Directed flow and freeze-out in microscopic models in A+A collisions at BES/FAIR/NICA energies

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in collaboration with

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Content

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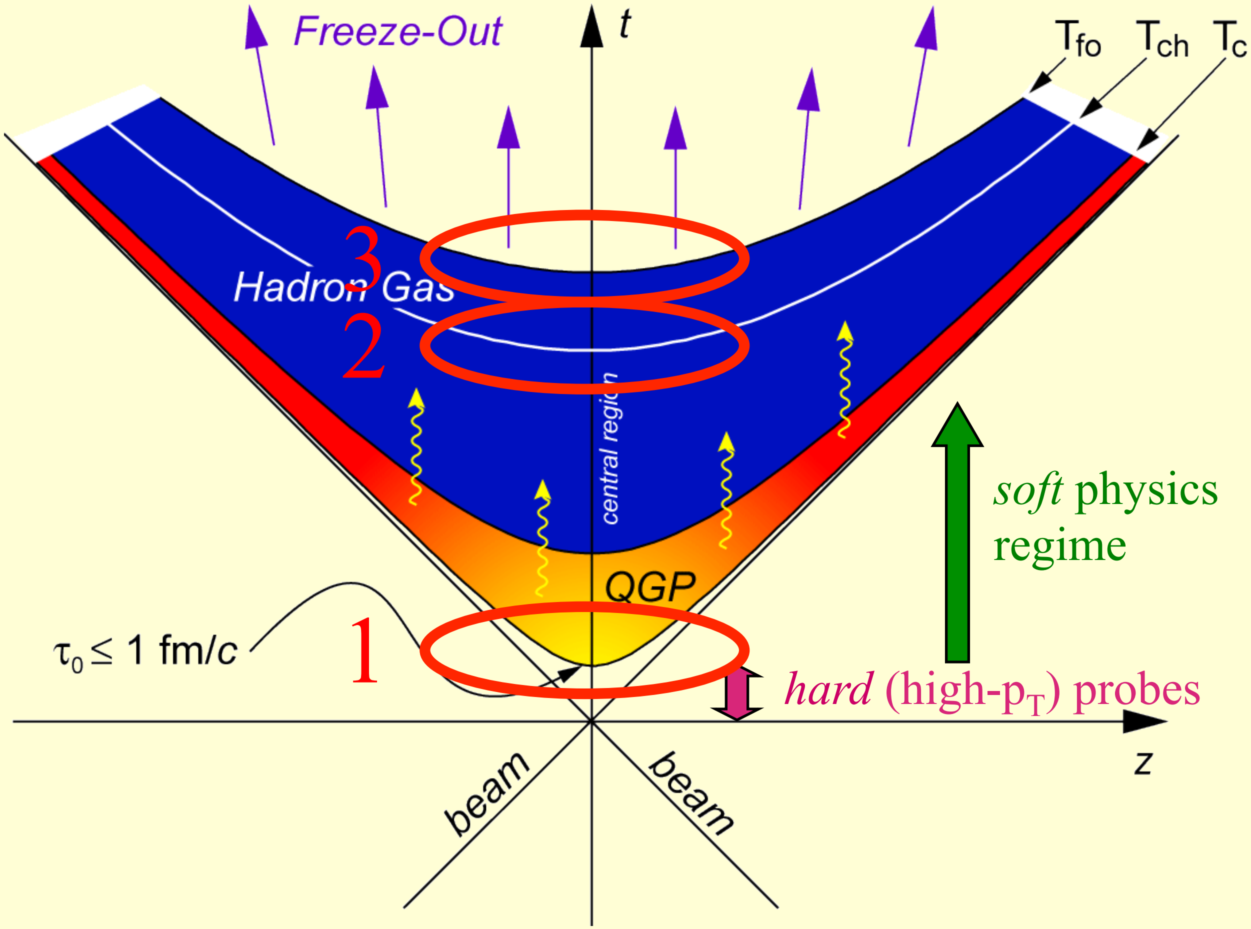
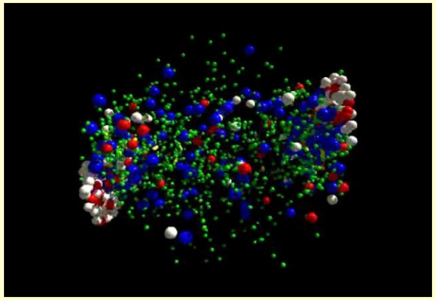
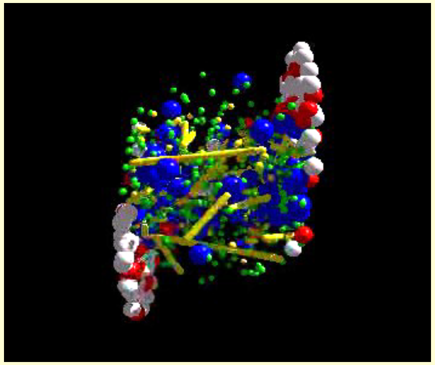
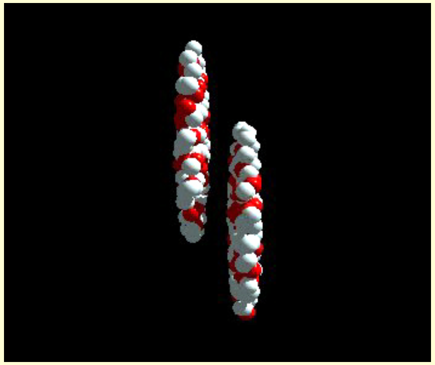
Motivation





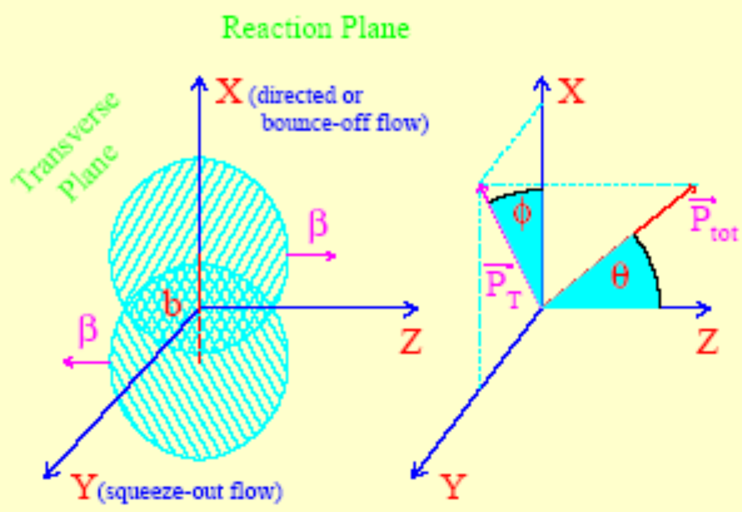




Chemical freezeout ($T_{ch} \leq T_c$): inelastic scattering ceases

Kinetic freeze-out ($T_{fo} \leq T_{ch}$): elastic scattering ceases

Definitions. Non-central Collisions (b>0)



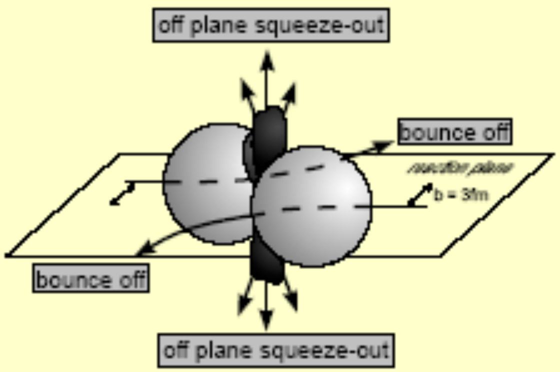
Flow Decomposition:

Transverse flow = Radial
+ Bounce-off + Squeeze-out

S. Voloshin and Y. Zhang, ZPC 70 (1996) 665

Modern analysis:

Transverse flow =
Radial + Directed + Elliptic + . . .
{isotropic} {anisotropic}



$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n\phi')\right)$$

Directed flow:

$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle \equiv \langle \cos(\phi') \rangle$$

Elliptic flow:

$$v_2 = \left\langle \left(\frac{p_x}{p_T}\right)^2 - \left(\frac{p_y}{p_T}\right)^2 \right\rangle \equiv \langle \cos(2\phi') \rangle$$

Distributions

Rapidity dependence

$$v_n(y, \Delta p_t, \Delta b) = \frac{\int_{\Delta p_t} \int_{\Delta b} \cos(n\phi) \frac{d^3N}{dydbdp_t} dp_t db}{\int_{\Delta p_t} \int_{\Delta b} \frac{d^3N}{dydbdp_t} dp_t db}$$

Transverse momentum dependence

$$v_n(p_t, \Delta y, \Delta b) = \frac{\int_{\Delta y} \int_{\Delta b} \cos(n\phi) \frac{d^3N}{dydbdp_t} dy db}{\int_{\Delta y} \int_{\Delta b} \frac{d^3N}{dydbdp_t} dy db}$$

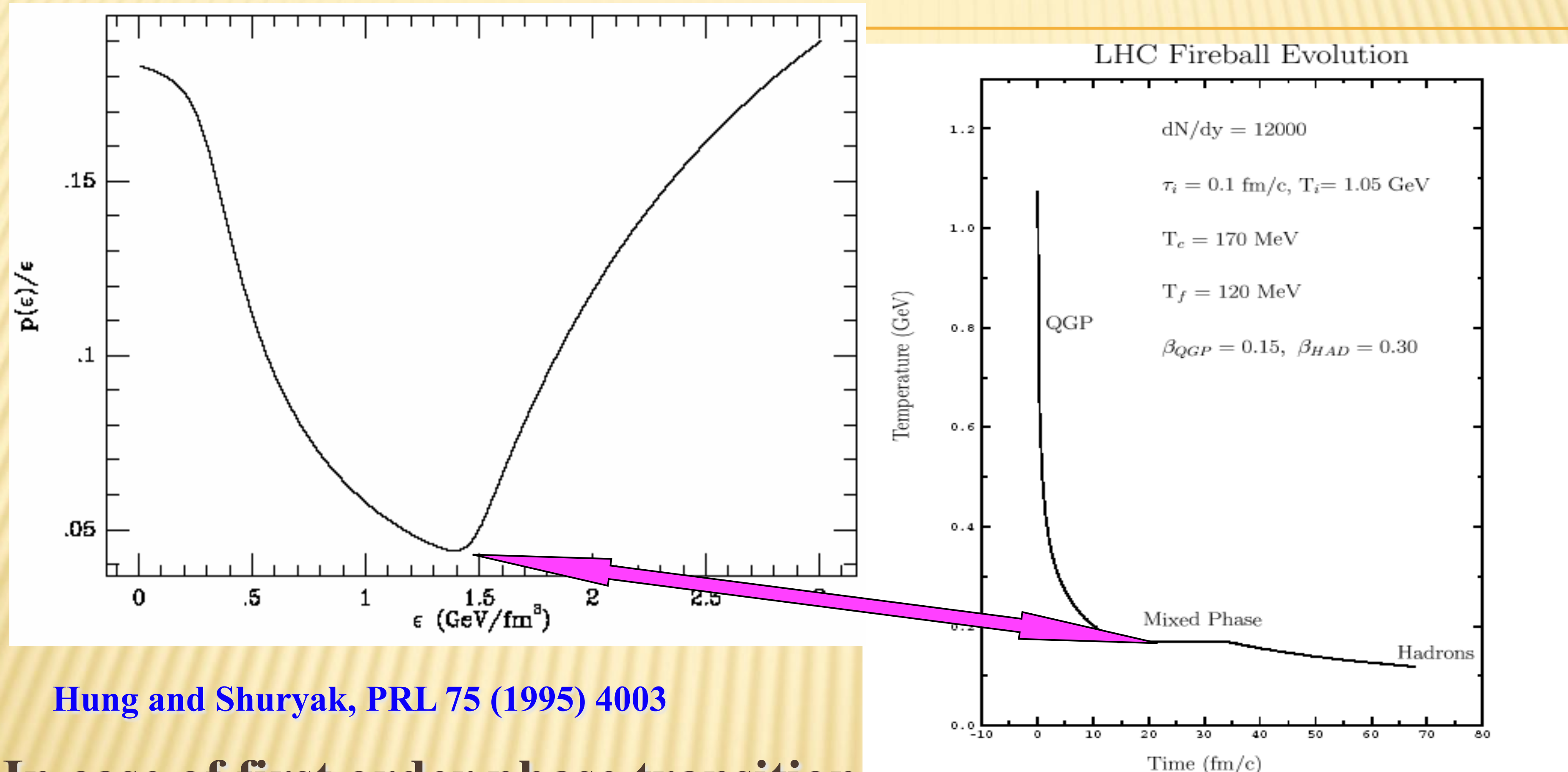
n=1,2,…

Centrality dependence

$$v_n(b, \Delta p_t, \Delta y) = \frac{\int_{\Delta p_t} \int_{\Delta y} \cos(n\phi) \frac{d^3N}{dydbdp_t} dp_t dy}{\int_{\Delta p_t} \int_{\Delta y} \frac{d^3N}{dydbdp_t} dp_t dy}$$

Motivation: connection to Equation of State

DISAPPEARANCE OF DIRECTED FLOW



Hung and Shuryak, PRL 75 (1995) 4003

Braun-Munzinger, NPA 661 (1999) 261c

In case of first order phase transition

$$\frac{dP}{d\varepsilon} = c_s^2 = 0$$

V_1 OF NUCLEONS AND FRAGMENTS AT LOWER ENERGIES

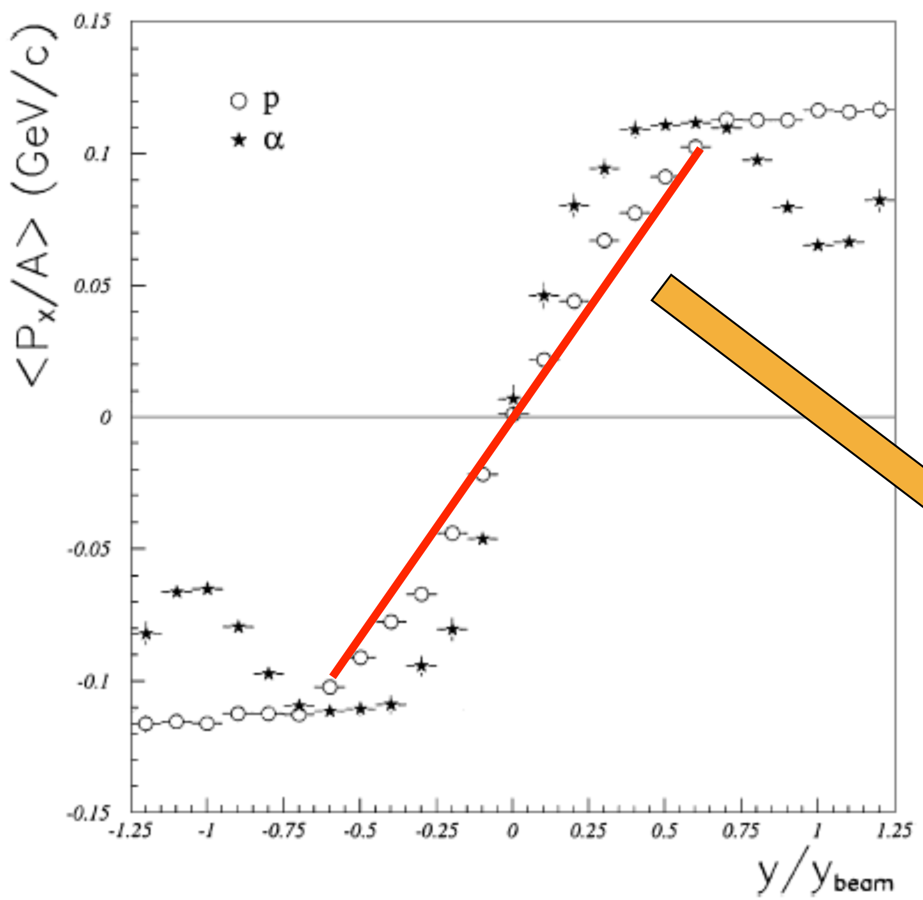


Figure 1 Average in-plane transverse momentum versus normalized rapidity in the reaction Au+Au at 800*A* MeV. The points at $y/y_{beam} < 0$ are reflected.

W. Reisdorf, H.G. Ritter
Annu.Rev.Nucl.Part.Sci. 47 (1997) 663

Plastic Ball Collaboration introduced a slope parameter

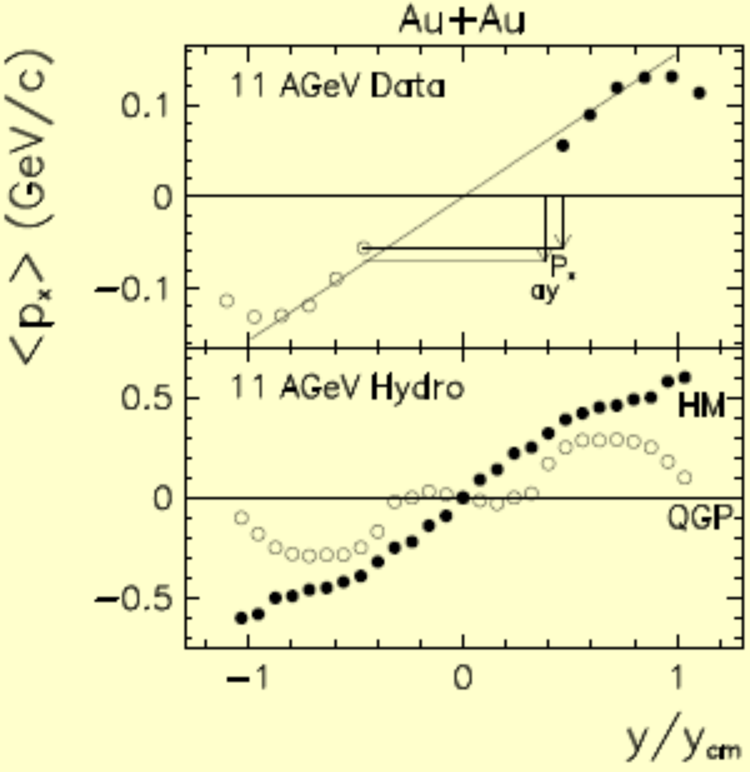
$$\mathbf{F} = \frac{d\langle p_x\rangle/A}{dy_n}, \quad y_n = y/y_{max}$$

$$\mathbf{F_y} = \frac{d\langle p_x\rangle/A}{dy}$$

Directed flow of nucleons and fragments has linear slope in normal direction => normal flow

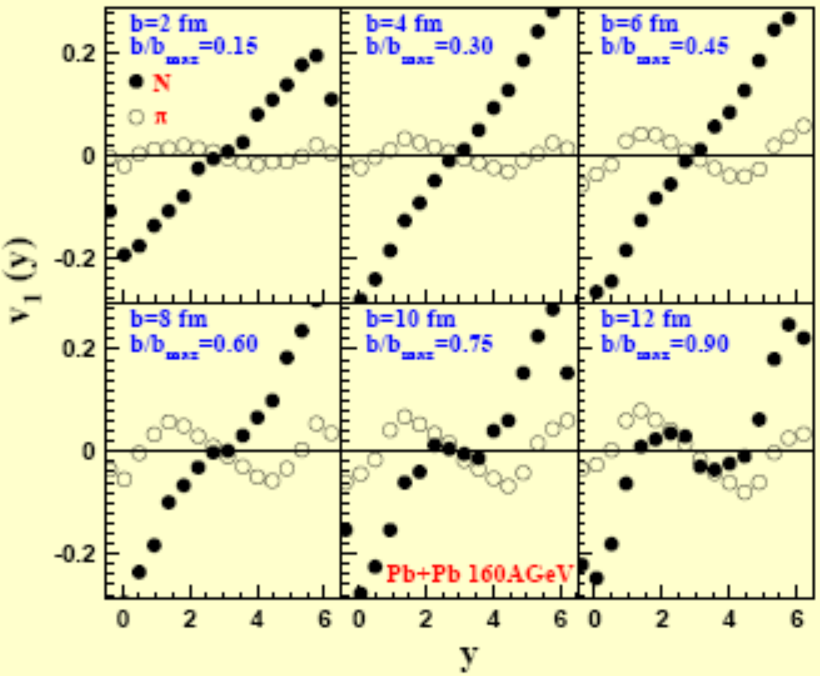
SOFTENING OF DIRECTED FLOW

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



Transition to the Quark-Gluon Plasma ⟶ decrease in pressure ⟶ softening of the directed flow

L. Bravina, PLB 334, 49 (1995)
H. Liu, S. Panitkin, N. Xu, PRC 59, 348 (1999)
R.J.M. Snellings *et al.*, PRL 84, 2803 (2000)
L. Bravina *et al.*, PRC 61, 064902 (2000)



Wiggle structure: The effect is more pronounced in peripheral and light-ion collisions, therefore, it cannot be explained by the softening of the EOS because of the formation of strings

Models at our disposal: UrQMD, DCM, QGSM...

