Directed flow and freeze-out in relativistic heavy-ion collisions at NICA and FAIR energies

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in collaboration with

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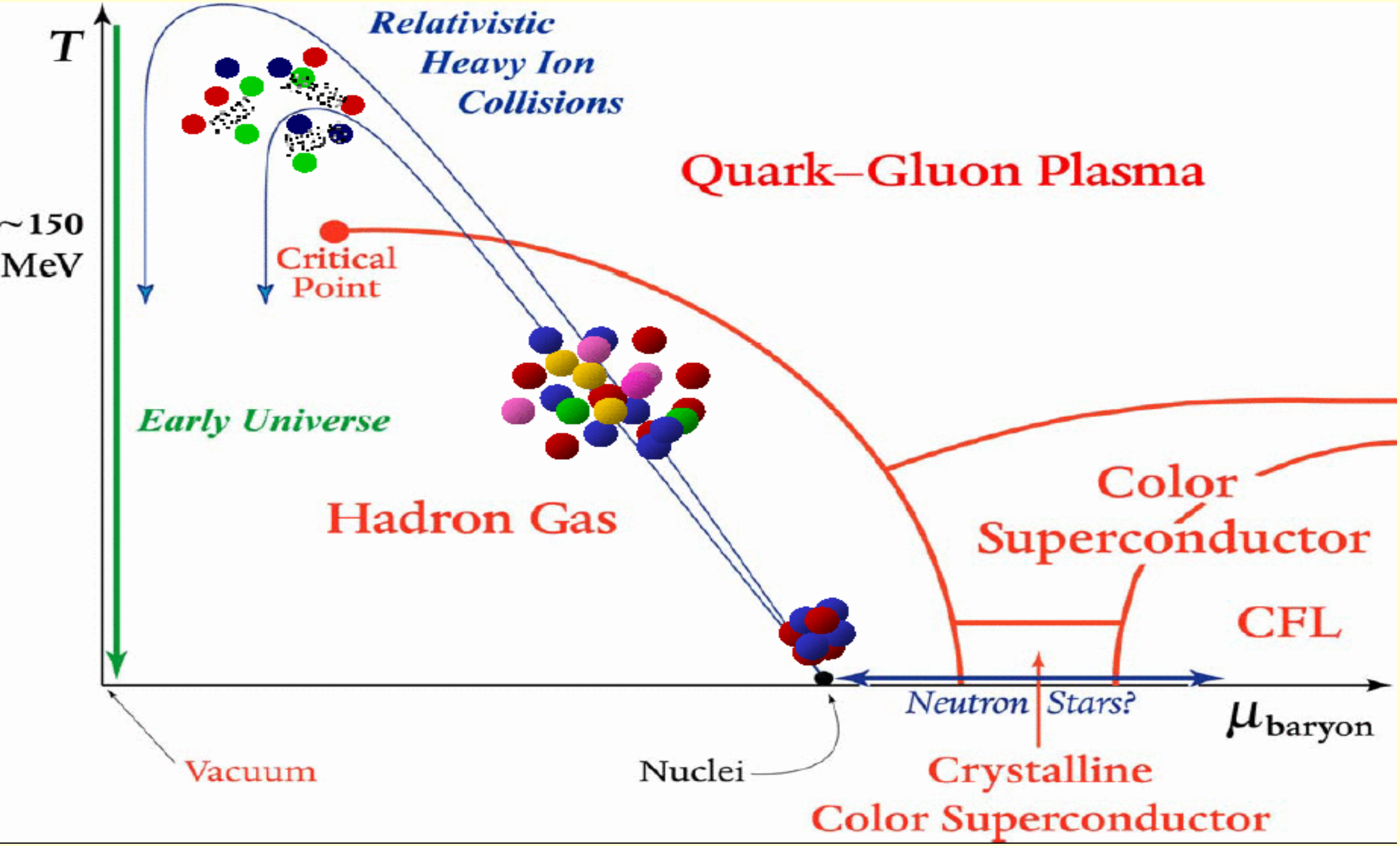
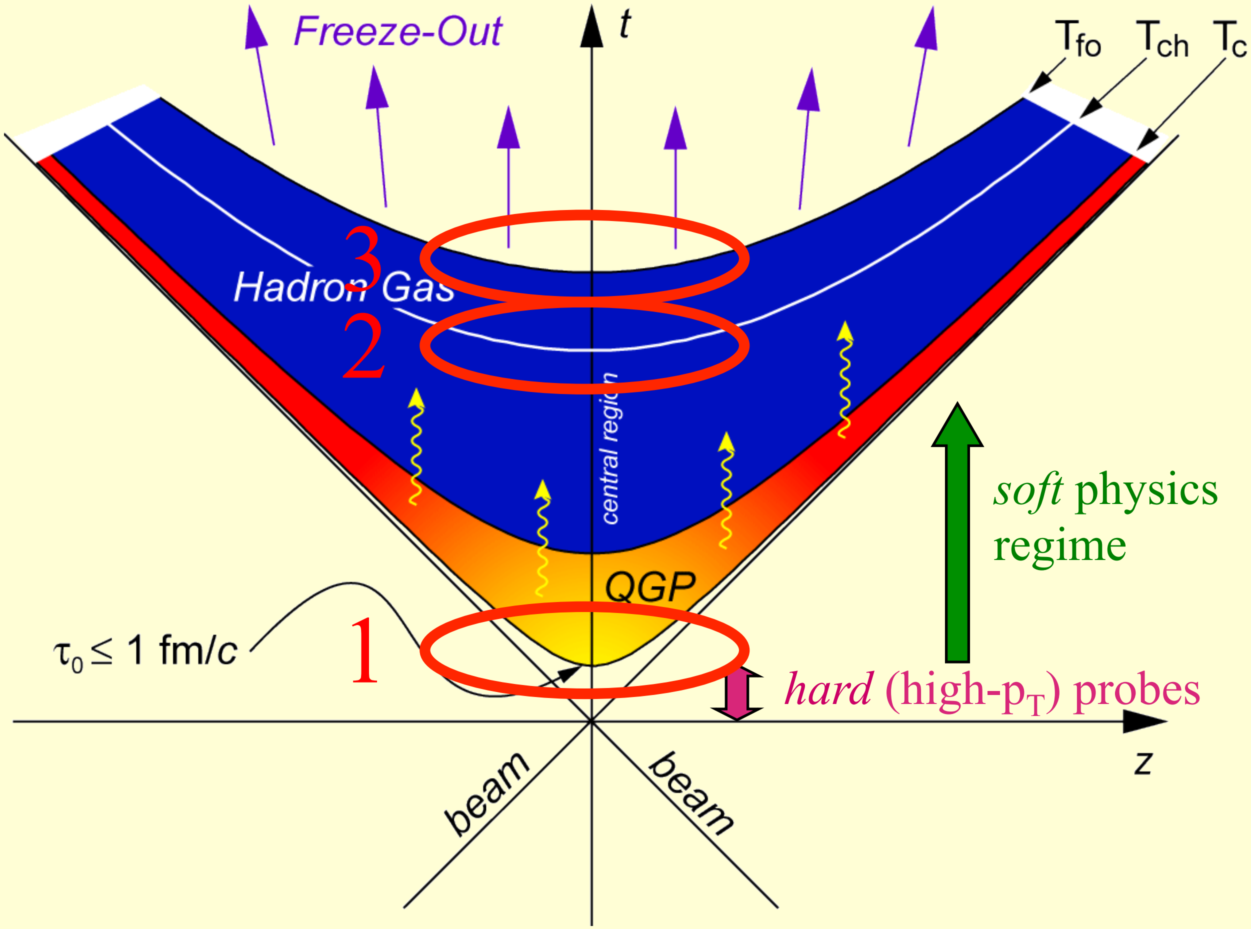
Content

