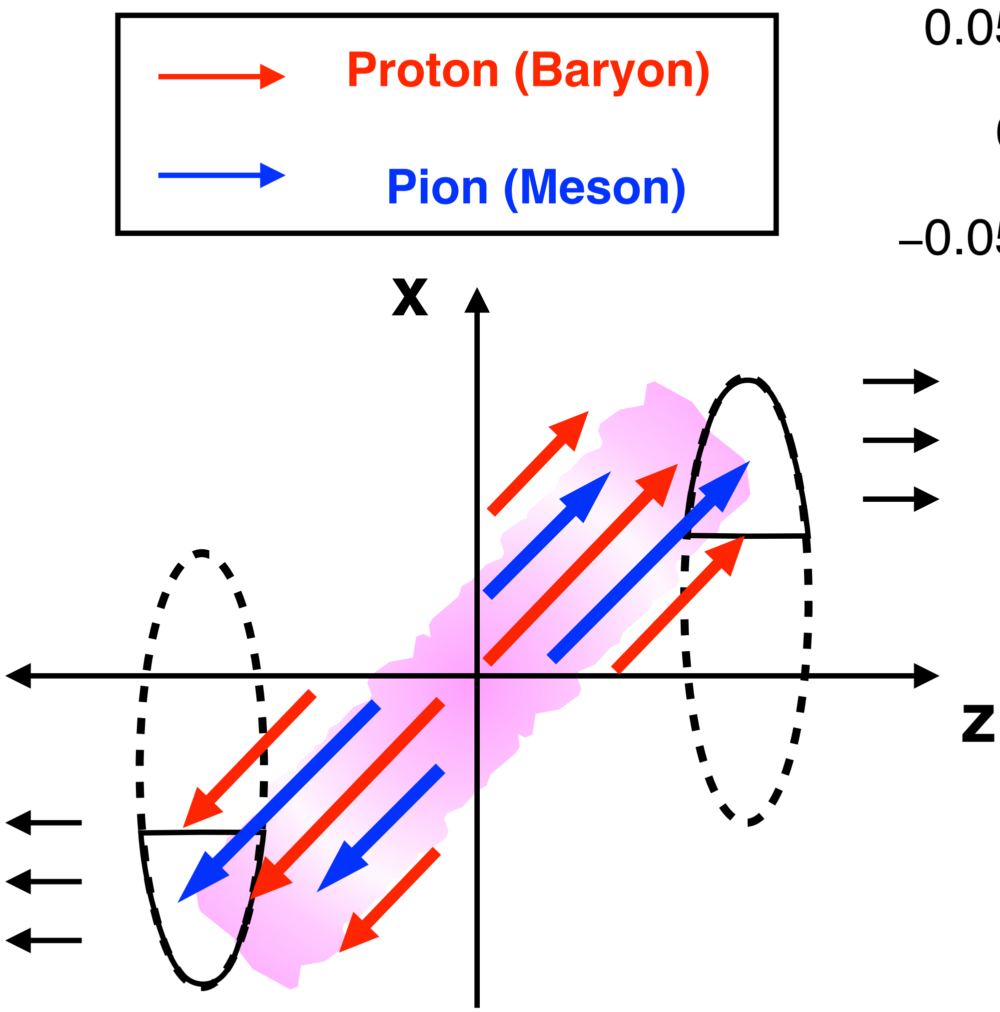
- ✓ **Interaction between produced pions and kaons with the spectator nucleons. Shadowing due to the baryon-meson interactions.**
- ✓ **Proton (baryon) and pion/kaon (mesons) have the opposite direction of v_1 slope.**