Directed flow at BES/FAIR/NICA

Beam energy scan results for v_1 (STAR)

S. Singha et al. (STAR Collab.), PoS CPOD2017 (2018) 004

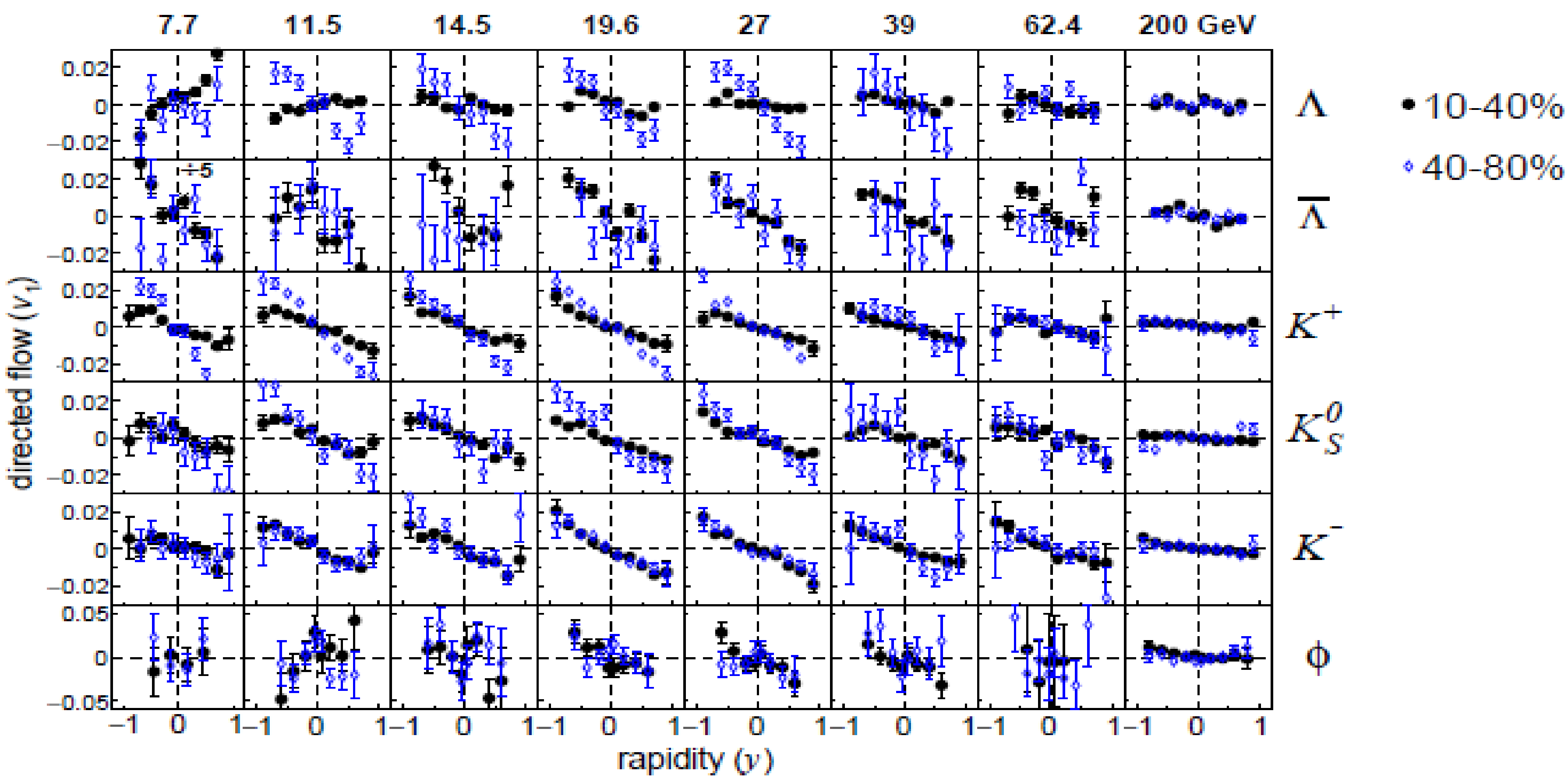
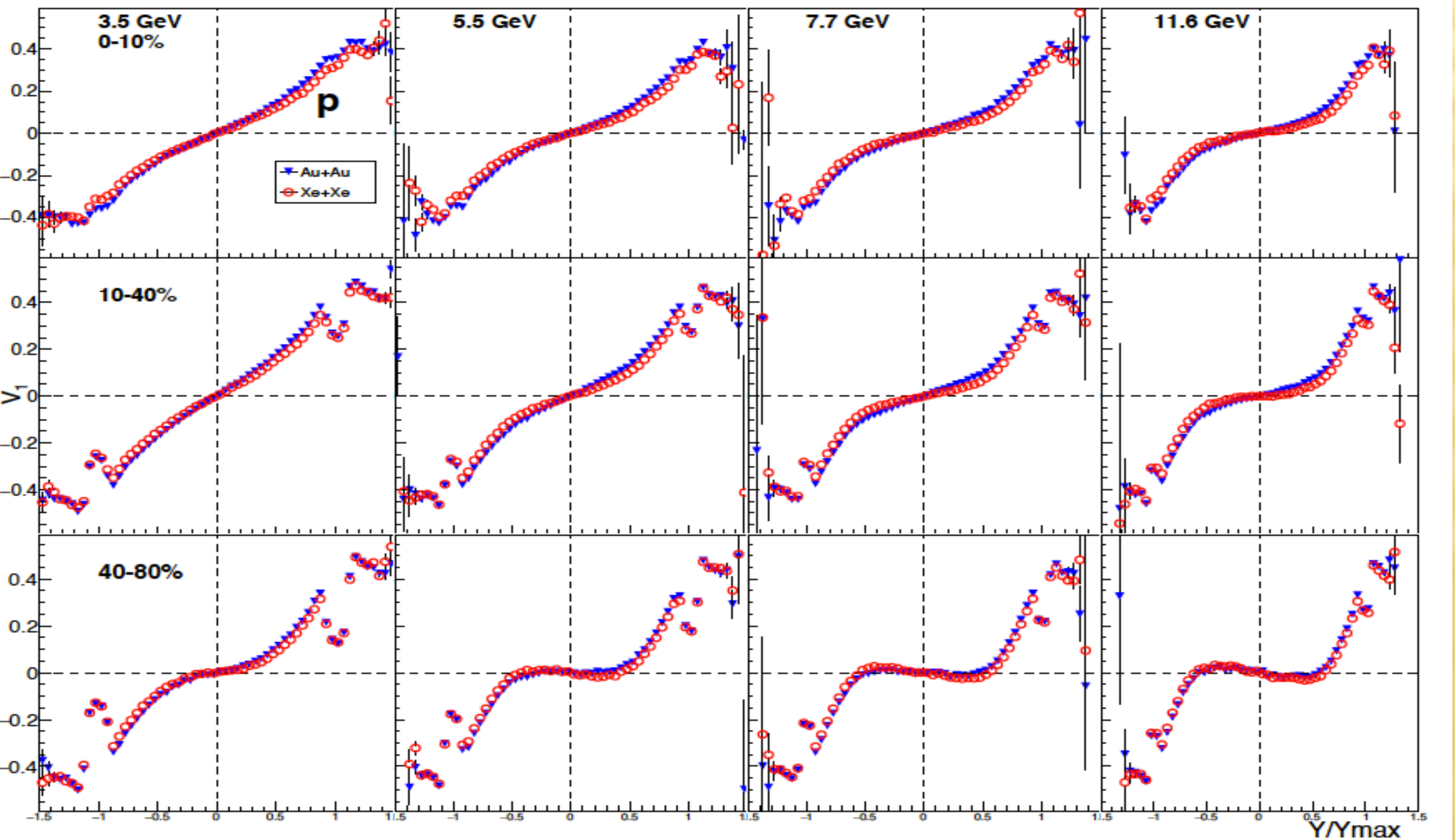


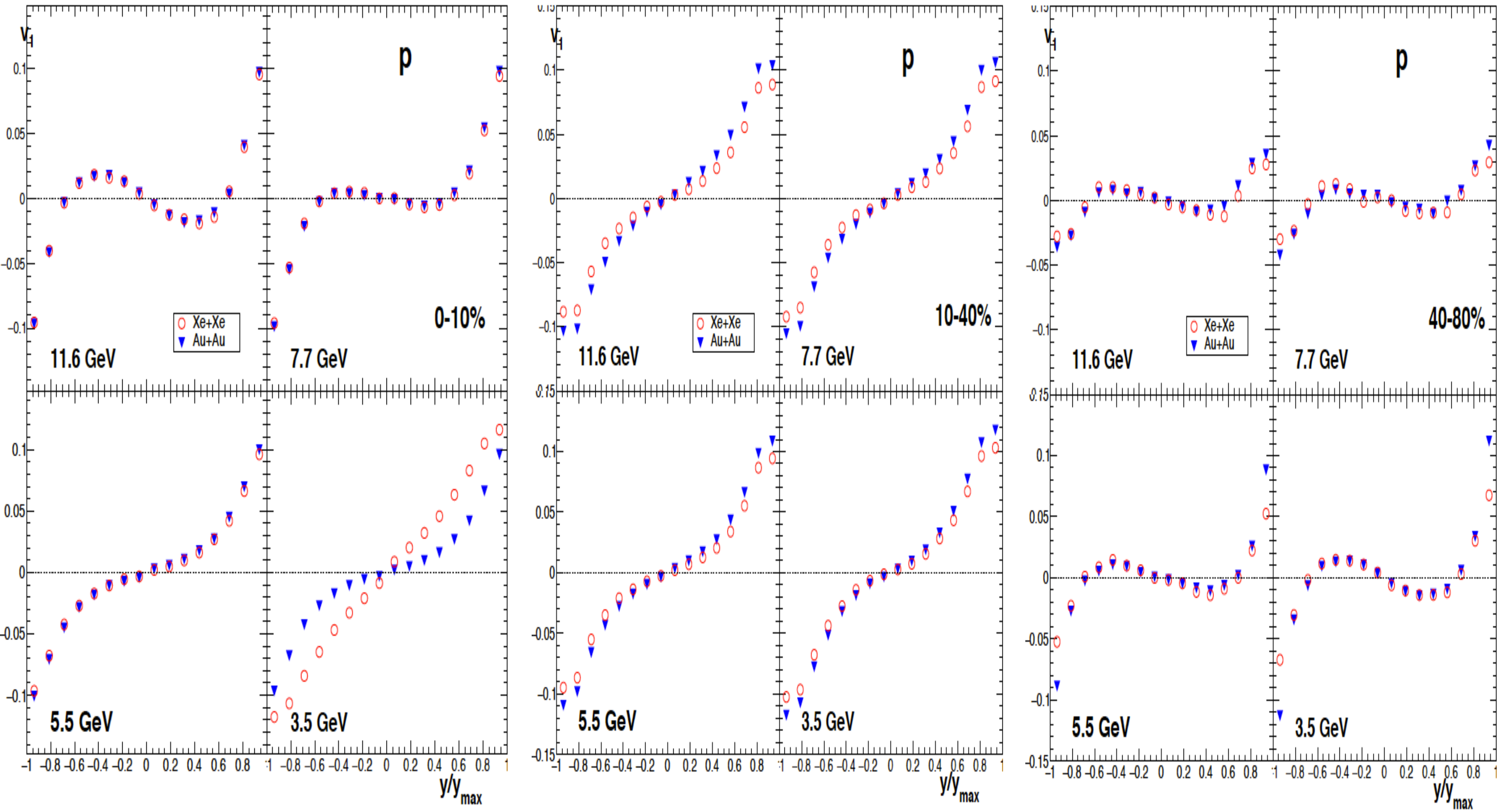
Figure 1: (Color online) Rapidity dependence of directed flow (v_1) for Λ, $\overline{\Lambda}$, K^+, K_s^0, K^- and ϕ in 10-40% and 40-80% Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 and 200 GeV.

V_1 (y) for protons , QGSM



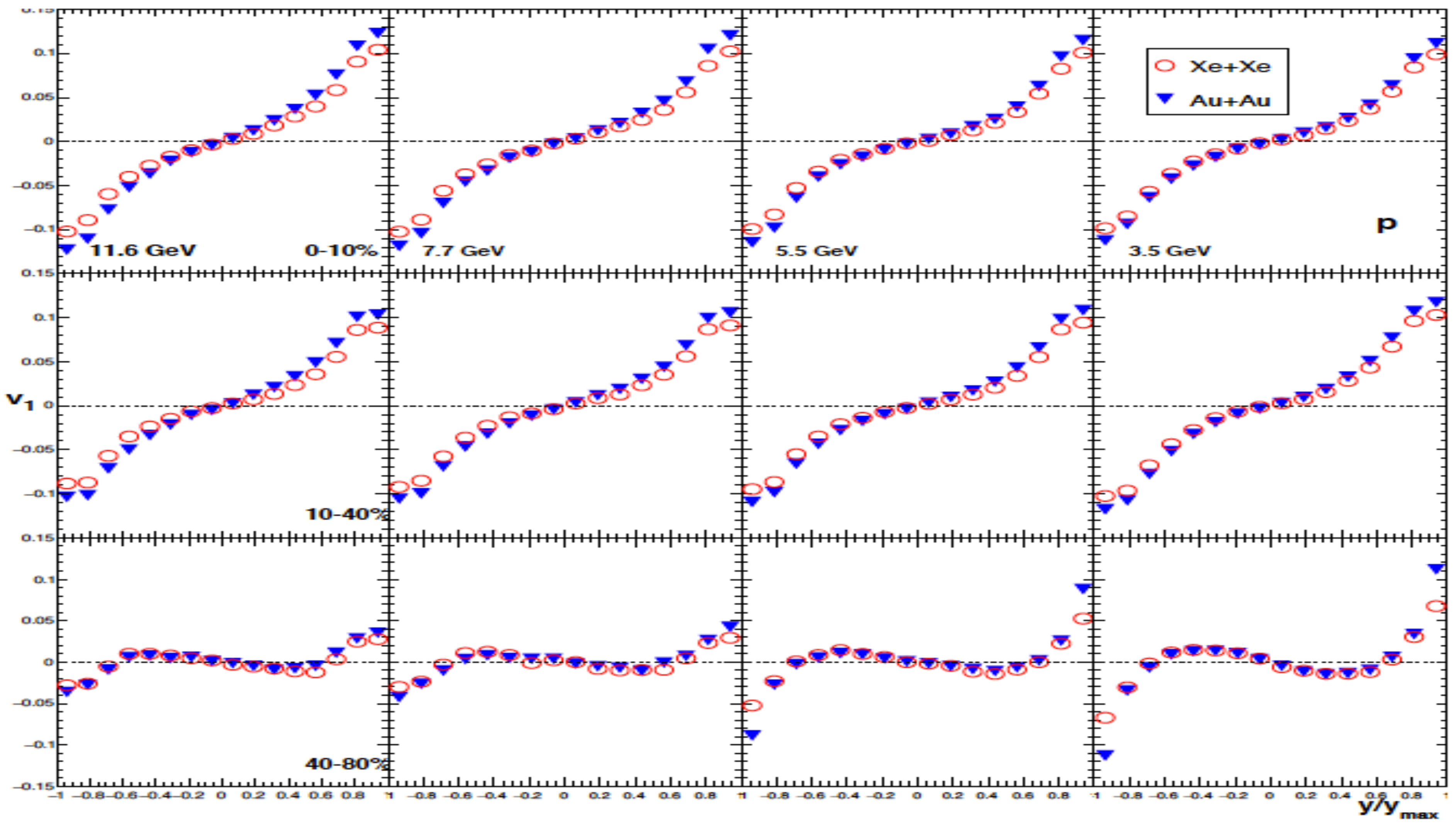
- Softening and development of antiflow at midrapidity with increasing impact parameter
- In central events – “normal” flow almost for all bombarding energies

V_1 (y) for protons , DCM



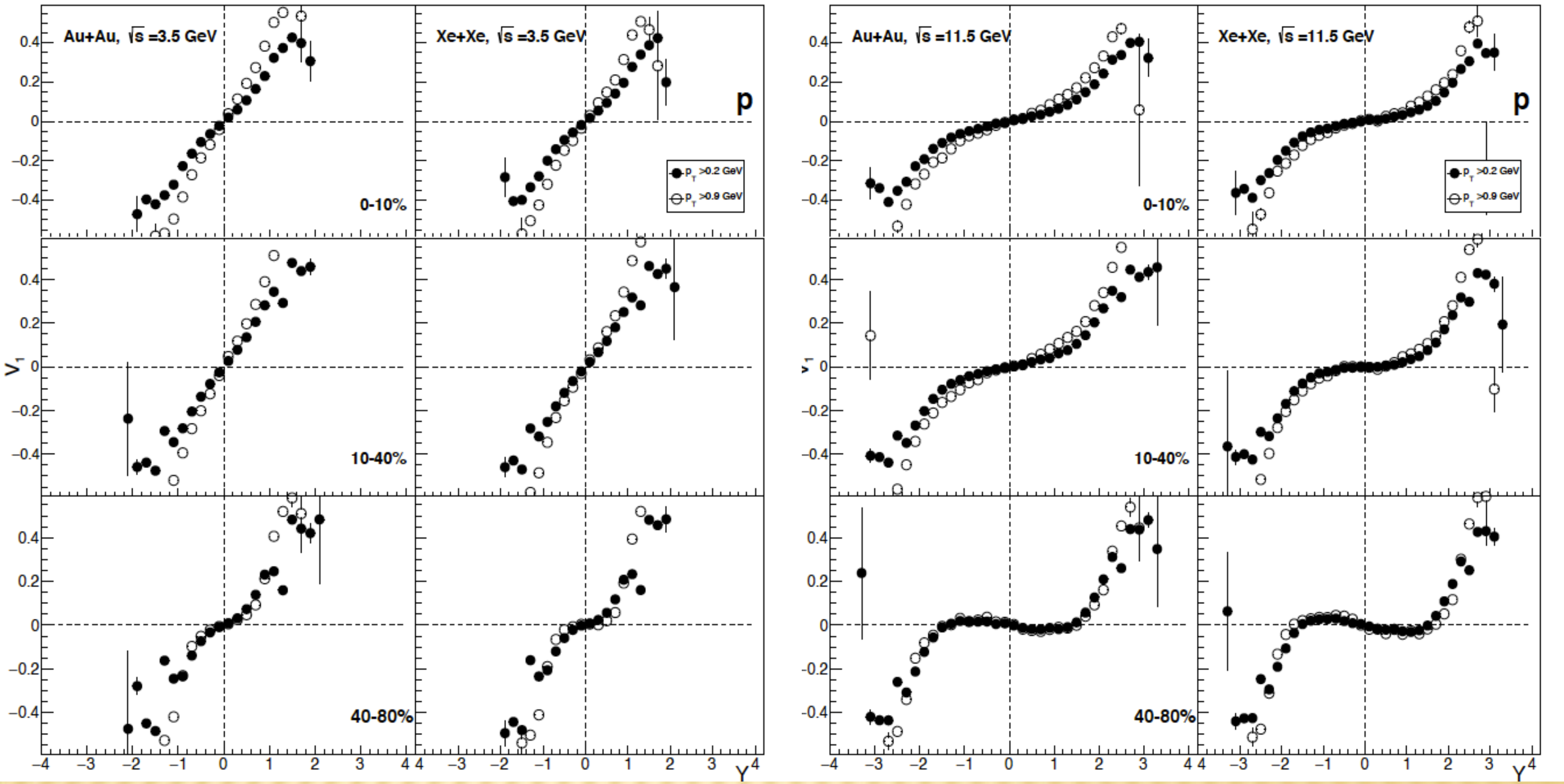
- Softening and development of antiflow at midrapidity with increasing impact parameter
- In central events – “normal” flow with decreasing CM energy
- Softening of v_1 at midrapidity is stronger for small colliding systems, whereas in case of QGP formation the effect should be opposite

V_1 (y) for protons , UrQMD



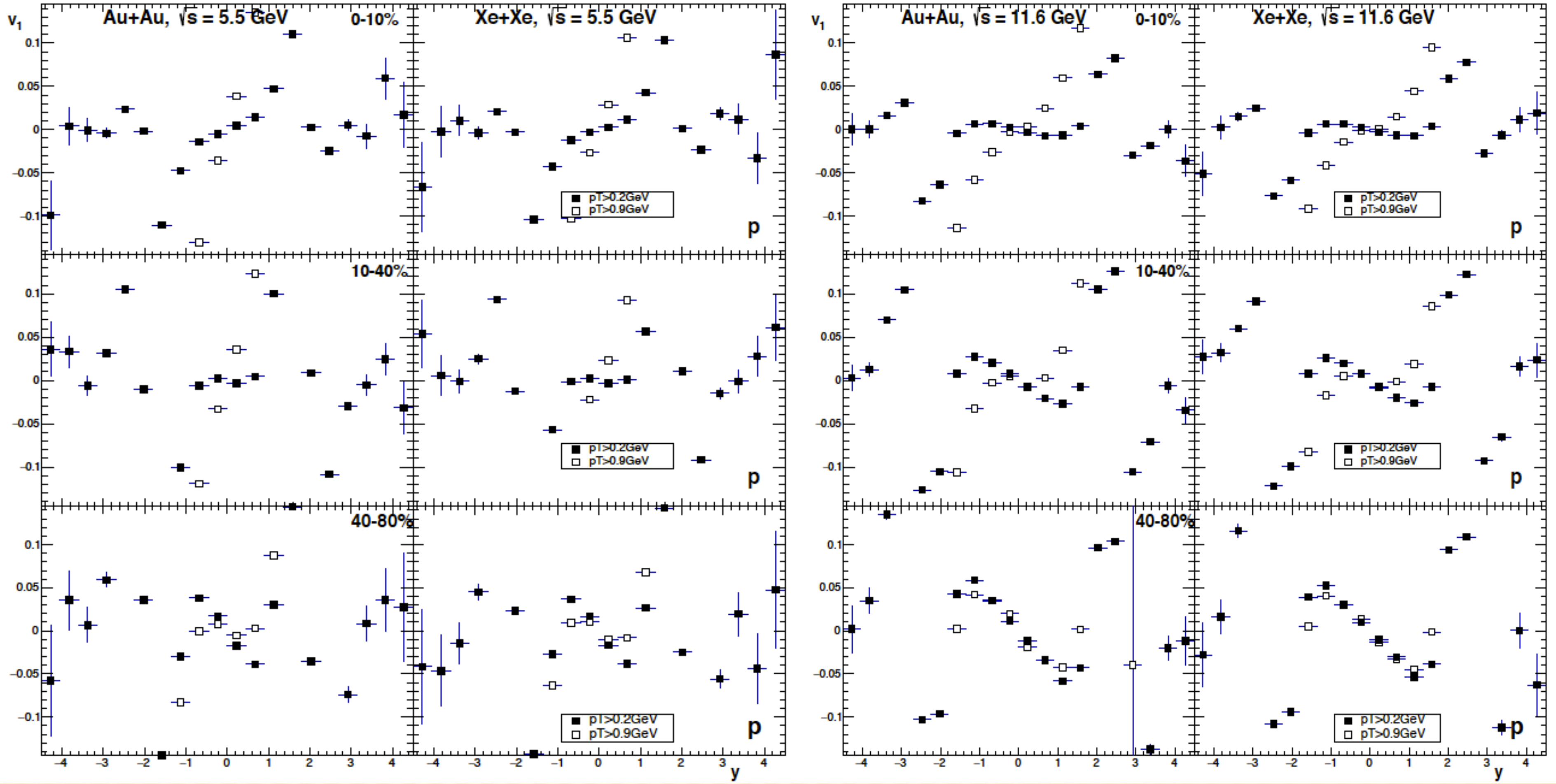
- Softening and development of antiflow at midrapidity with increasing impact parameter
- In central events – always “normal” flow
- Almost no difference between Xe+Xe and Au+Au