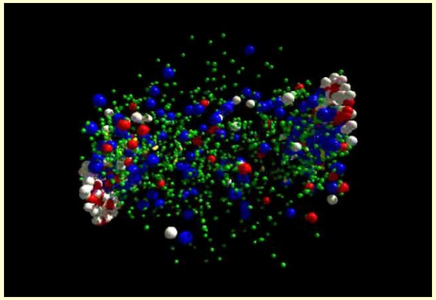
- *Motivation. Why flow?*
- *Flow: how to quantify this phenomenon*
- *Connection to Equation of State*
- *Directed flow at FAIR and NICA energies*
- *Directed flow and freeze-out*
- *Summary and perspectives*

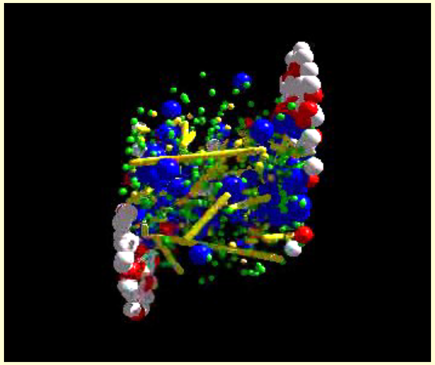
Present status of the Equation of State

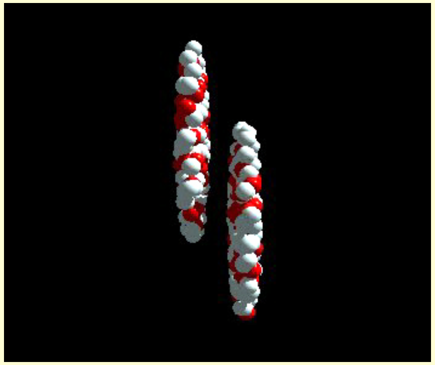


Motivation







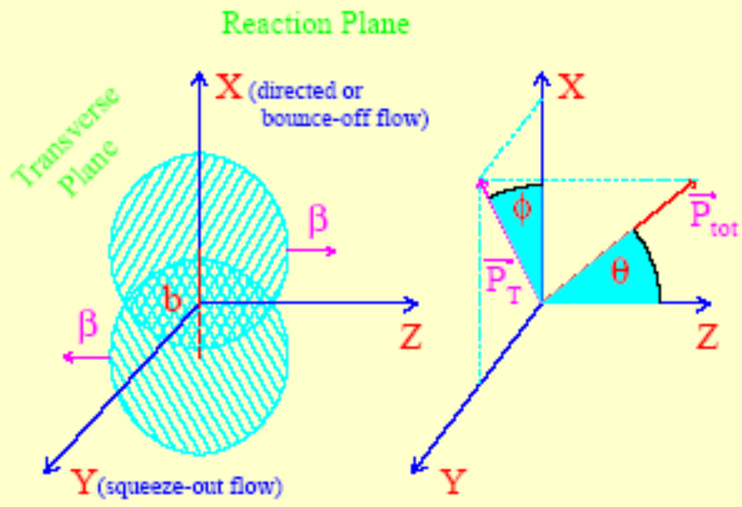


Chemical freezeout ($T_{ch} \leq T_c$): inelastic scattering ceases
Kinetic freeze-out ($T_{fo} \leq T_{ch}$): elastic scattering ceases

Flow:

We have to quatify this phenomenon

Definitions. Non-central Collisions (b>0)



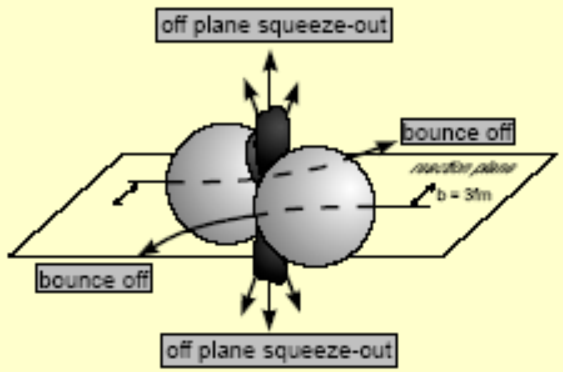
Flow Decomposition:

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

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

n=1,2,…

Centrality dependence

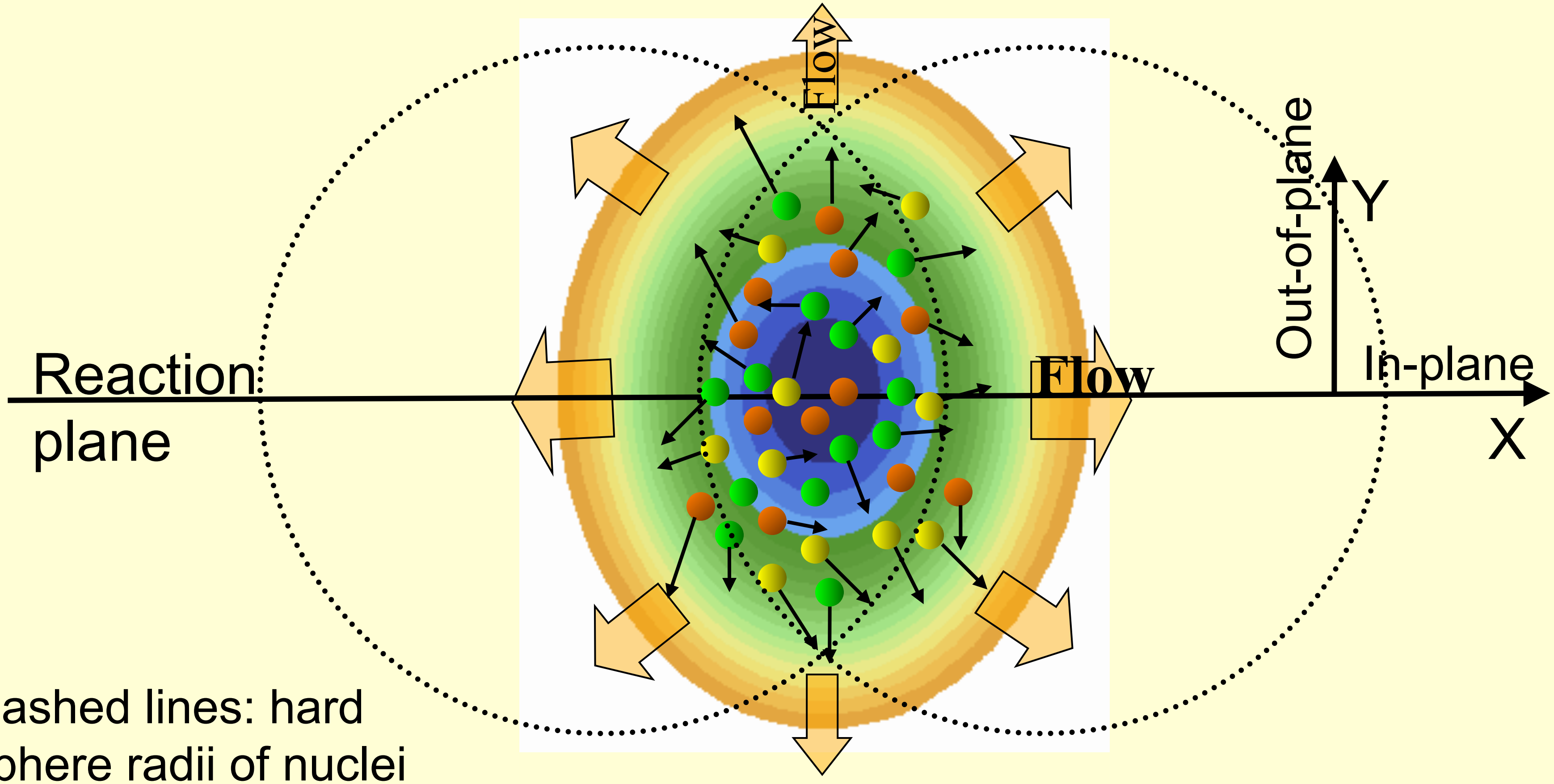
$$v_n(b, \Delta p_t, \Delta y) = \frac{\int_{\Delta p_t} \int_{\Delta y} \cos(n\phi) \frac{d^3N}{dydbdp_t} dp_t dy}{\int_{\Delta p_t} \int_{\Delta y} \frac{d^3N}{dydbdp_t} dp_t dy}$$

Motivation: connection to Equation of State

F. Retiere, QM2004 talk

Flow (in the transverse plane)

A mid-peripheral collision



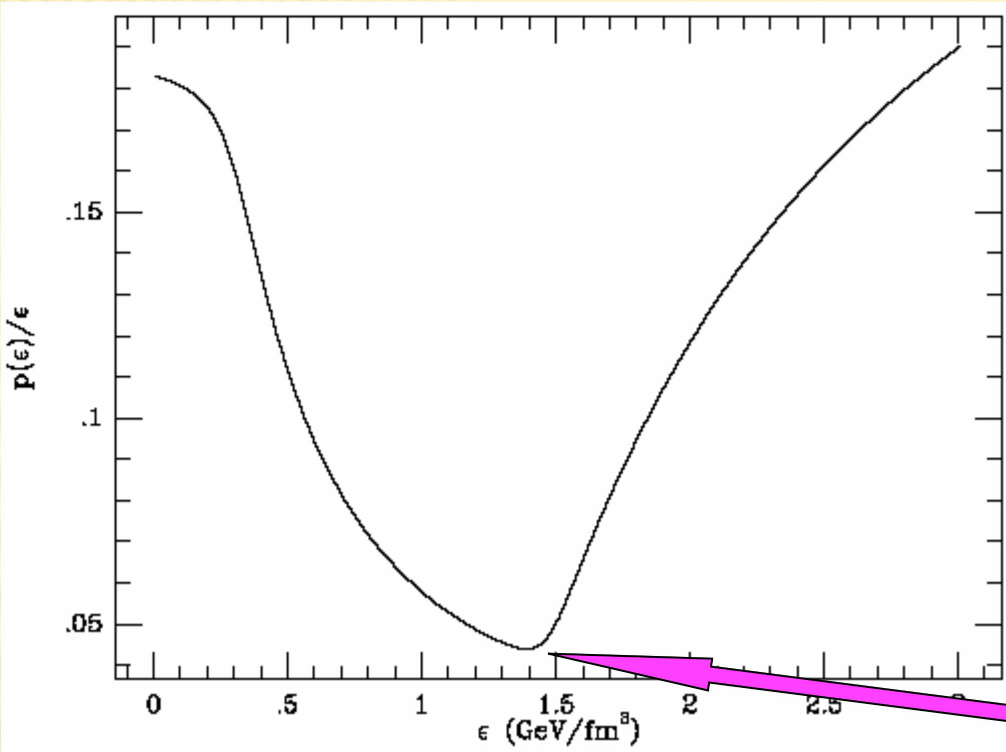
Dashed lines: hard sphere radii of nuclei