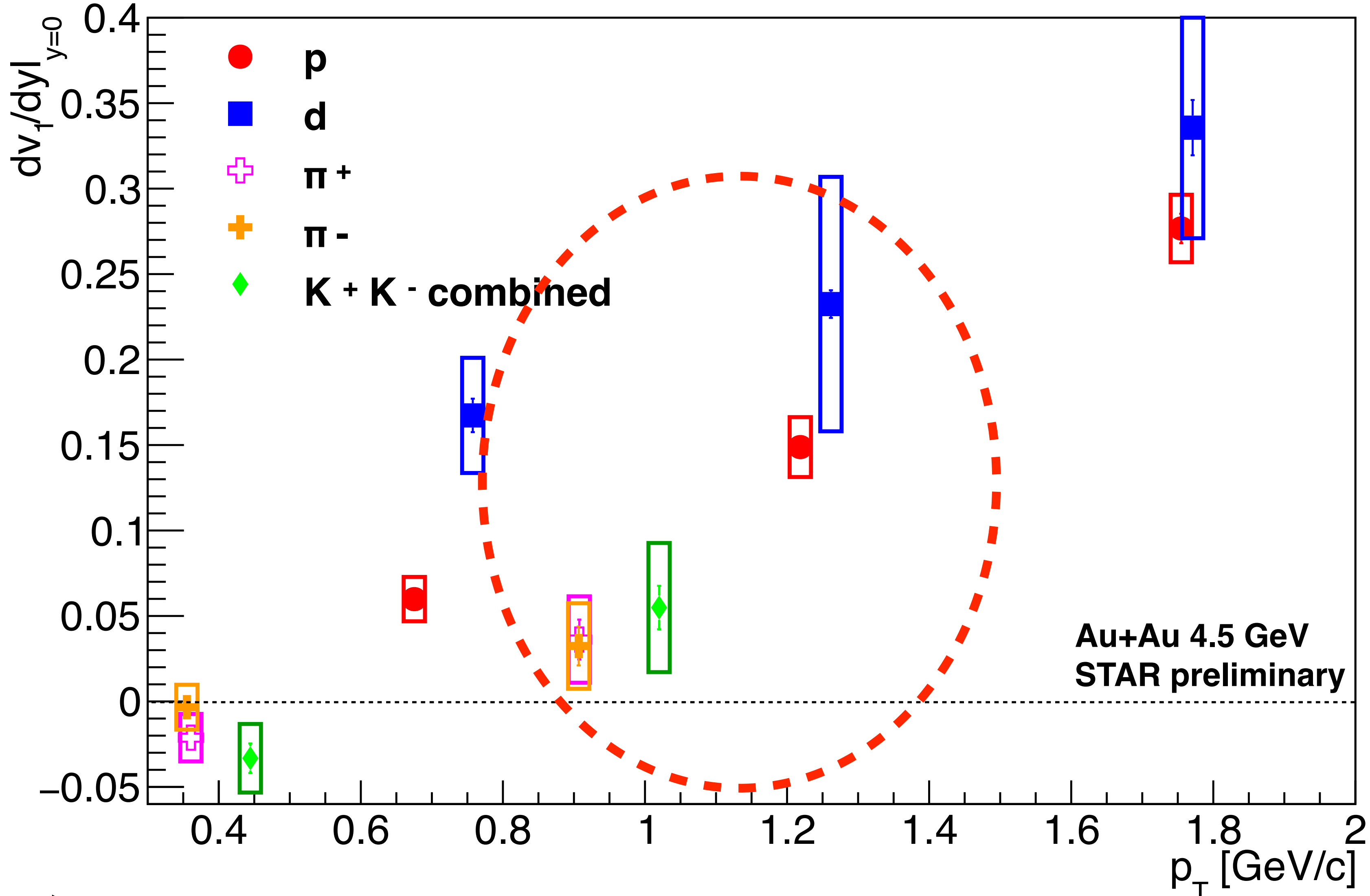
p_T dependence of v_1 slope

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