V_1 (y,p_T) for protons , QGSM



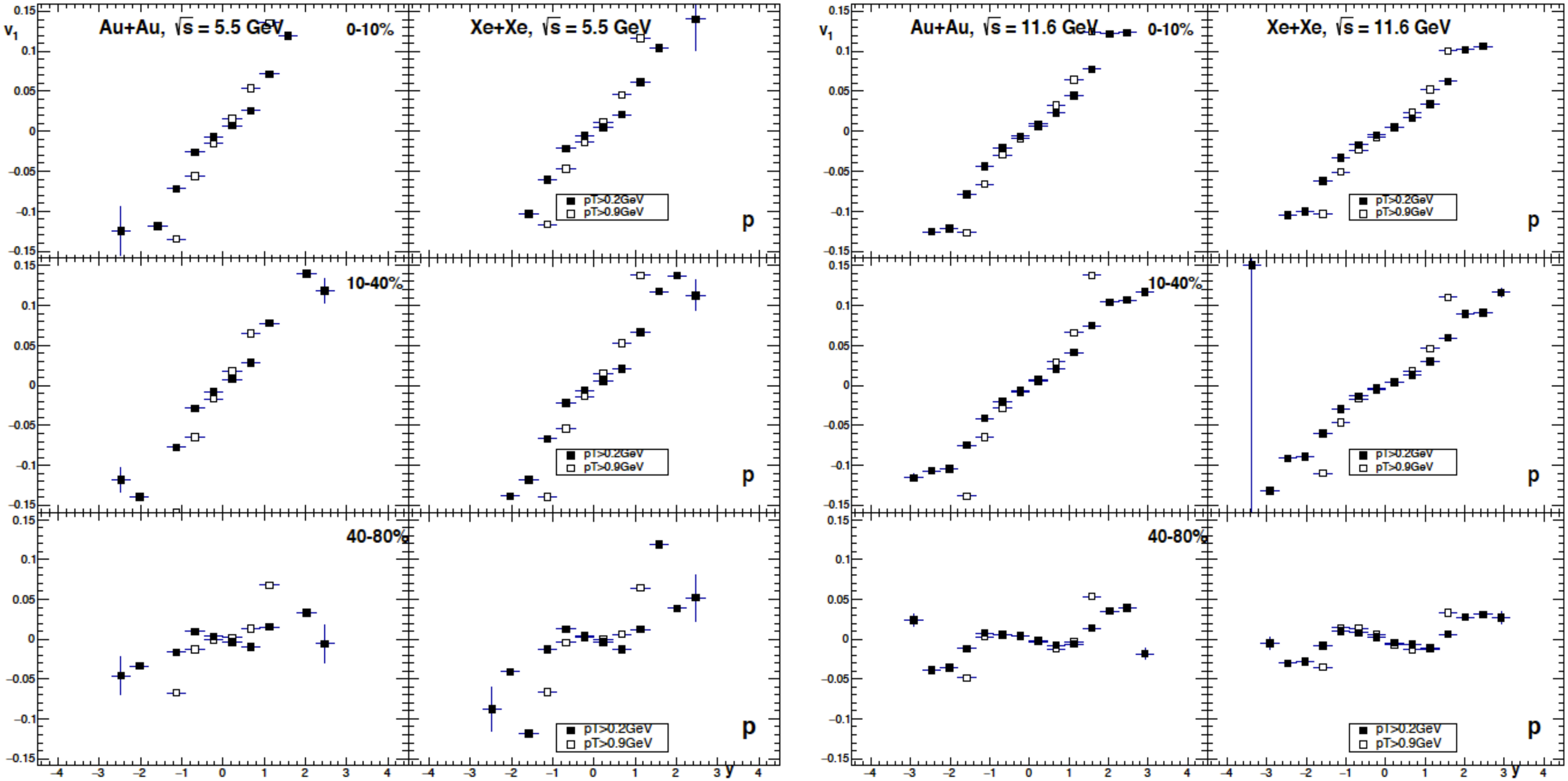
- Spectra for protons with P_T > 0.2 GeV/c and P_T > 0.9 GeV/c
- Almost no difference, especially, at midrapidity

V_1 (y,p_T) for protons , DCM



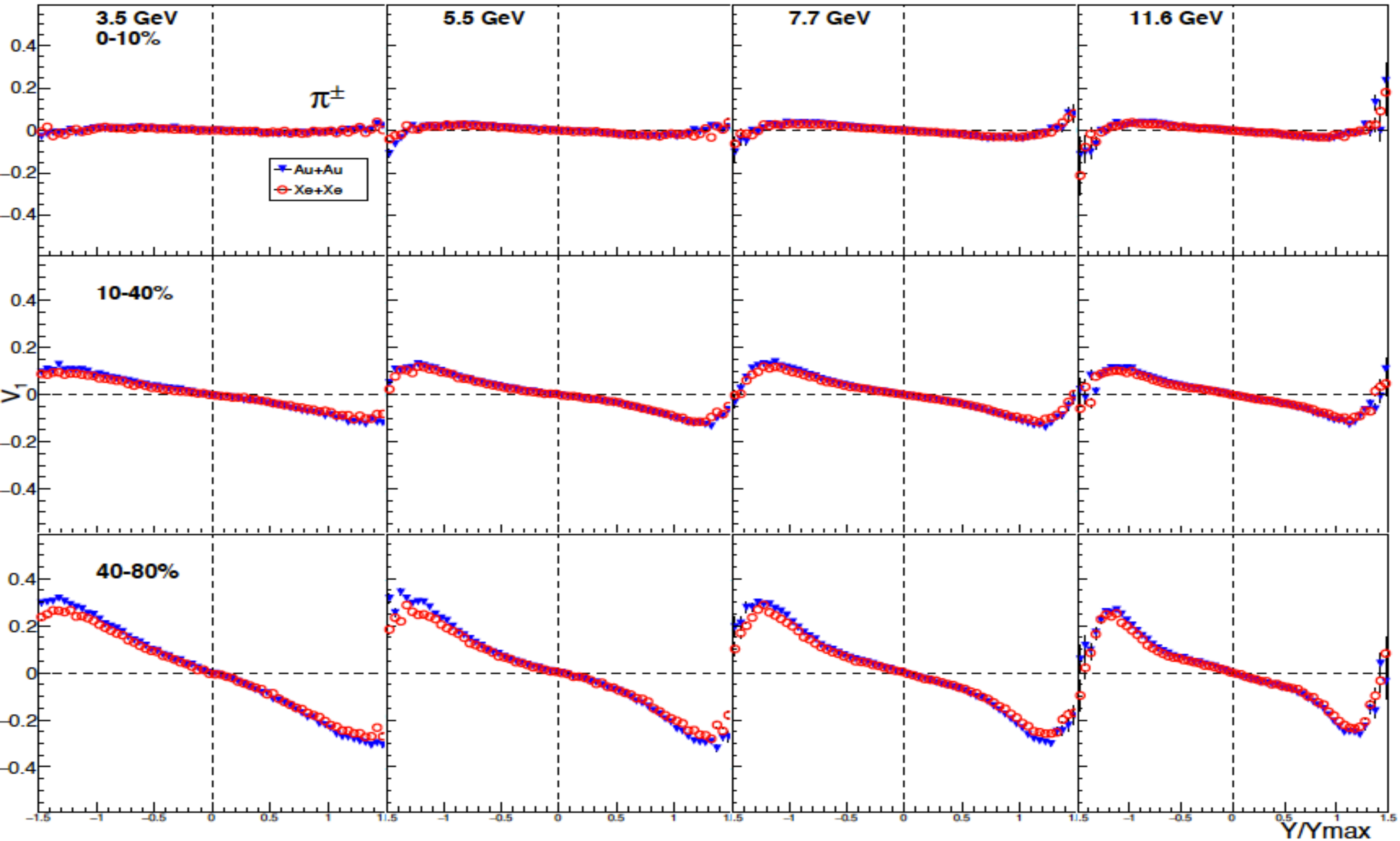
- **Spectra have spiky structure**
- **Clear difference between different parts of P_T - spectra**

V_1 (y,p_T) for protons , UrQMD



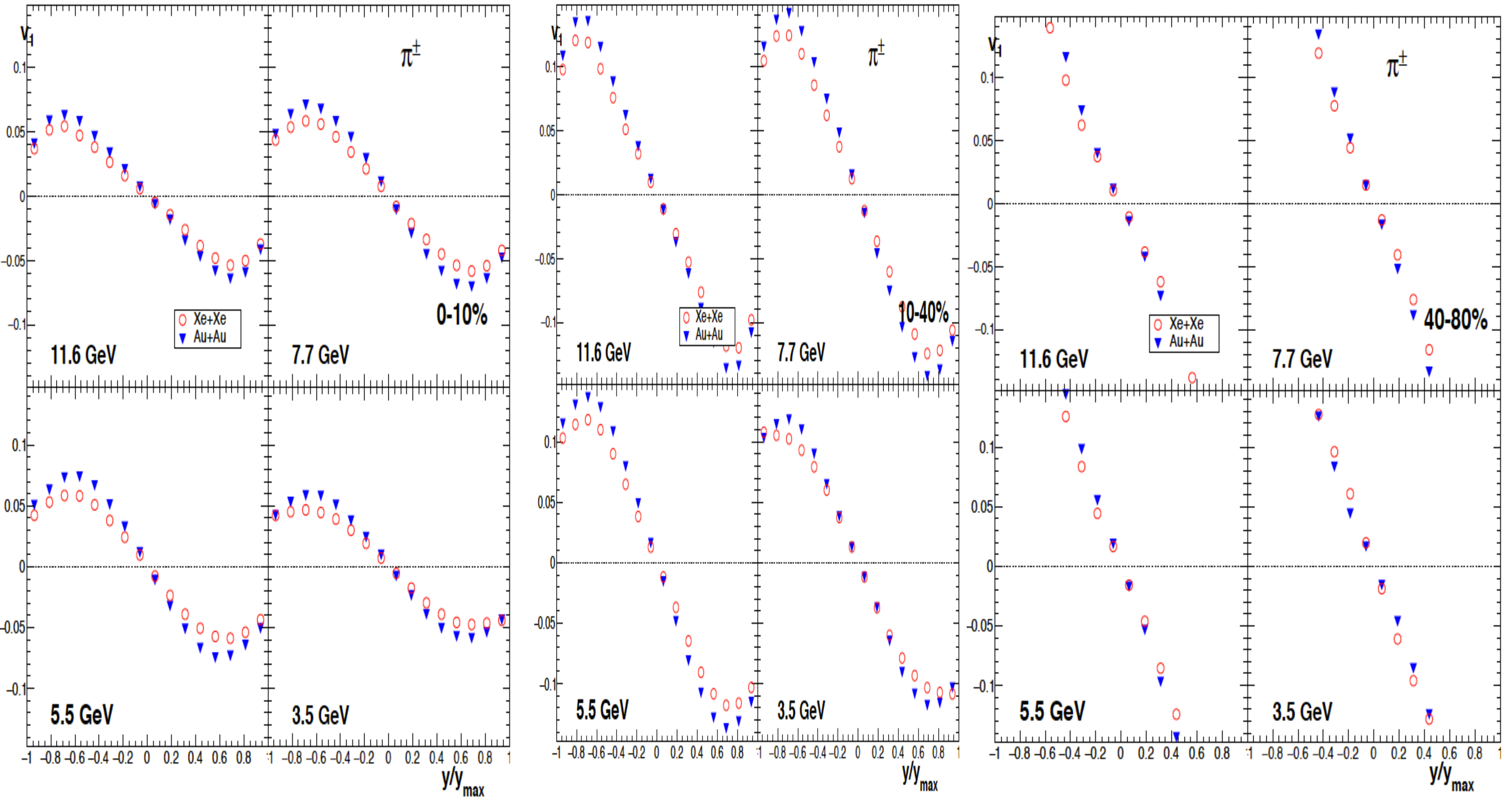
- No difference for both, Au+Au and Xe+Xe, @11.6 GeV
- Clear difference for collisions @ 5.5 GeV

V_1 (y) for pions, QGSM



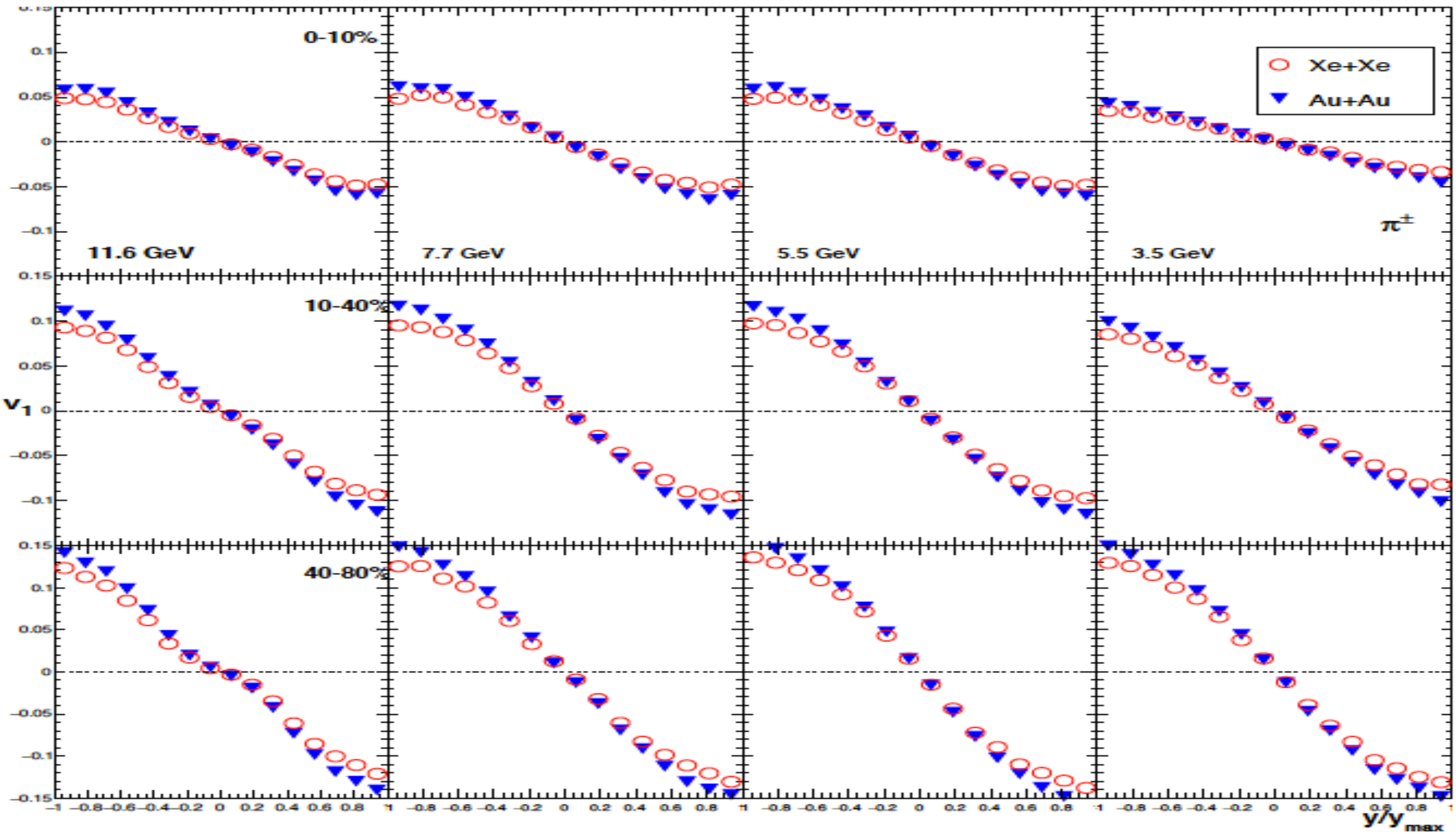
- Pions always have antiflow
- Stronger effect for more peripheral collisions

V_1 (y) for pions, DCM



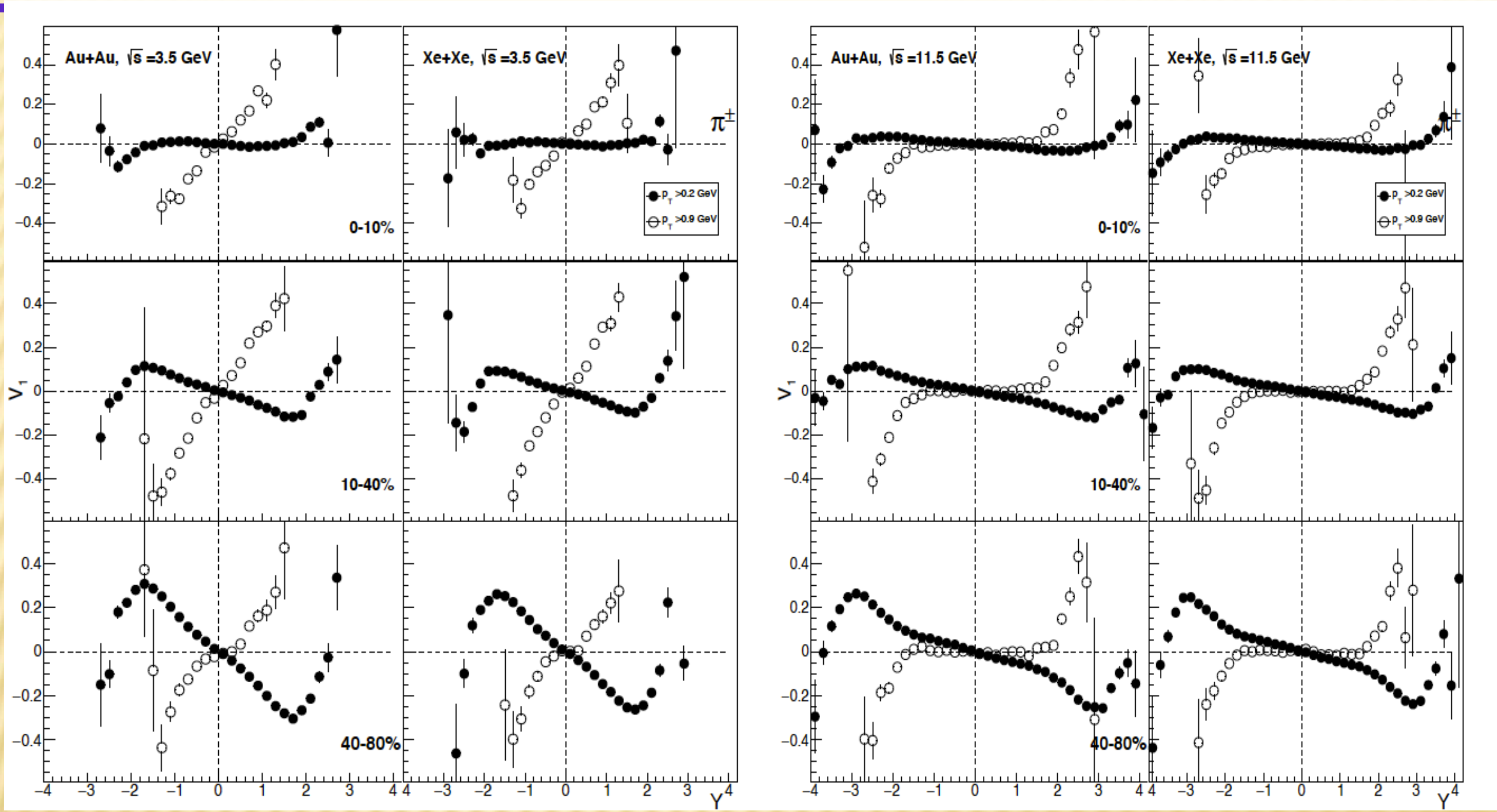
- The same conclusions: **Pions always have antiflow**
- **Stronger effect for more peripheral collisions**

V_1 (y) for pions, UrQMD



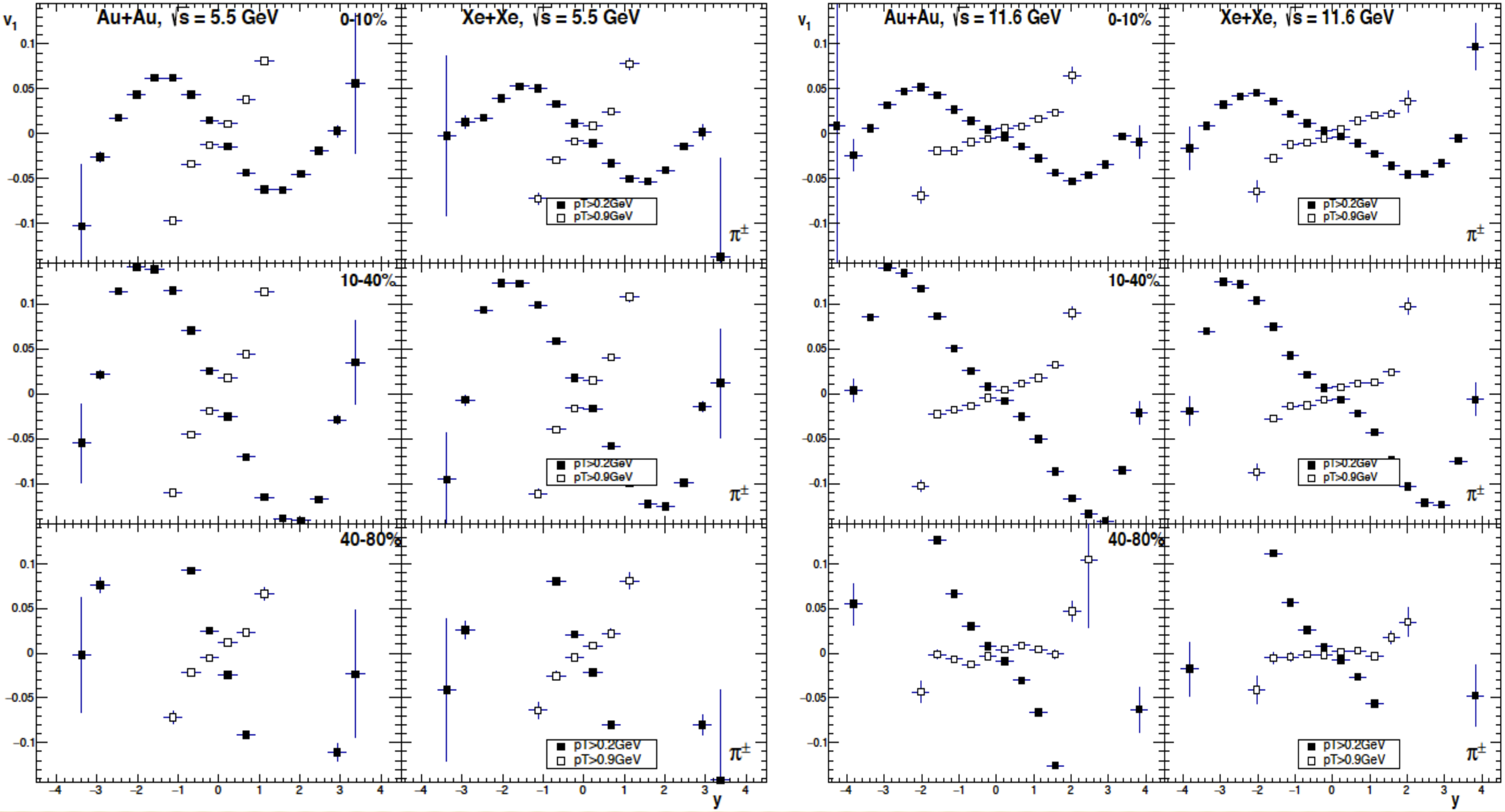
- The same conclusions: **Pions always have antiflow**
- **Stronger effect for more peripheral collisions**