Re-interactions ➔ **FLOW**

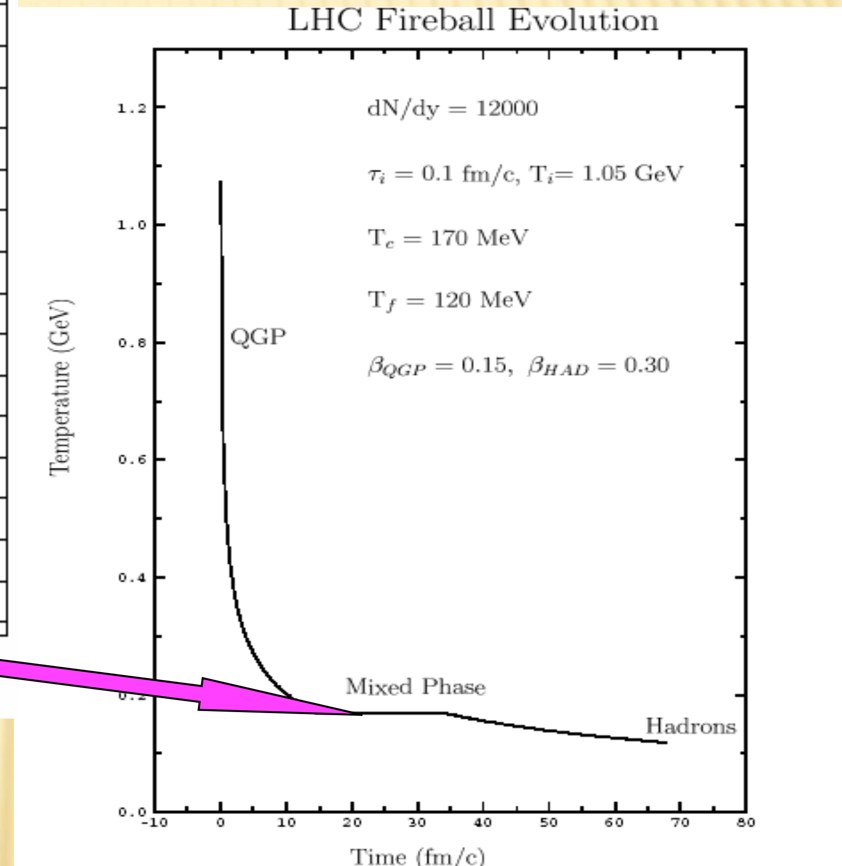
Re-interactions among what? **Hadrons, partons or both?**

In other words, what equation of state?