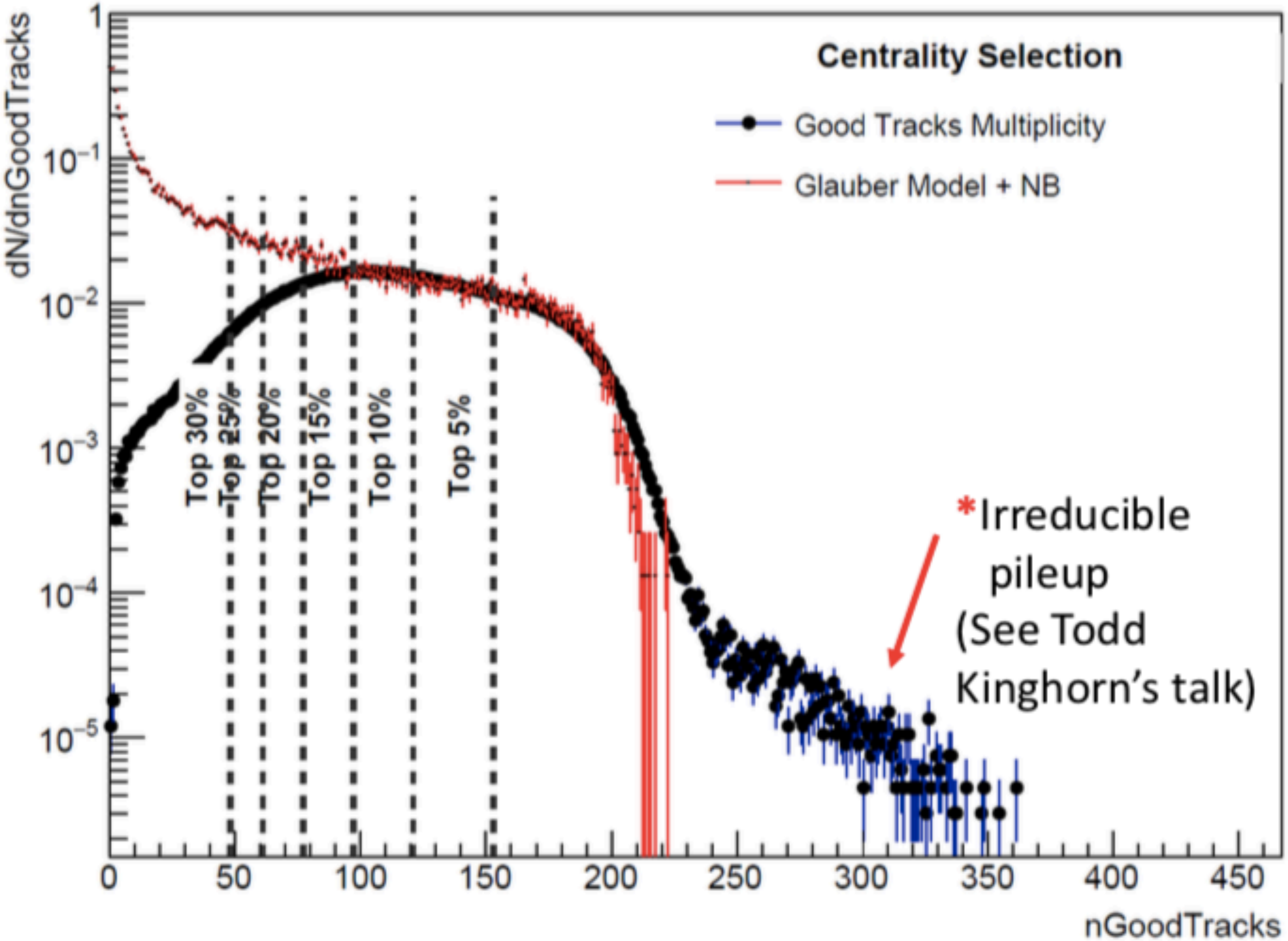
➡collective flow influence is considered to be more dominant than the shadowing effect.