V_1 (y,p_T) for pions, QGSM



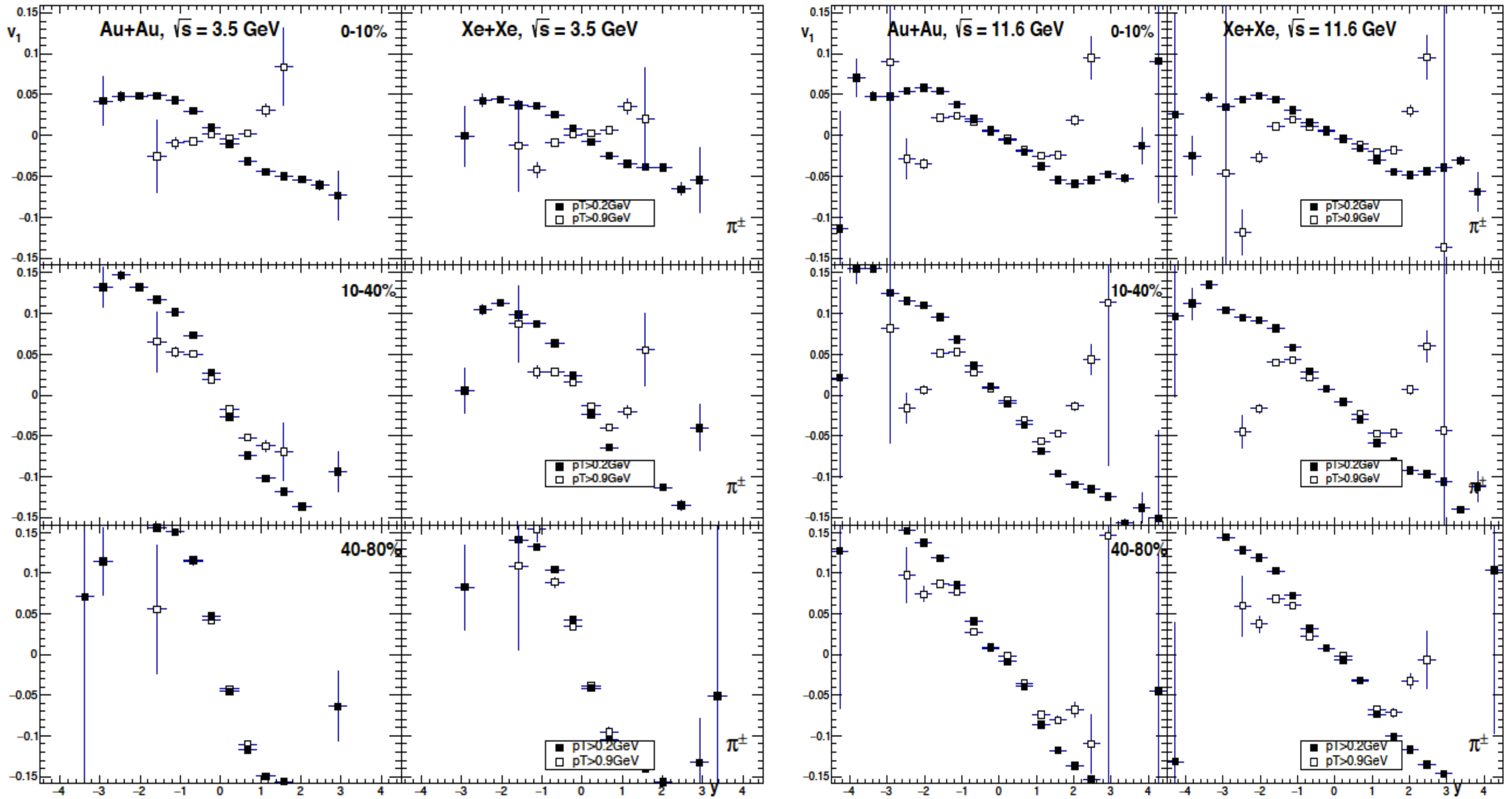
- Drastic difference: high-P_T pions have almost zero V_1 at midrapidity at 11.5 GeV
- and normal flow at 3.5 GeV

V_1 (y,p_T) for pions, DCM



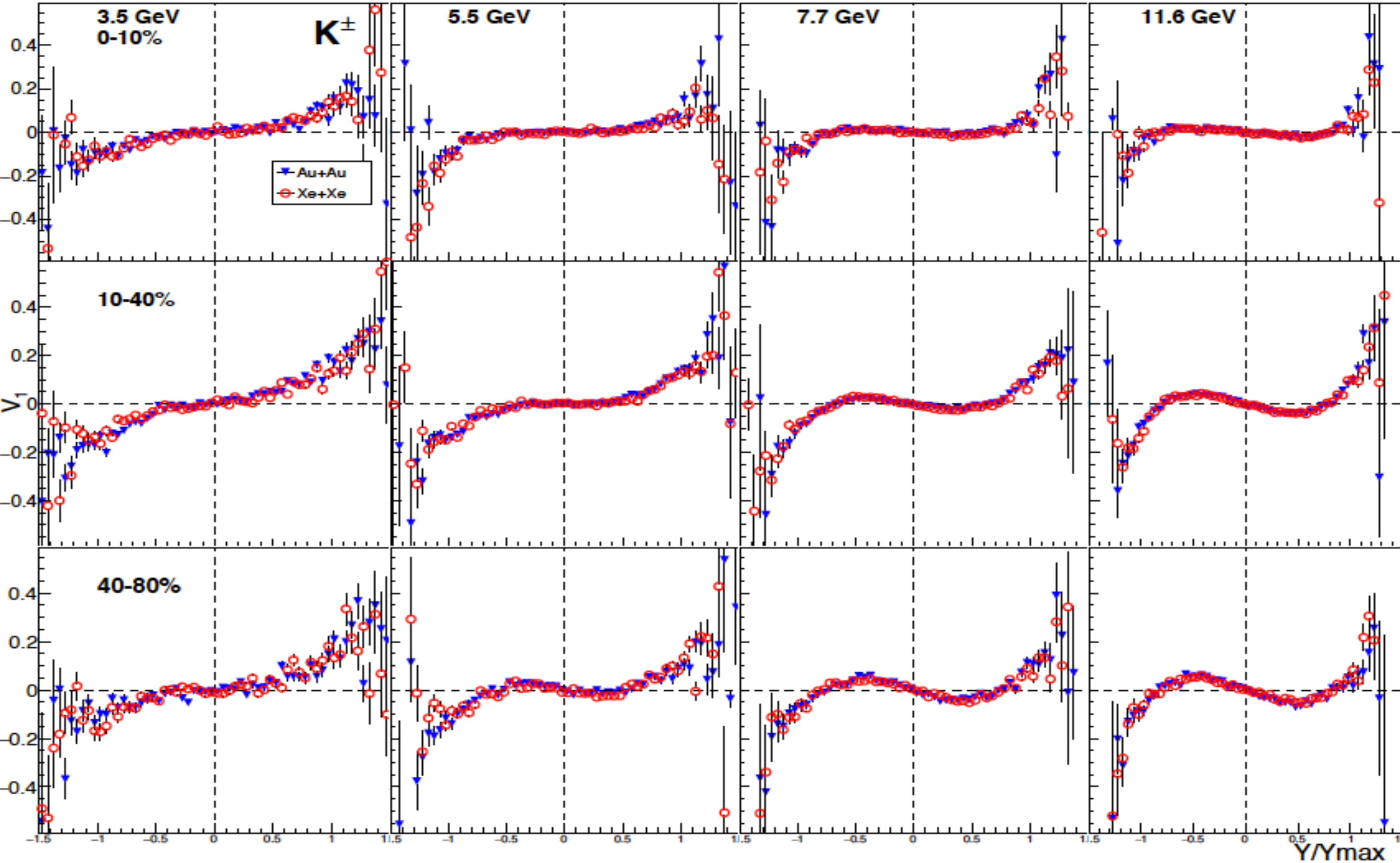
- **Here V_1 of high-P_T pions reveals normal flow already at 11.6 GeV**

V_1 (y,p_T) for pions, UrQMD



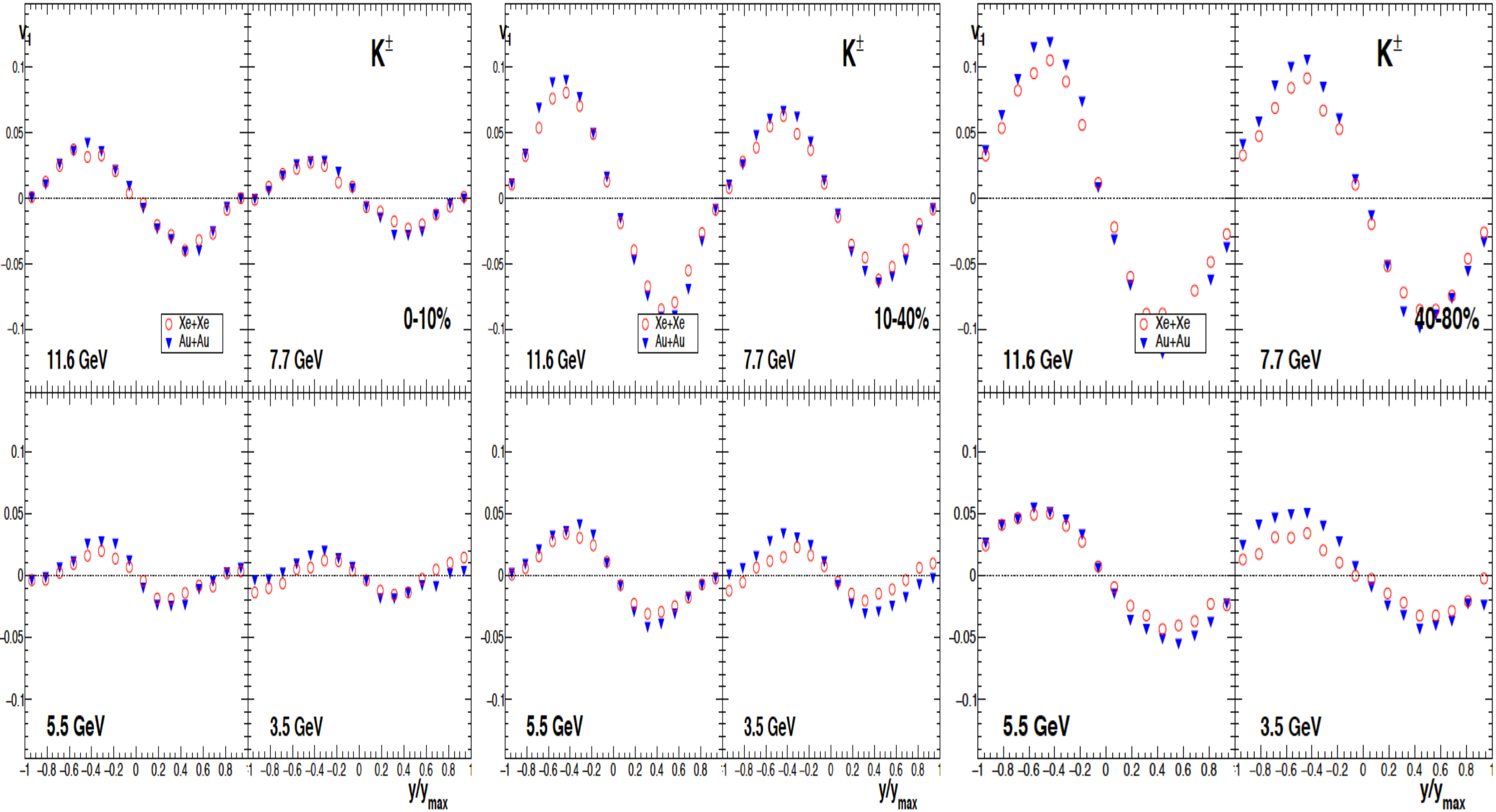
- **Directed flow of high-P_T pions has normal slope only for central collisions at 3.5 GeV**

V_1 (y) for kaons, QGSM



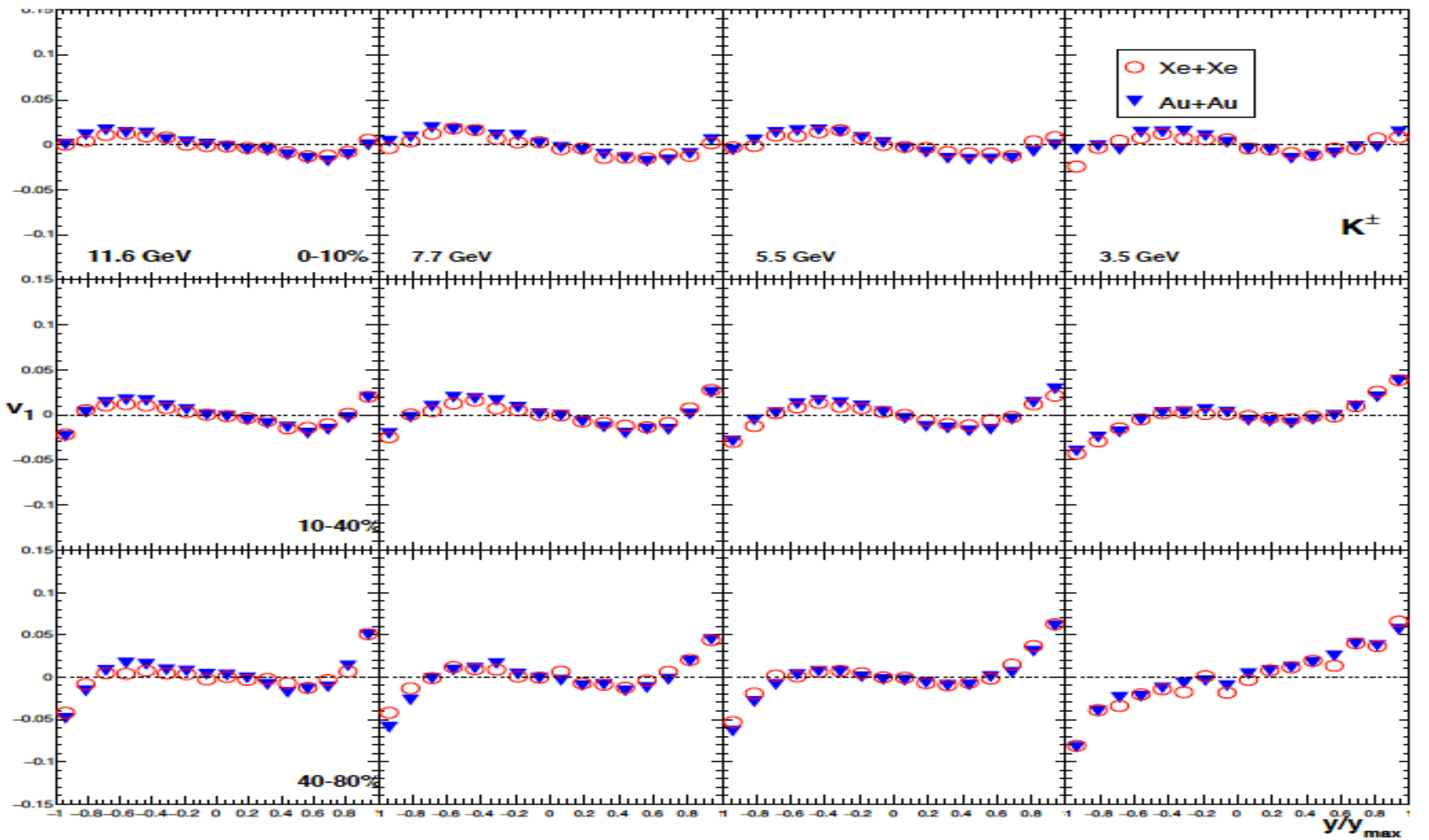
- Kaons have antiflow at higher energies and normal flow − at lower ones
- Stronger effect for more peripheral collisions

V_1 (y) for kaons, DCM



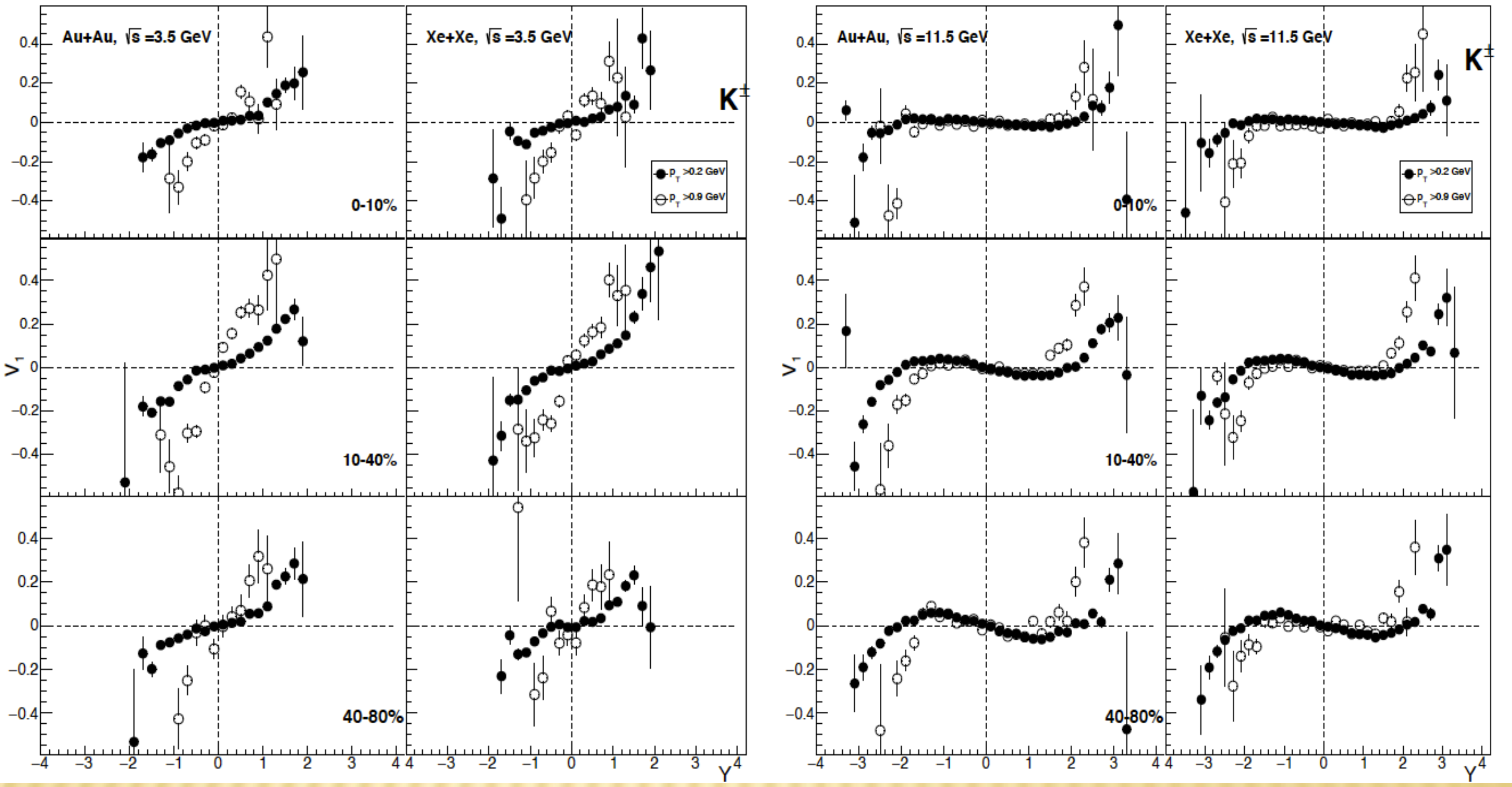
Stable antiflow behavior for all energies and centralities

V_1 (y) for kaons, UrQMD



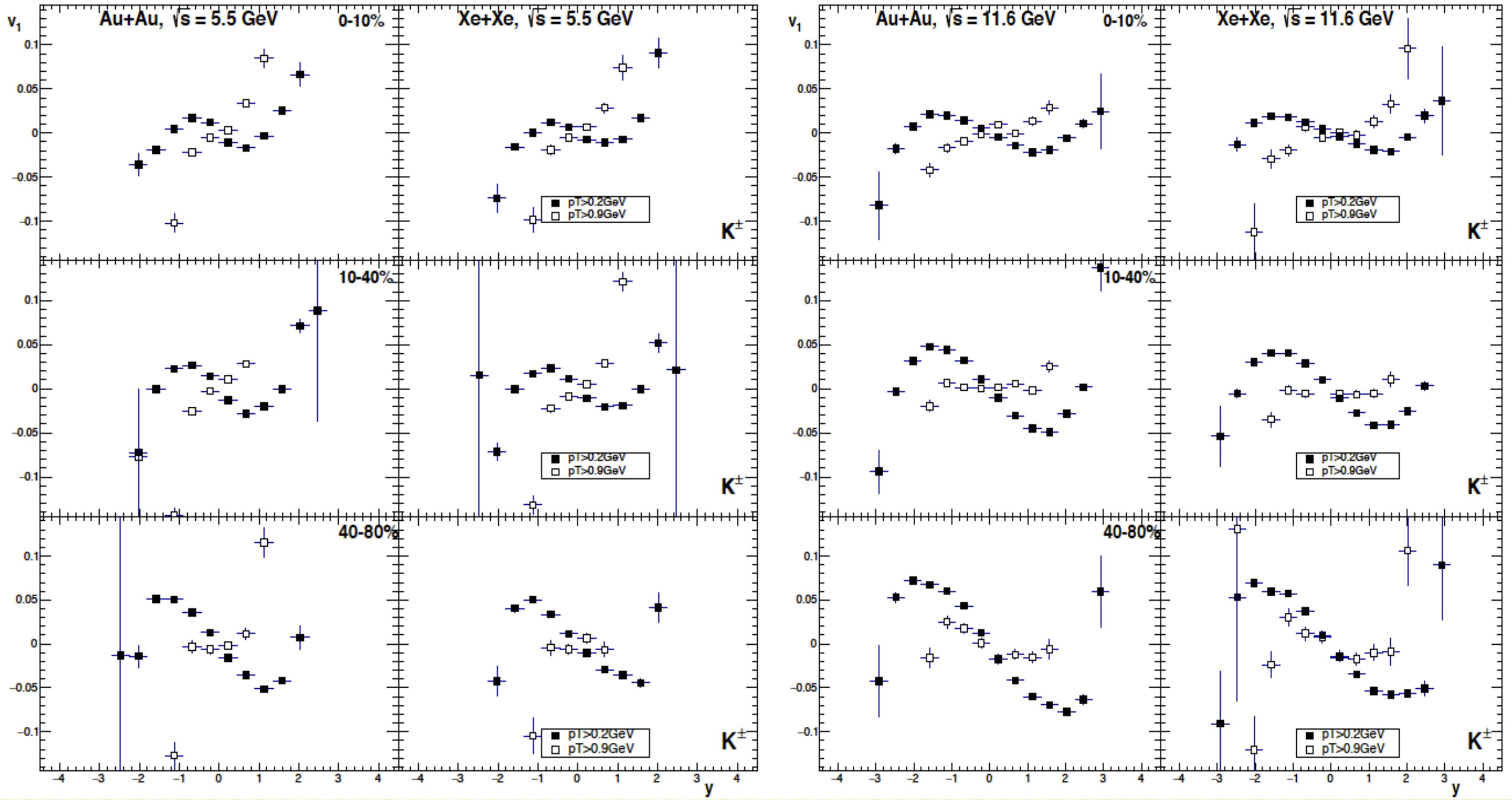
- **Antiflow for all but peripheral collisions at 3.5 GeV ?!**

V_1 (y,p_T) for kaons, QGSM



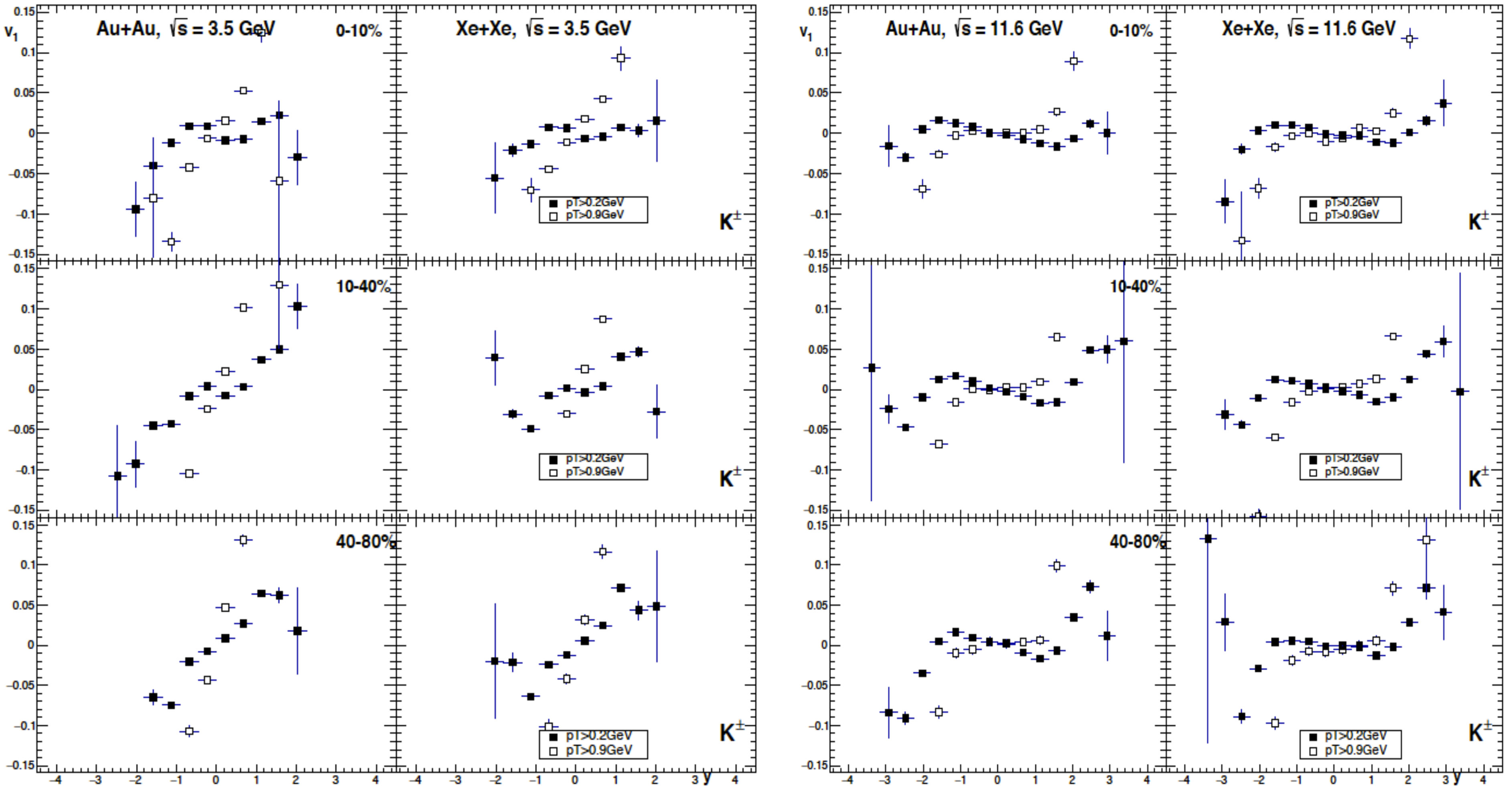
- Transition from antiflow to normal flow – at lower energies and especially for high-P_T kaons

V_1 (y,p_T) for kaons, DCM



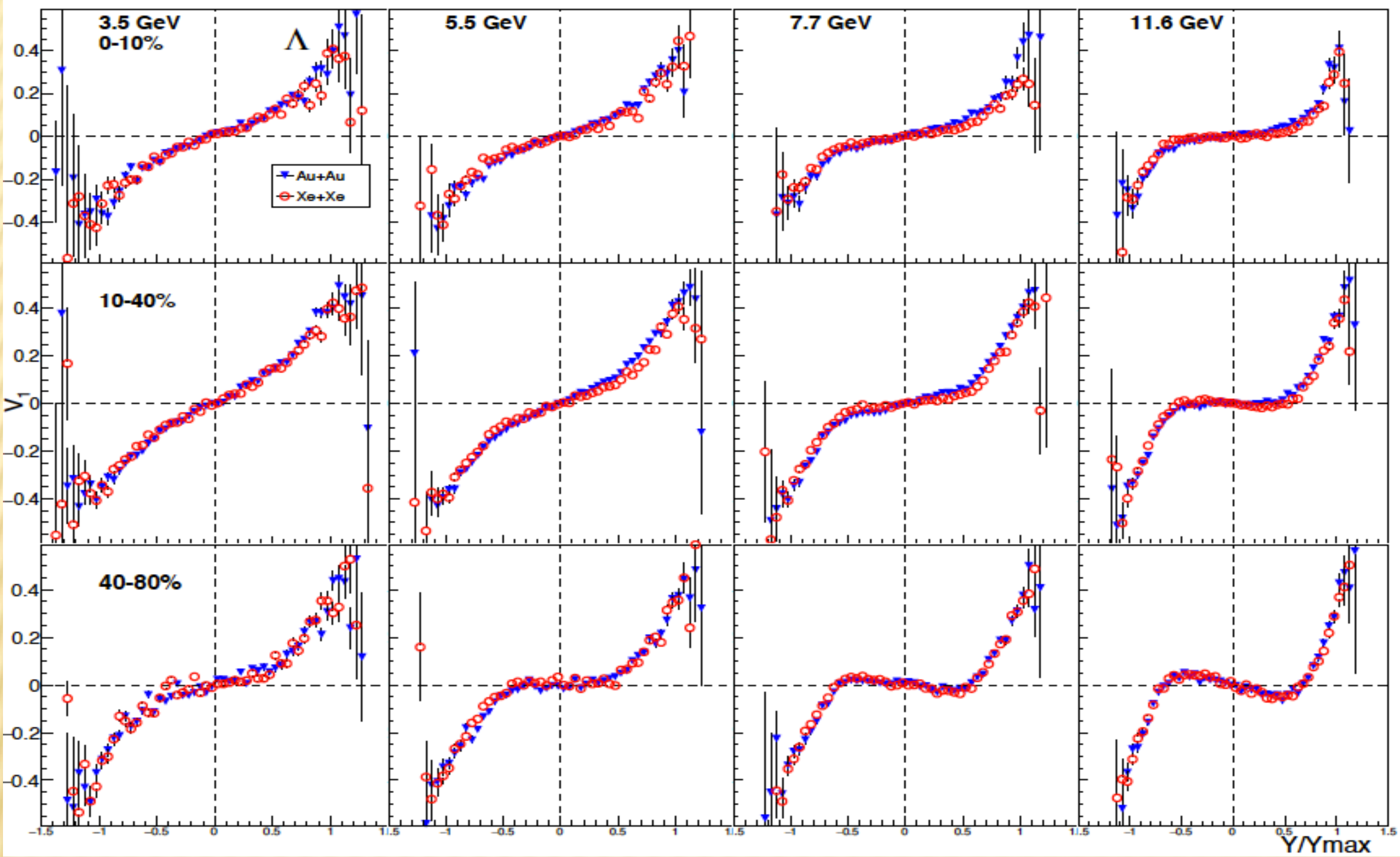
- **High-P_T kaons develop normal flow**

V_1 (y,p_T) for kaons, UrQMD



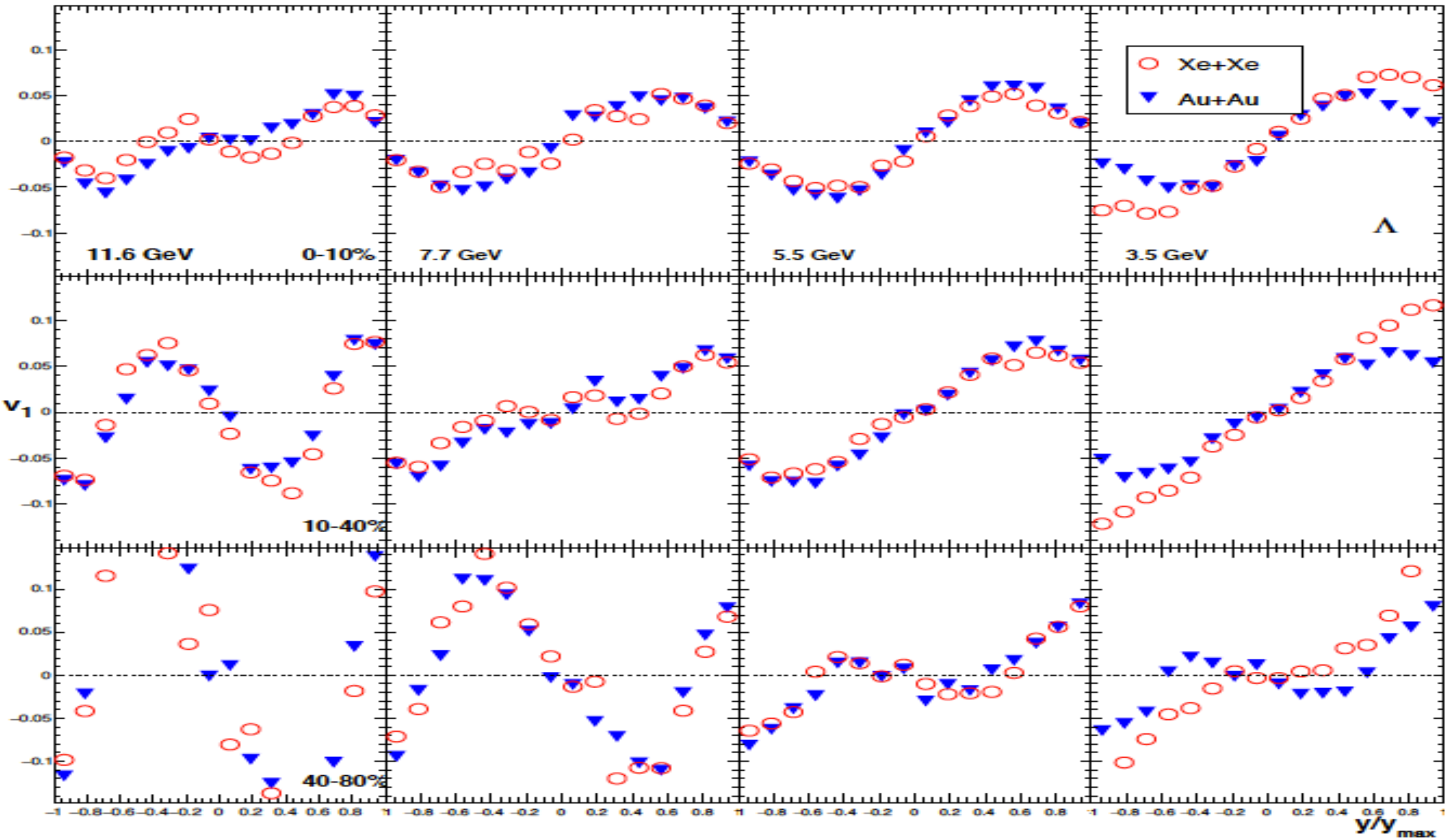
- Normal flow for kaons at 3.5 GeV
- At 11.6 GeV – significant softening of V_1 for high-P_T kaons

V_1 (y) for Lambdas, QGSM



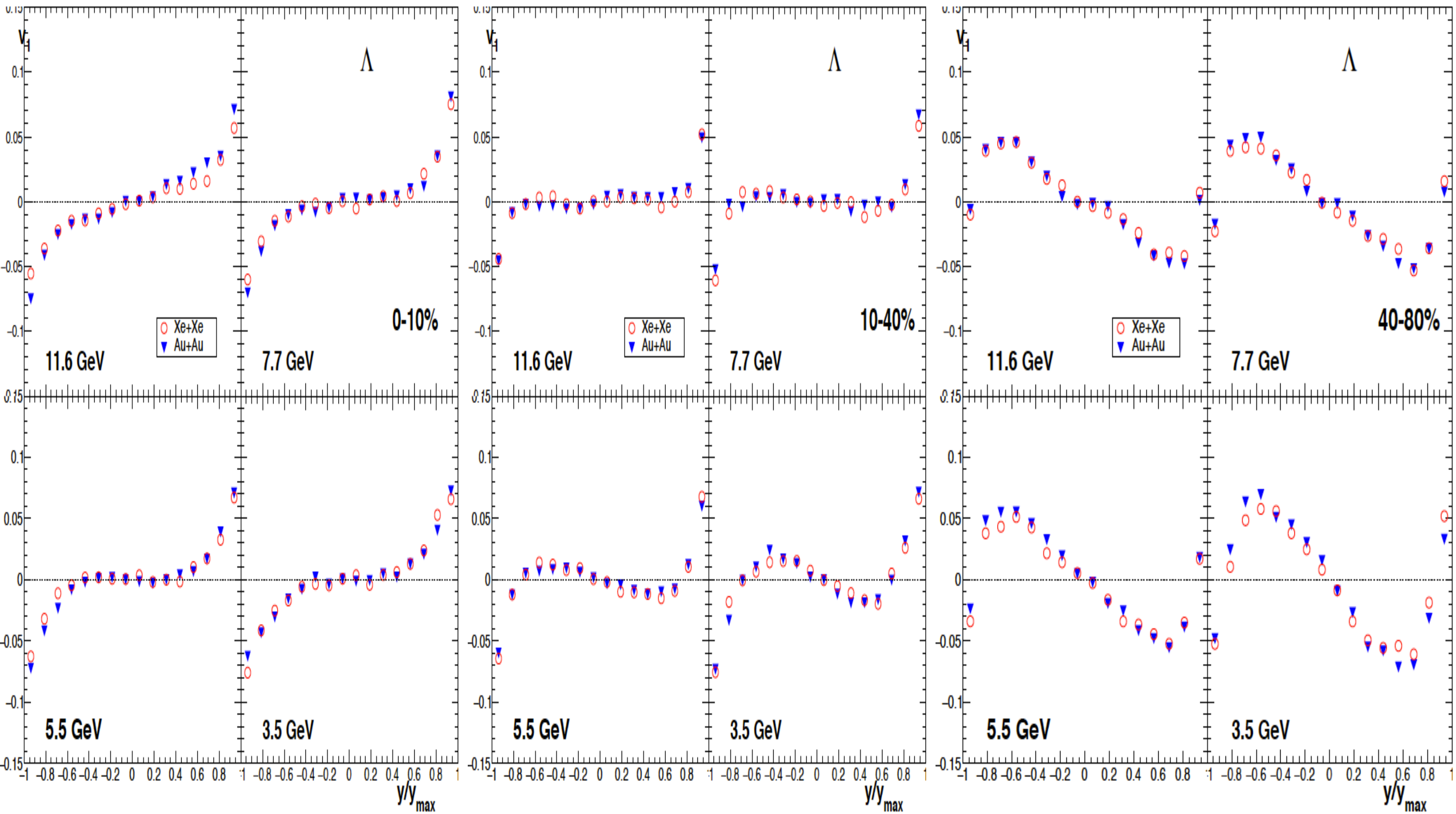
- **Behavior of Lambda´s V_1 is similar to that of protons**

V_1 (y) for Lambdas, DCM



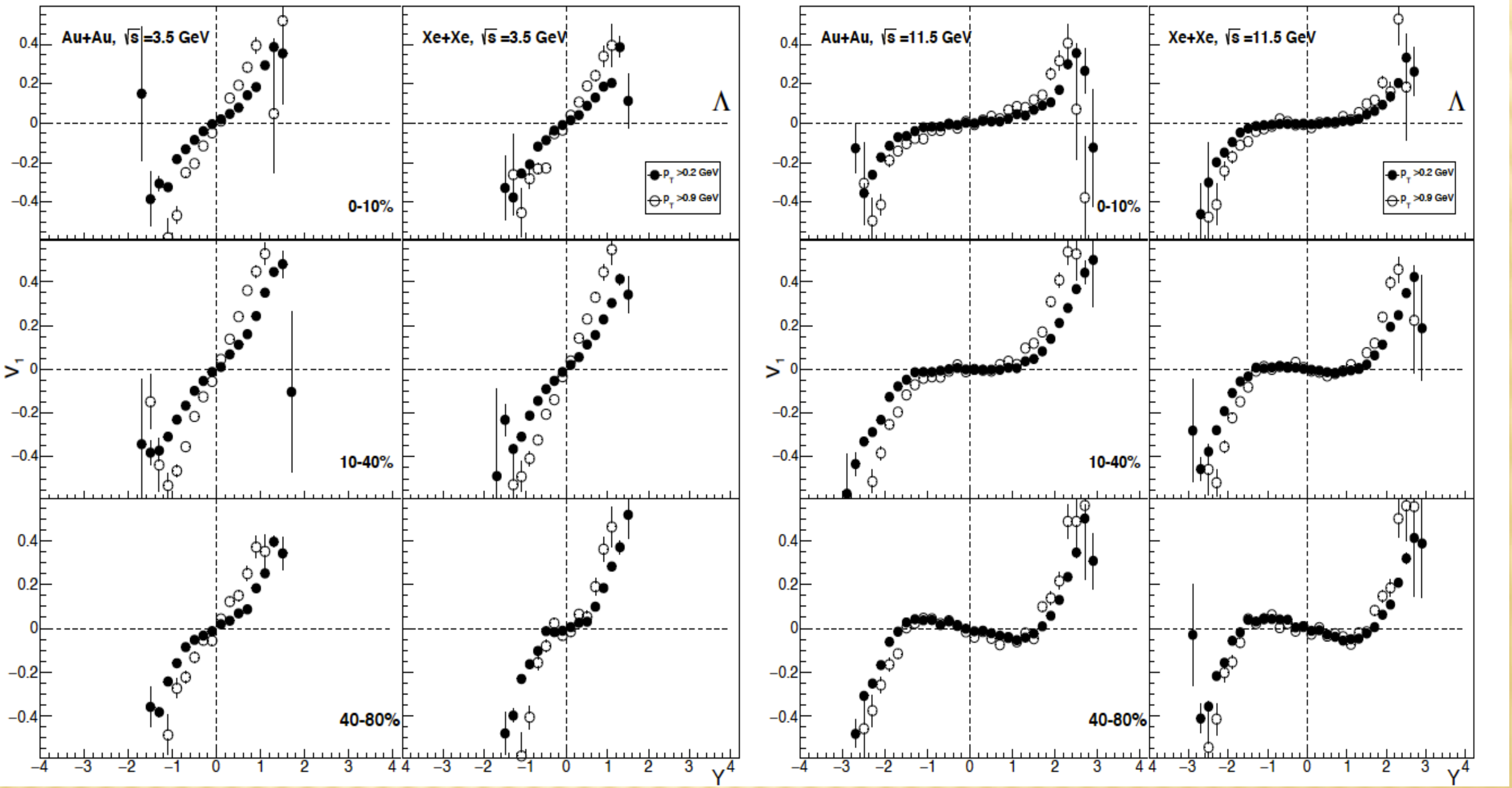
- **Transition from antiflow to normal flow with decreasing energy**