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

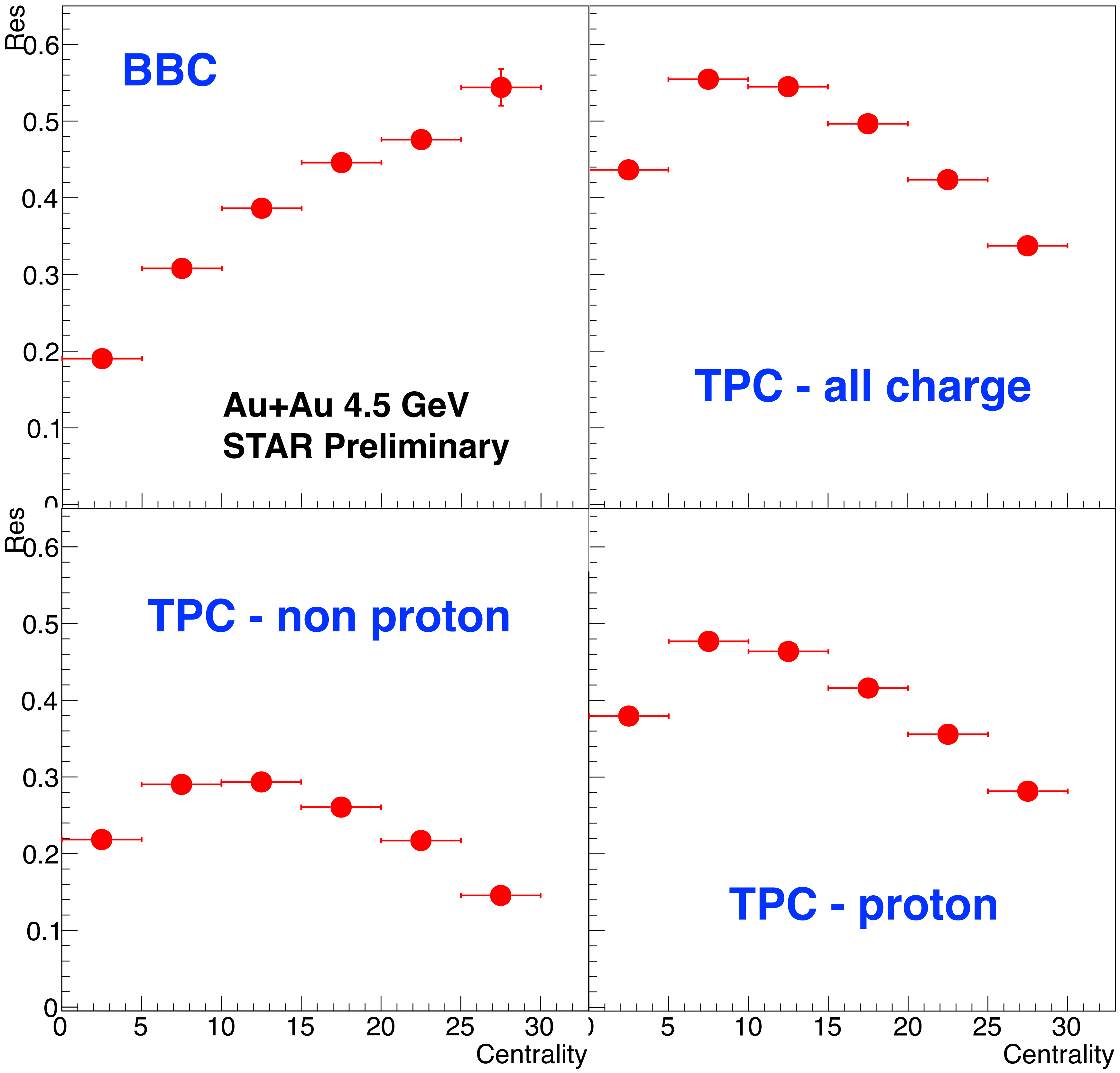
Centrality definition



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

- No correction
- Re-centering
- Re-centering+Flattening