V_1 (y) for Lambdas, UrQMD



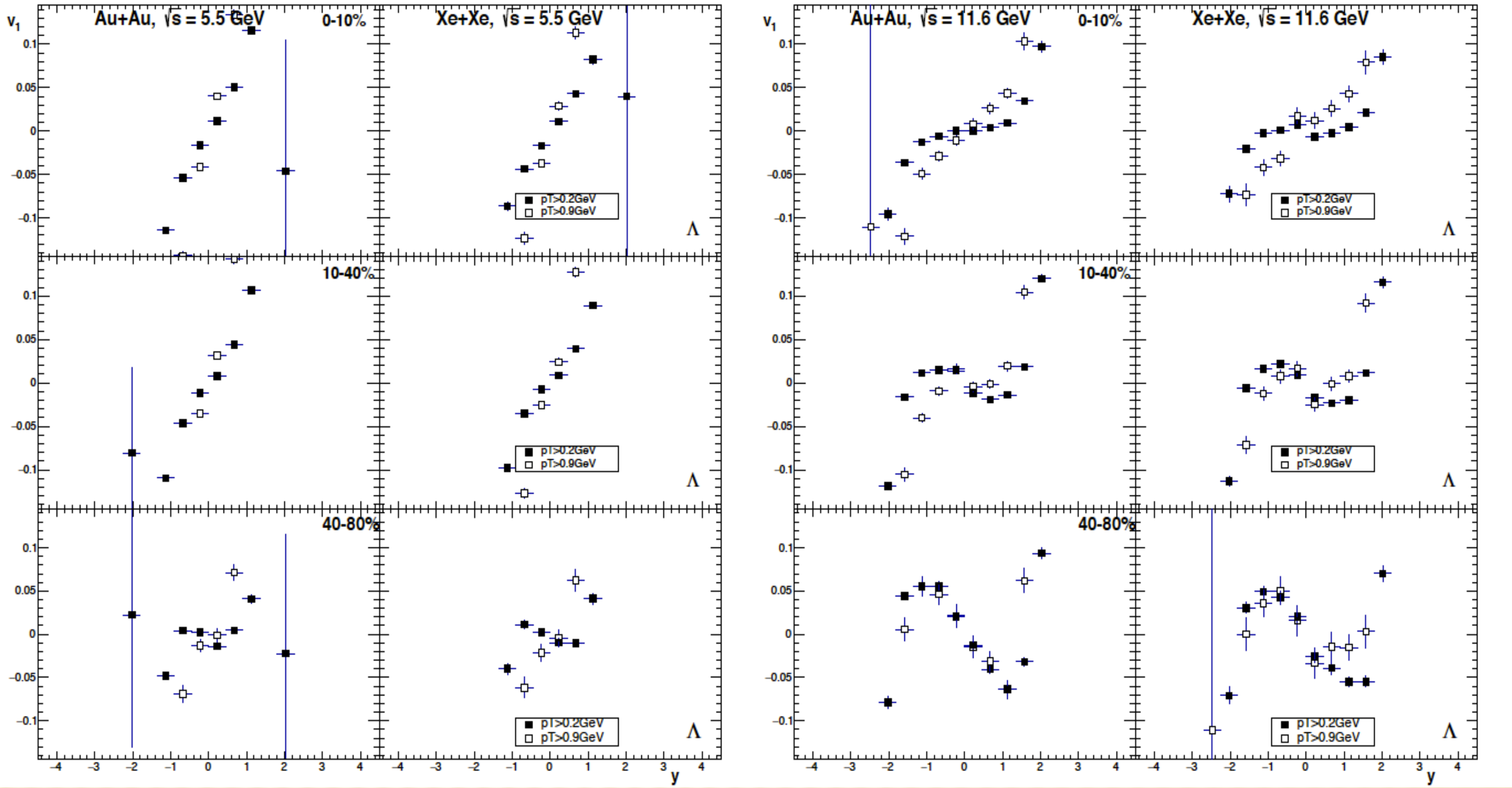
- **Normal flow in central collisions at higher energies and (weak) antiflow at low energies**

V_1 (y,p_T) for Lambdas, QGSM



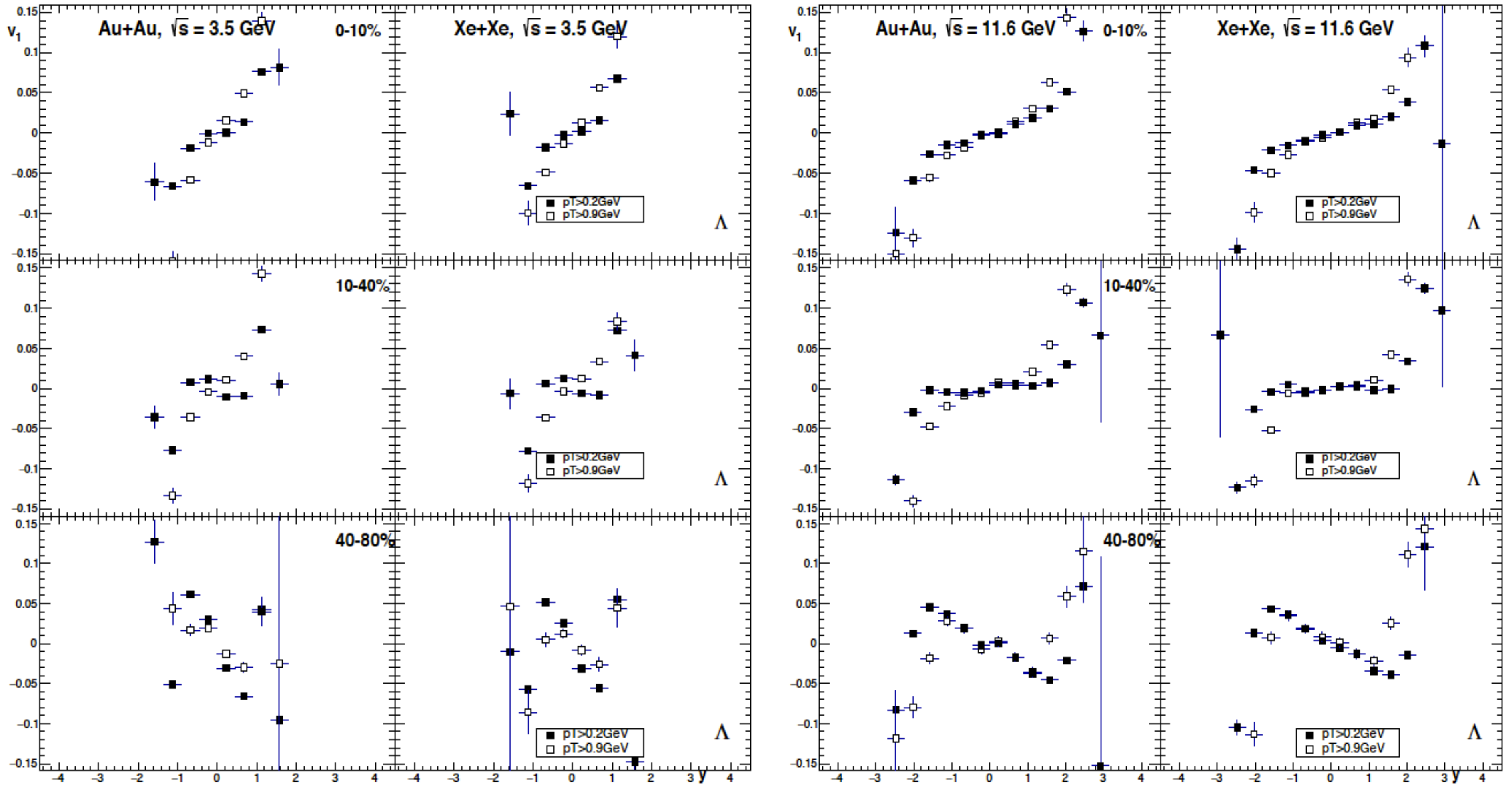
- Small difference between V_1 of low-P_T and high-P_T Lambdas
- Very similar to V_1 of protons

V_1 (y,p_T) for Lambdas, DCM



- Similar to V_1 of protons in DCM

V_1 (y,p_T) for Lambdas, UrQMD

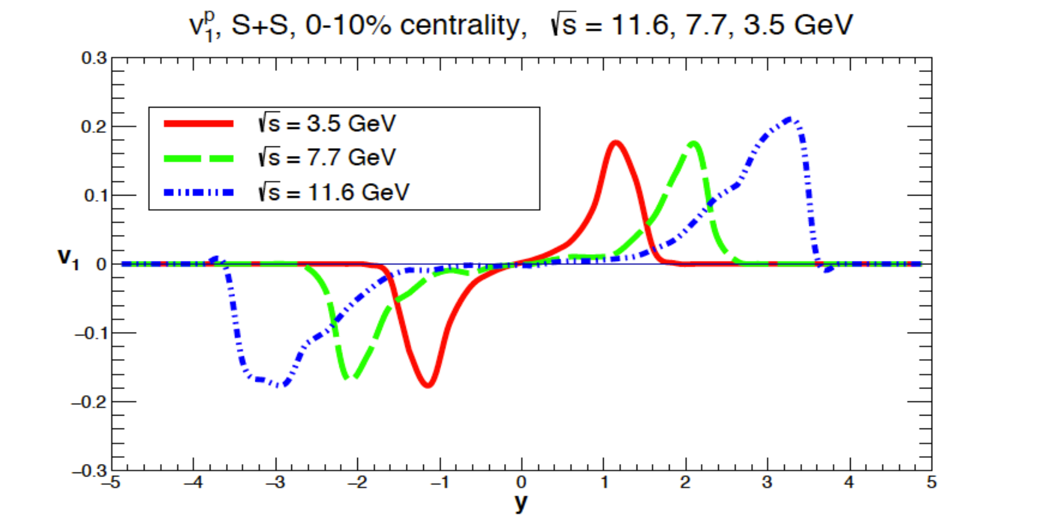


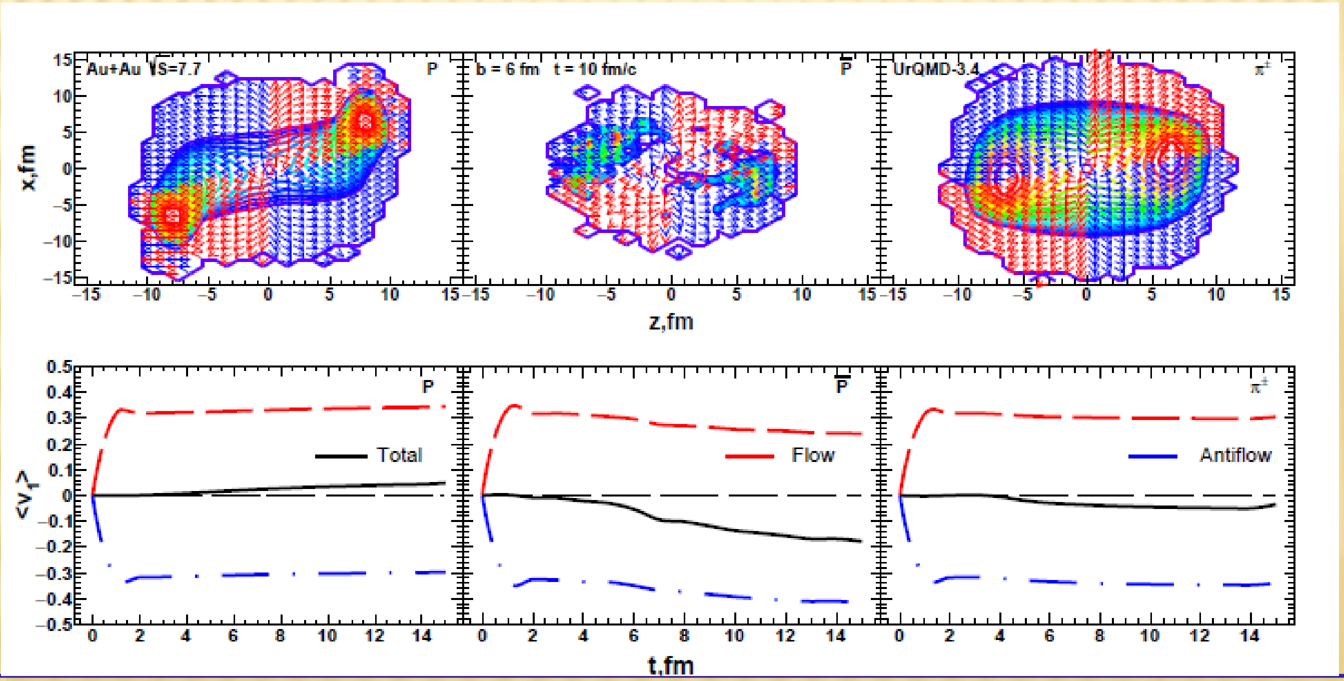
- **High-P_T Lambdas develop normal directed flow**

Directed flow in HI collisions at FAIR/NICA energies

Origin of changing of proton directed flow from antiflow to normal flow with decrease of CM energy in microscopic transport models

Universe 5, 69 (2019)

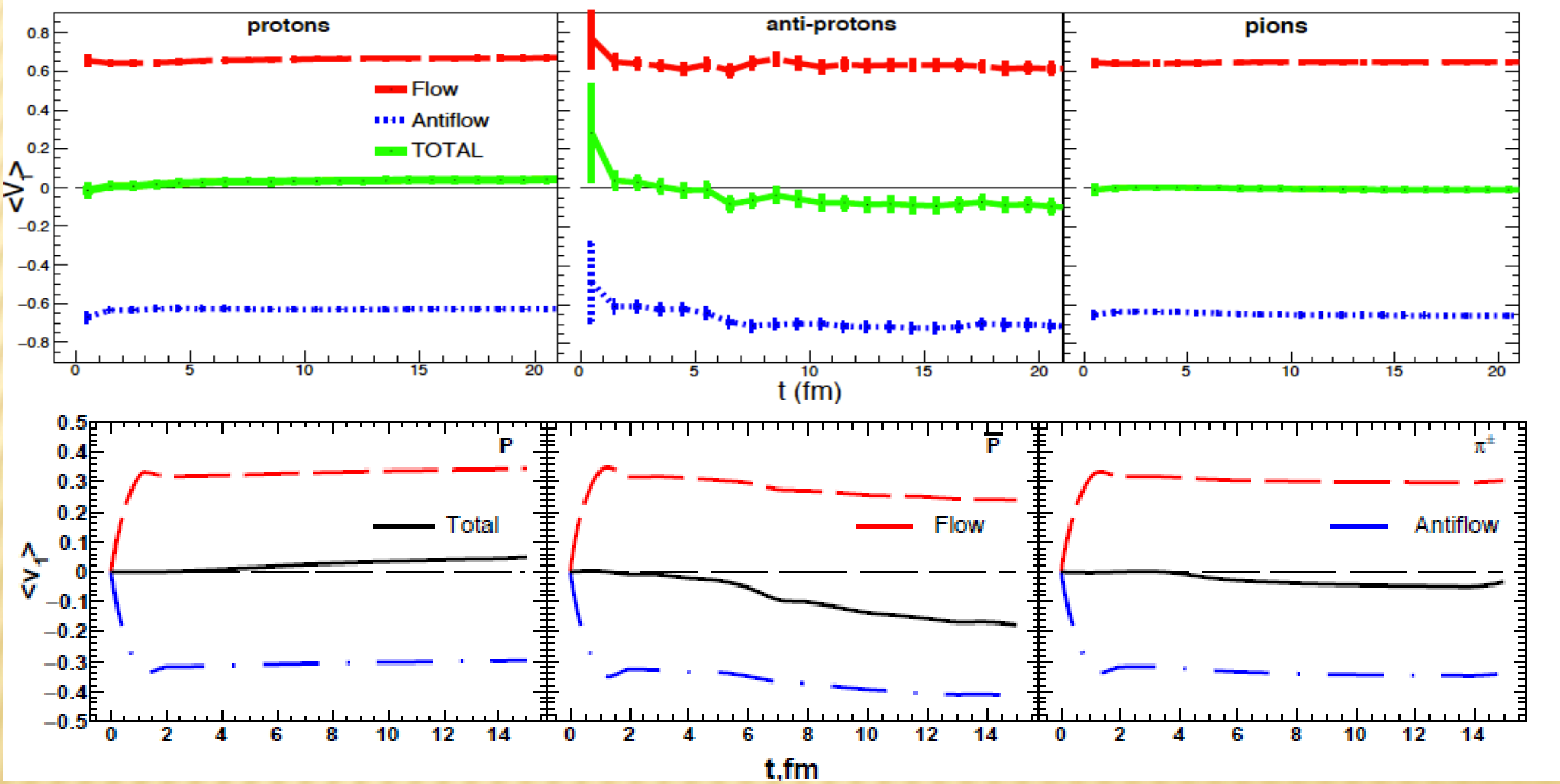




- **Directed flow = Normal flow – Antiflow**

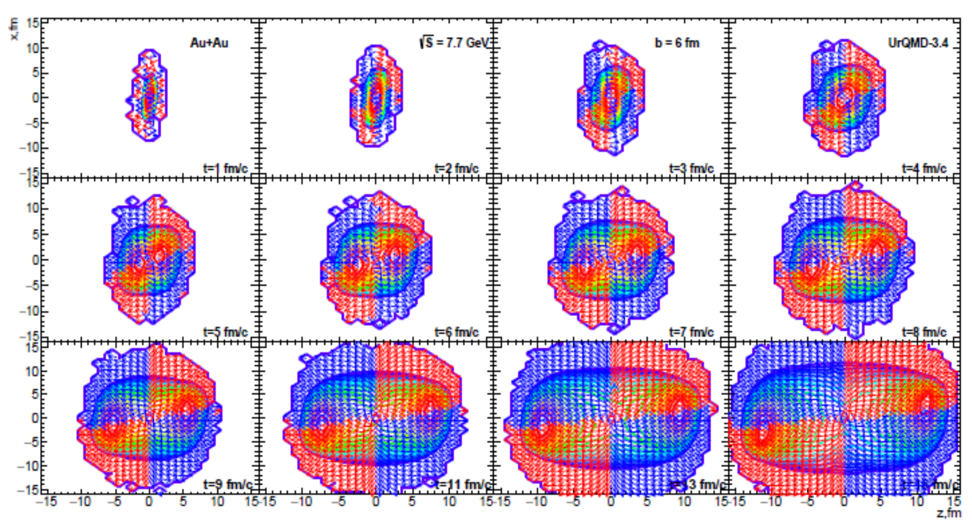
Directed flow in HI collisions at FAIR/NICA energies

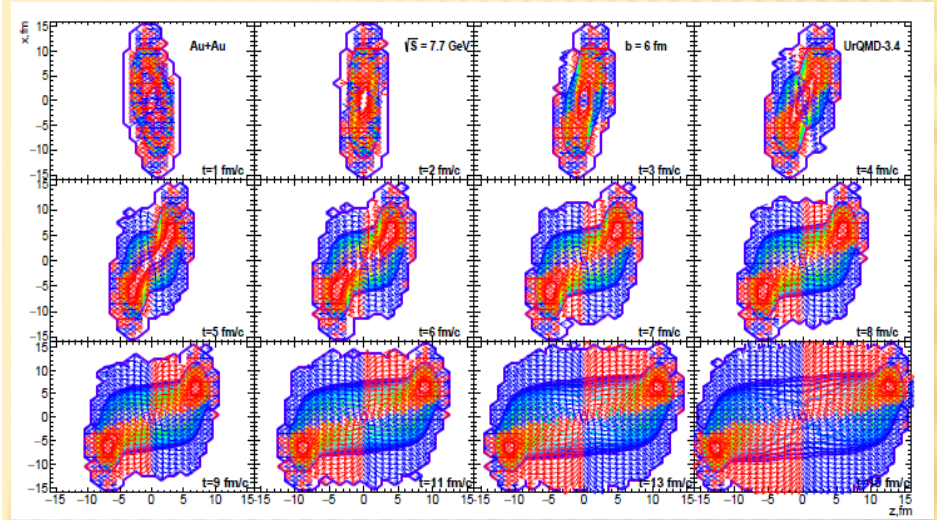
Comparison between UrQMD and QGSM

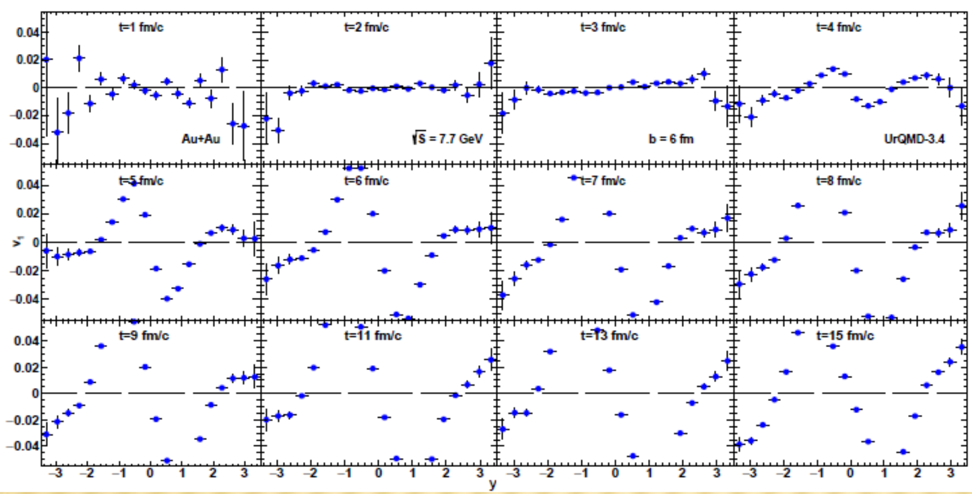


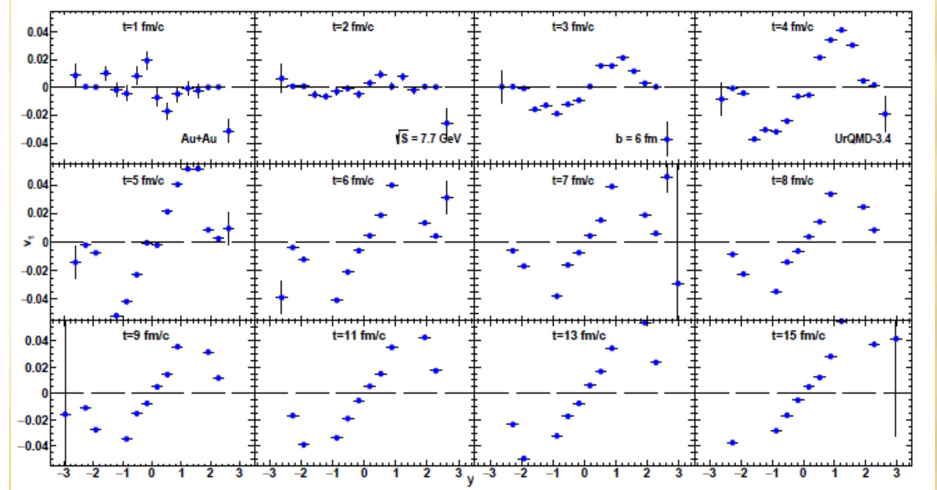
- Directed flow = Normal flow – Antiflow in all transport models

Time development of directed flow



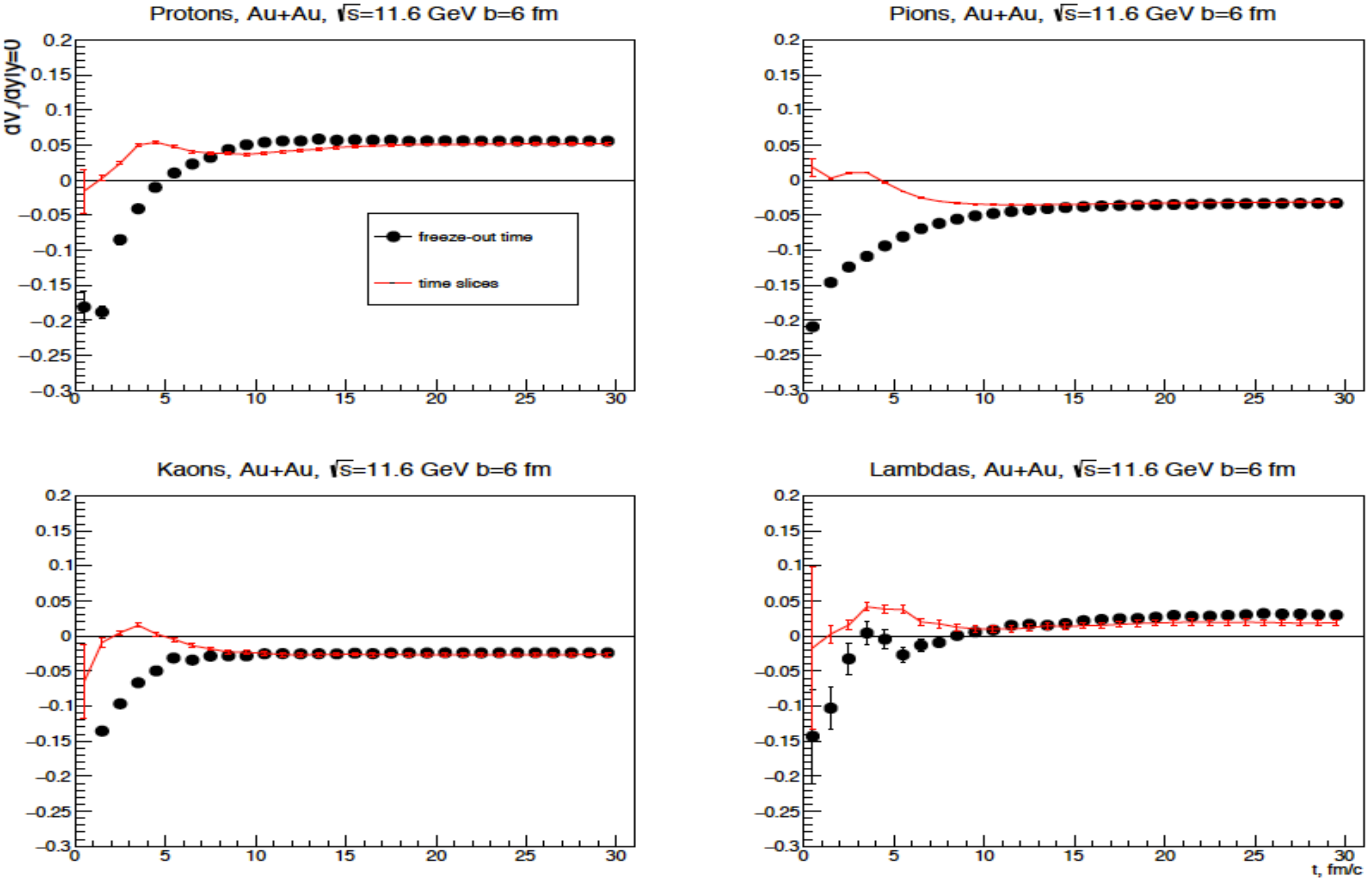






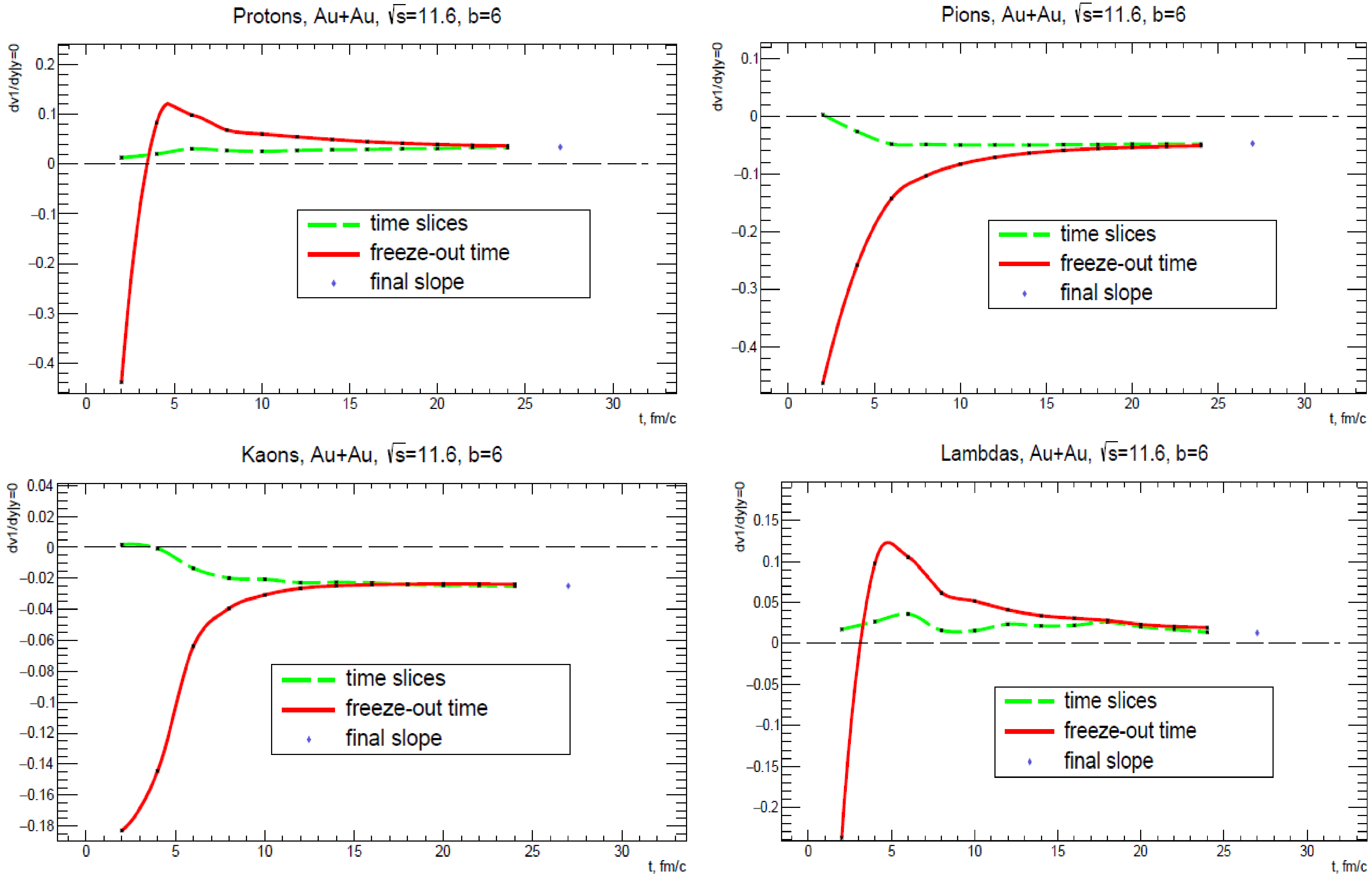
- **It appears that V_1 of both pions and protons at midrapidity is formed not earlier than 5 – 6 fm/c**

Time development of directed flow, QGSM



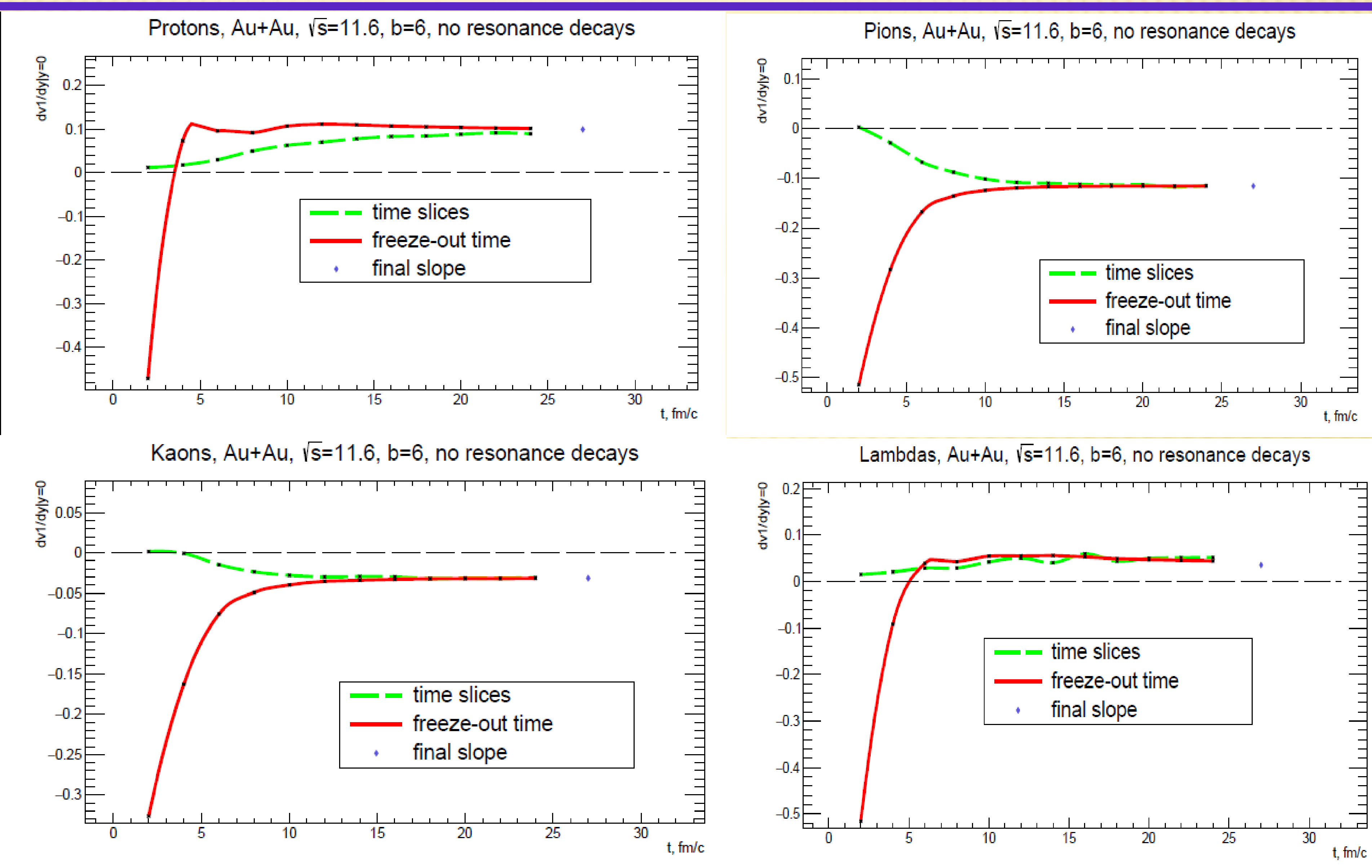
- **V_1 of mesons and baryons at midrapidity is formed at approximately 6 – 10 fm/c**

Time development of directed flow, UrQMD



- V_1 of mesons and baryons at midrapidity is formed at approximately 6 – 10 fm/c

Influence of resonances on the development of V_1



- **Difference is seen only for Lambdas and for protons (not so distinct) at t ≈ 5 fm/c**

Directed flow of hadrons in 3-fluid hydro THESEUS

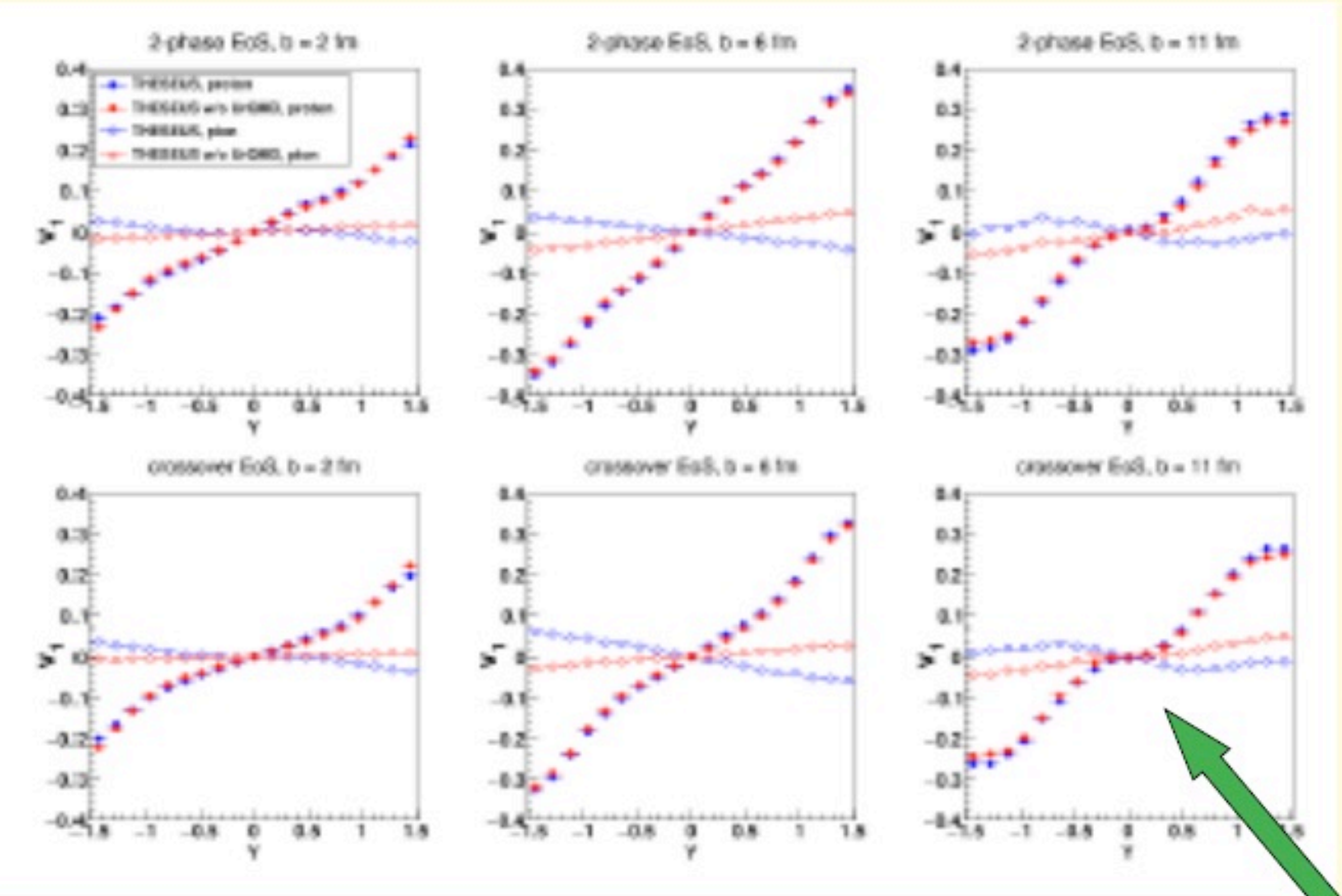
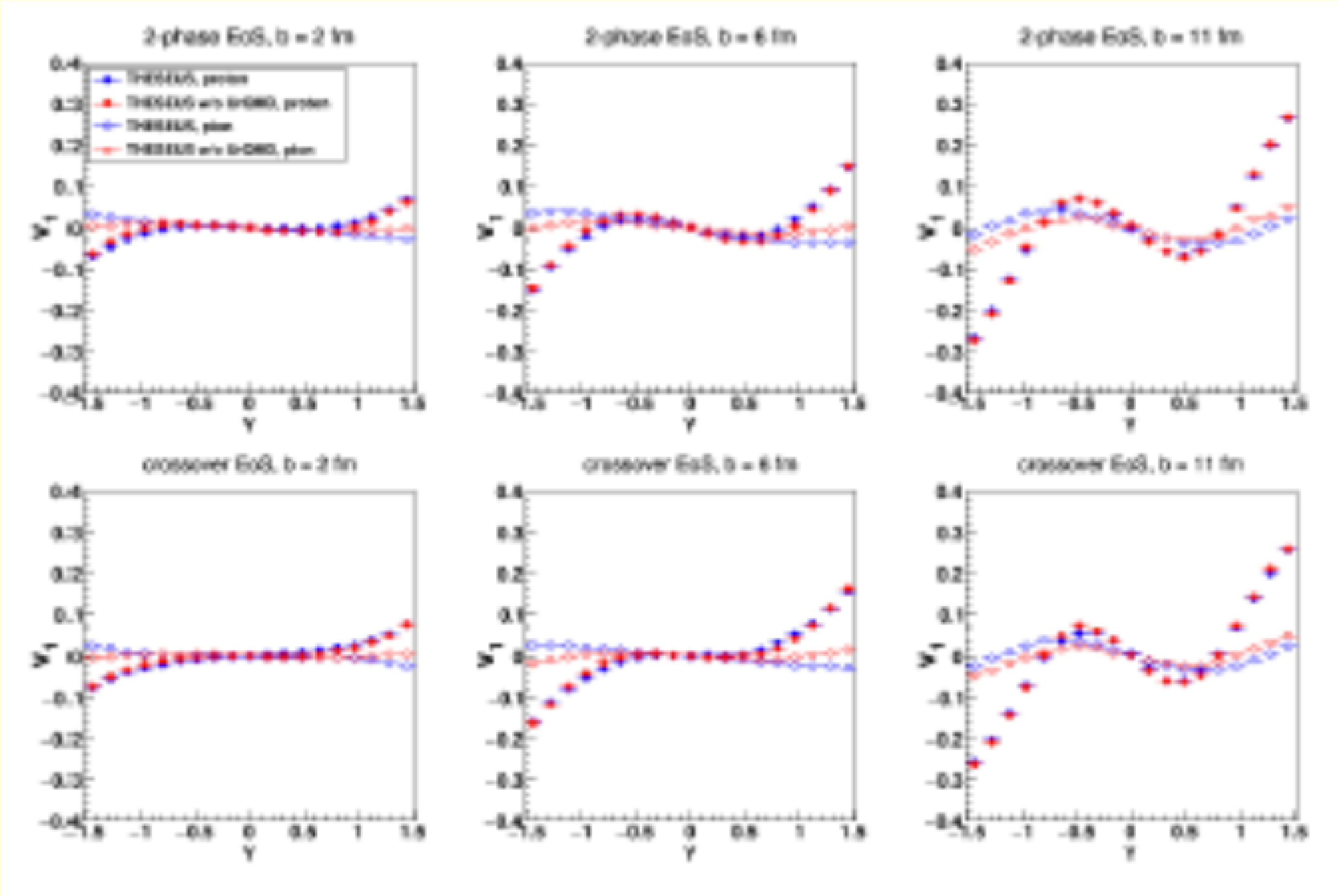


Figure 5. Two upper rows: Directed flow (v_1) of protons (full symbols) and pions (open symbols) for central (b = 2 fm), semicentral (b = 6 fm) and peripheral (b = 11 fm) Au+Au collisions at E_{lab} = 8 A GeV. The upper row is for the 2-phase EoS while the lower row shows results for the crossover EoS. In each panel we show the direct comparison of THESEUS with (blue symbols) and without (red symbols) UrQMD afterburner. Remarkable is the effect of turning pion flow to antiflow due to hadronic rescattering in the dense baryonic medium.

P. Batyuk, … Yu. Ivanov et al., 1711. 07959

Directed flow of hadrons in 3-fluid hydro THESEUS

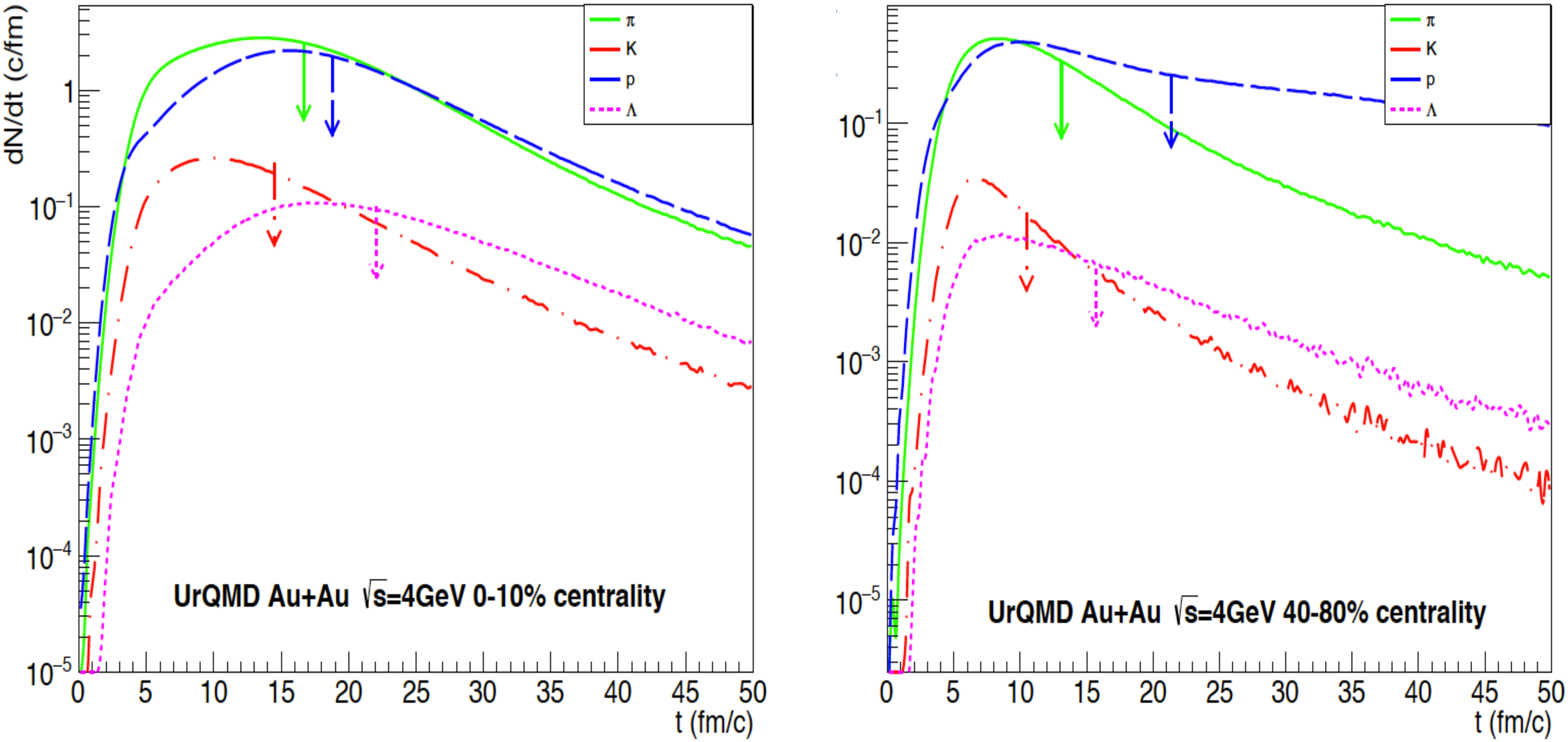


igure 6. Same as in Fig. 5
ut for E_{lab} = 30 A GeV.

P. Batyuk, … Yu. Ivanov et al., 1711. 07959

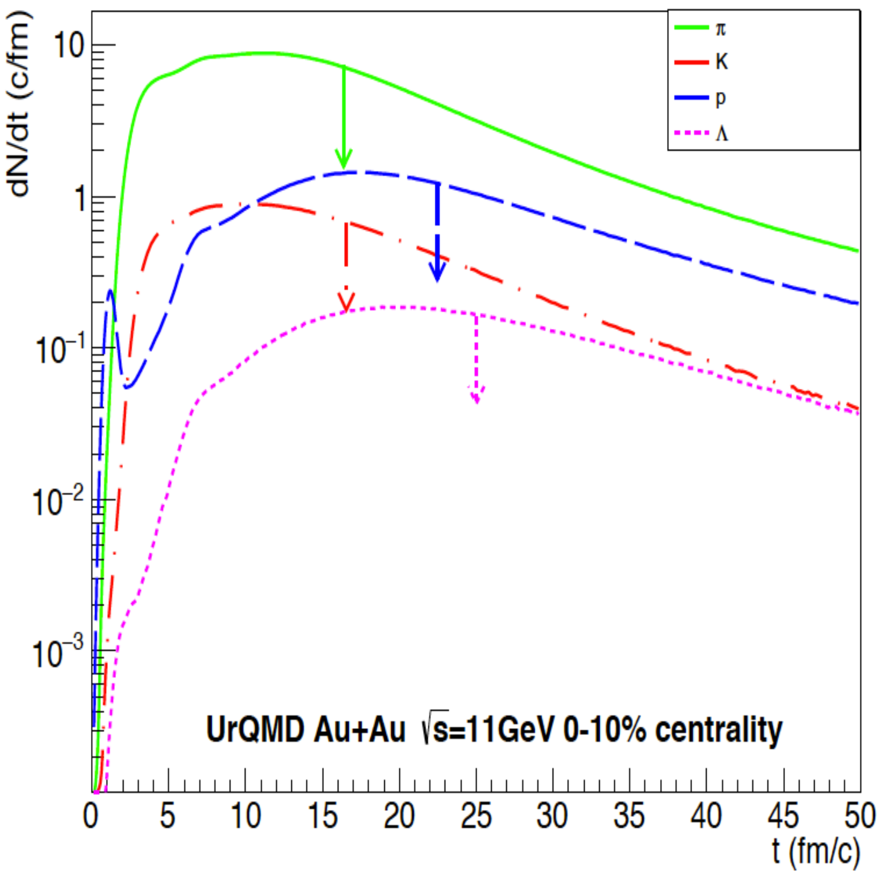
Directed flow and freeze-out

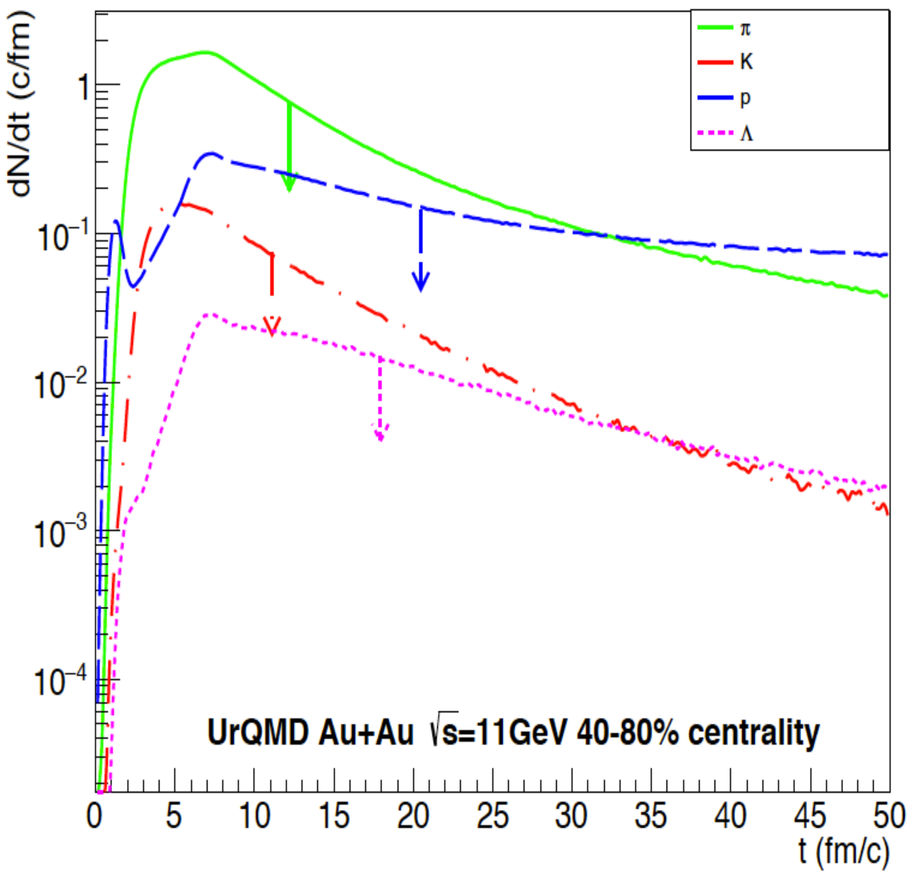
Sequential freeze-out of hadrons at NICA energies



- There is no sharp freeze-out for different hadrons

Sequential freeze-out of hadrons at NICA energies

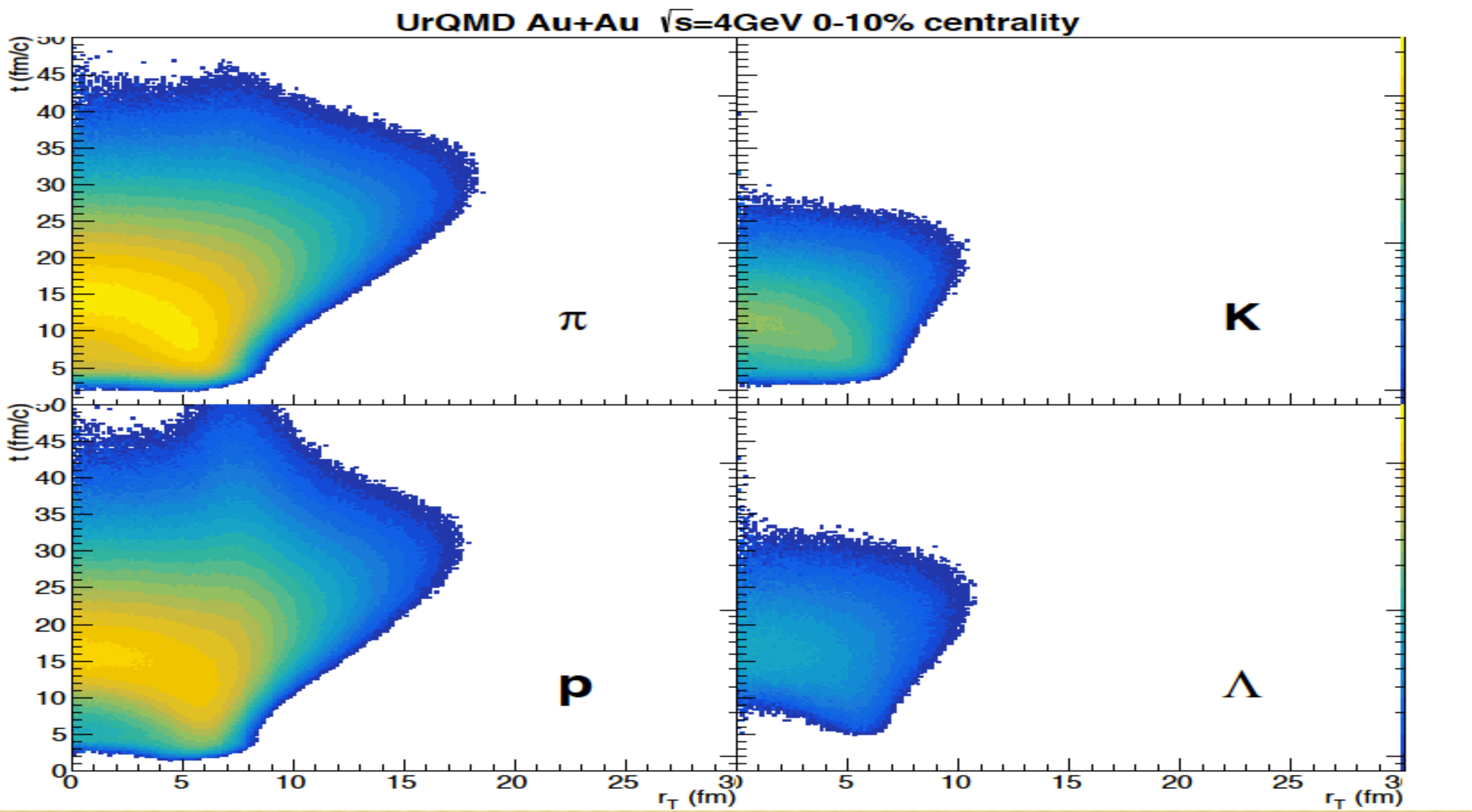




- **The order of freeze-out is as follows: mesons (kaons and pions), nucleons and lambdas**

Freeze-out of hadrons at NICA energies

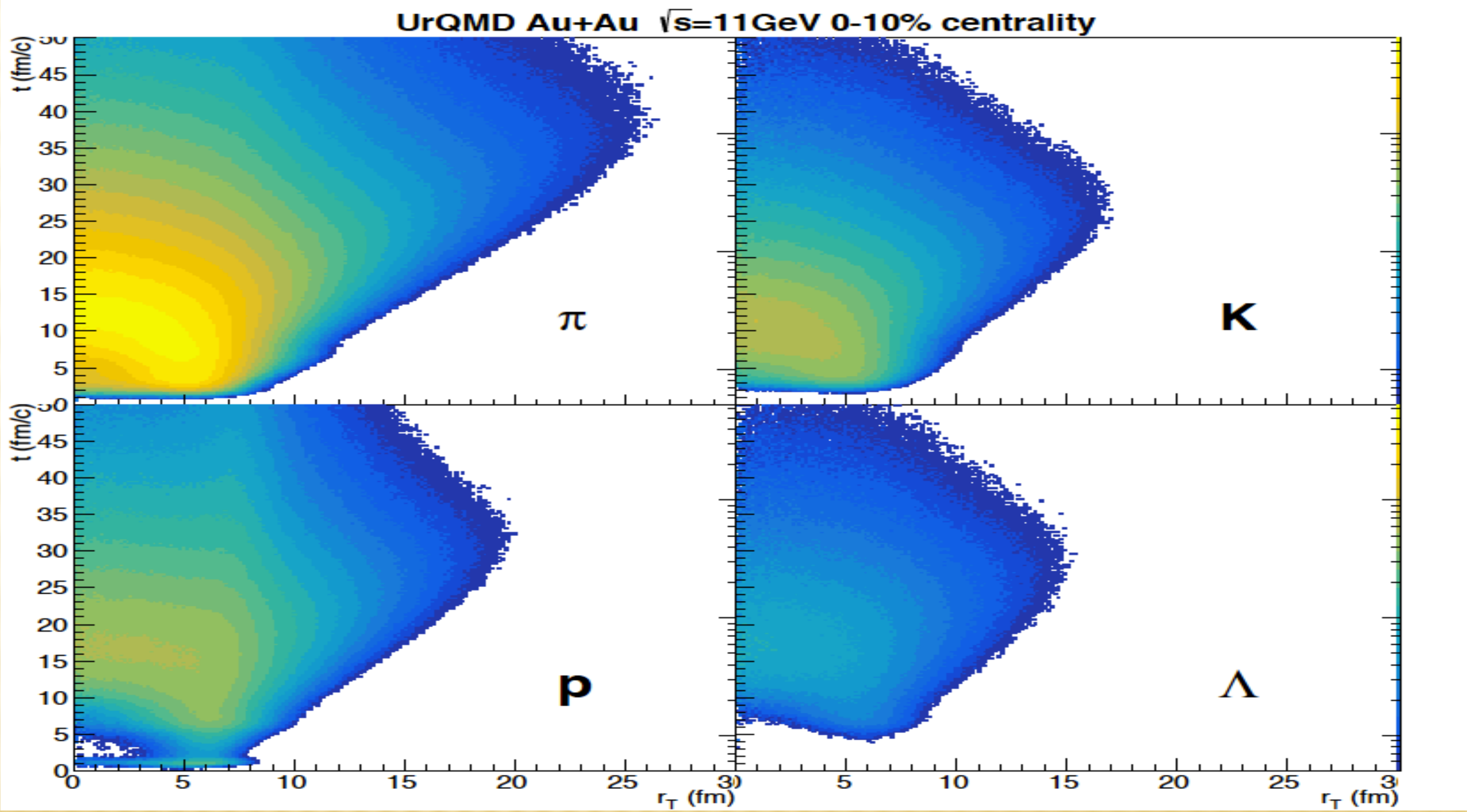
Au+Au @ 4 GeV ; 0 − 10%



Transverse radius distribution $d^2N\ dR_T\ dt$

Freeze-out of hadrons at NICA energies

Au+Au @ 11 GeV ; 0 − 10%



- Baryons with small R_T are not emitted earlier than 5 fm/c

CONCLUSIONS

◆ Directed flow = Normal Flow – Antiflow

Normal Flow ≥ Antiflow (except of the midrapidity range)

◆ The softening of the flow can be misinterpreted as the softening of EOS due to formation of the QGP, but:

QGP → the effect is stronger for semi-central collisions

Cascade → the effect is stronger for semi-peripheral and peripheral ones

◆ At energies about few GeV: normal directed flow of protons at midrapidity in central collisions and antiflow in peripheral ones. Mesons – antiflow for all centralities.

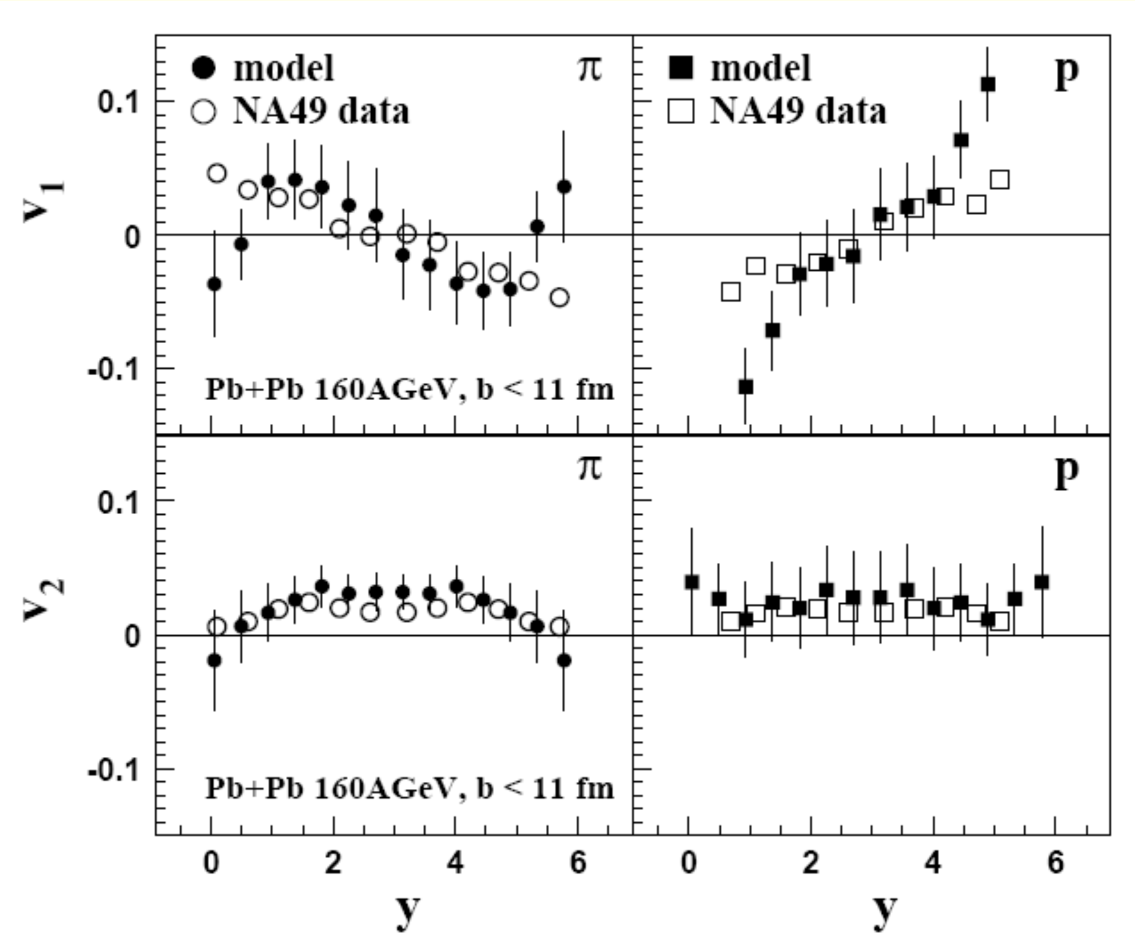
◆ The directed flow of high-P_T is elongated in normal direction

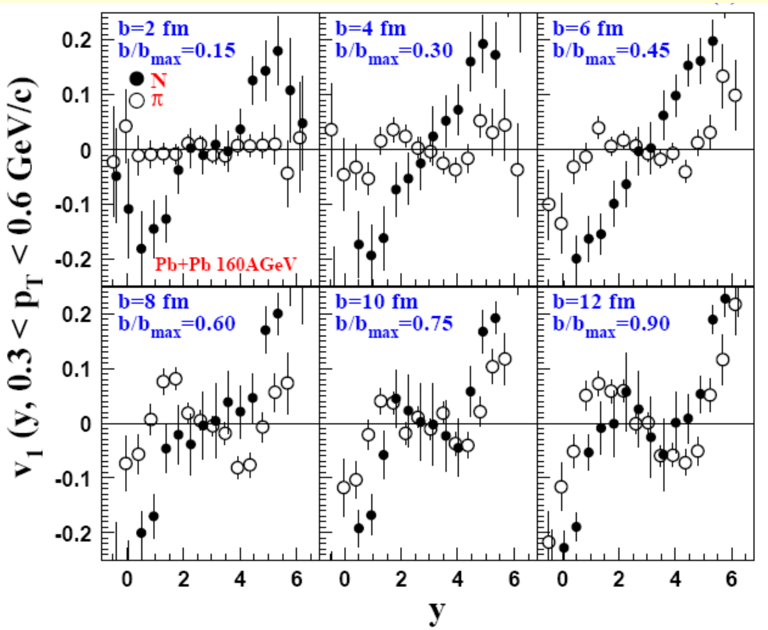
◆ Development of directed flow of hadrons at midrapidity in transport models takes about 6-8 fm/c (or longer)

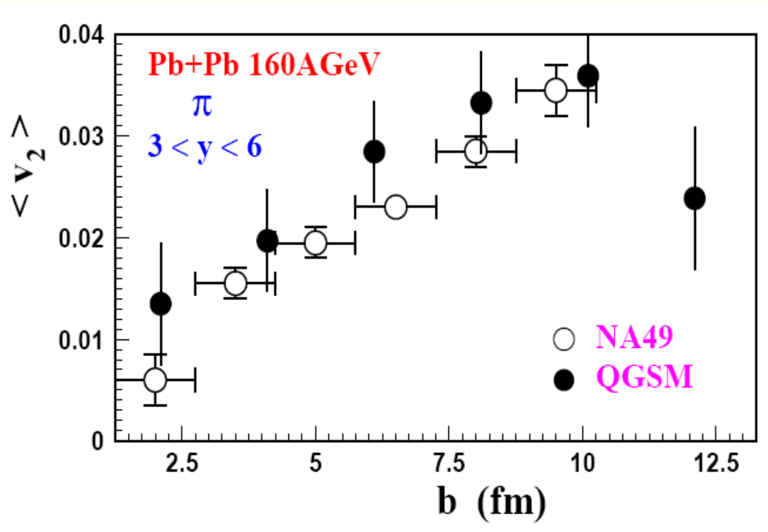
◆ Three transport models give different predictions of magnitude and (sometimes) elongation of V_1 of hadrons at lower energies Exp. data are needed for tuning of the models

Back-up Slides

Comparison with QGSM calculations







E. Zabrodin et al. , PRC 63 (2003) 034902;
L. Bravina et al., PRC 61 (2000) 064802