DISAPPEARANCE OF DIRECTED FLOW



Hung and Shuryak, PRL 75 (1995) 4003



In case of first order phase transition

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

Braun-Munzinger, NPA 661 (1999) 261c

V1 OF NUCLEONS AND FRAGMENTS AT LOWER ENERGIES

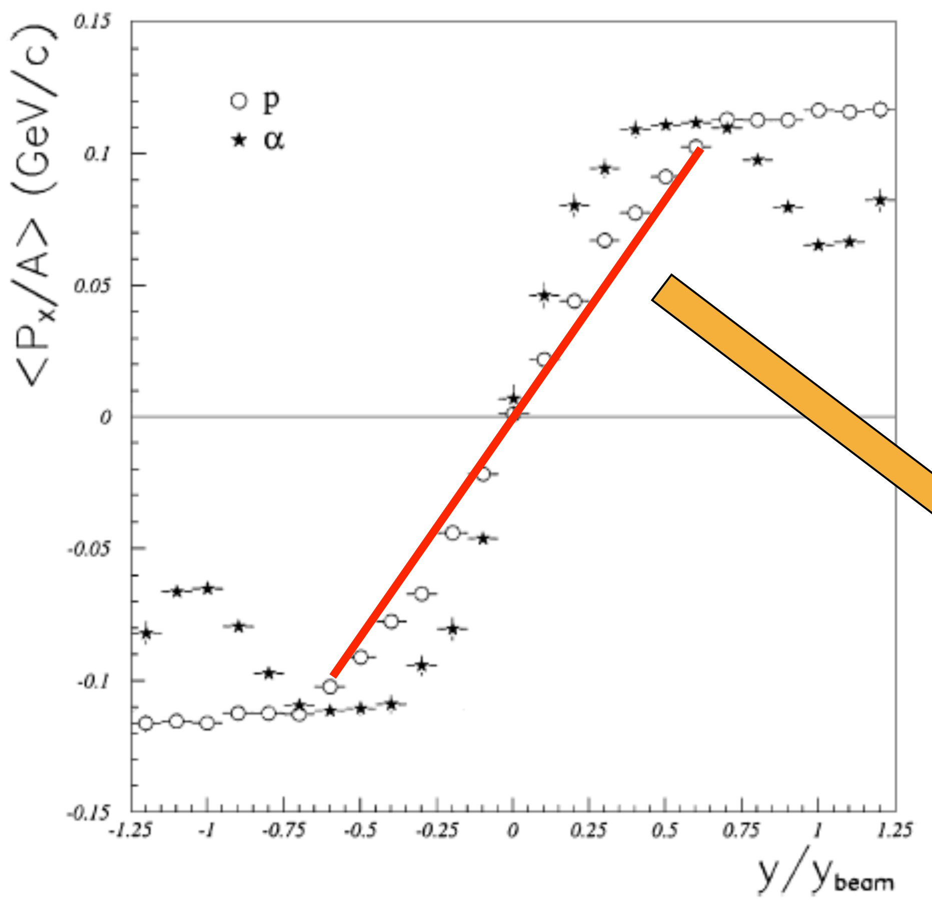


Figure 1 Average in-plane transverse momentum versus normalized rapidity in the reaction Au+Au at 800*A* MeV. The points at $y/y_{beam} < 0$ are reflected.

Plastic Ball Collaboration introduced a slope parameter

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

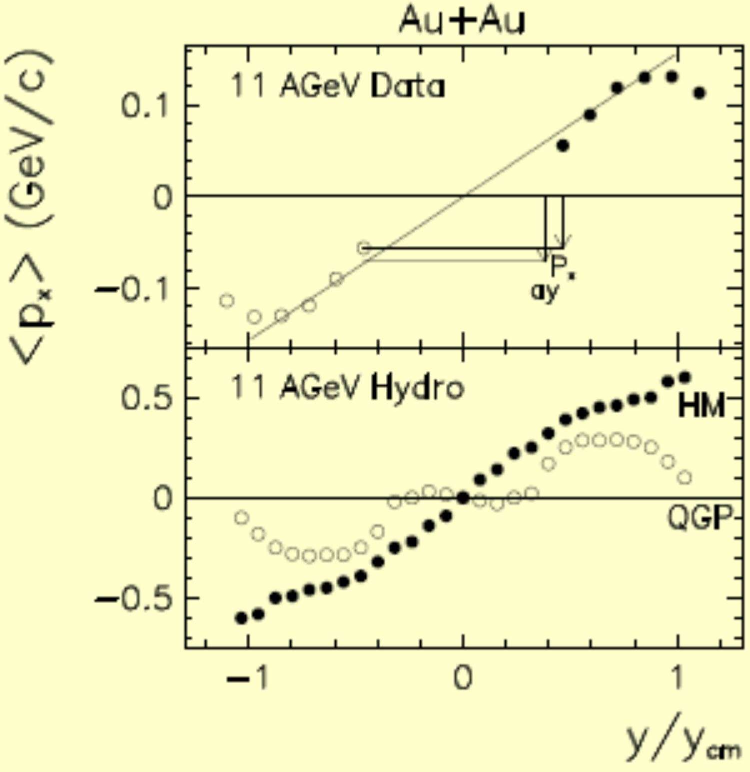
$$\mathbf{F_y} = \frac{d\langle p_x\rangle/A}{dy}$$

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

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

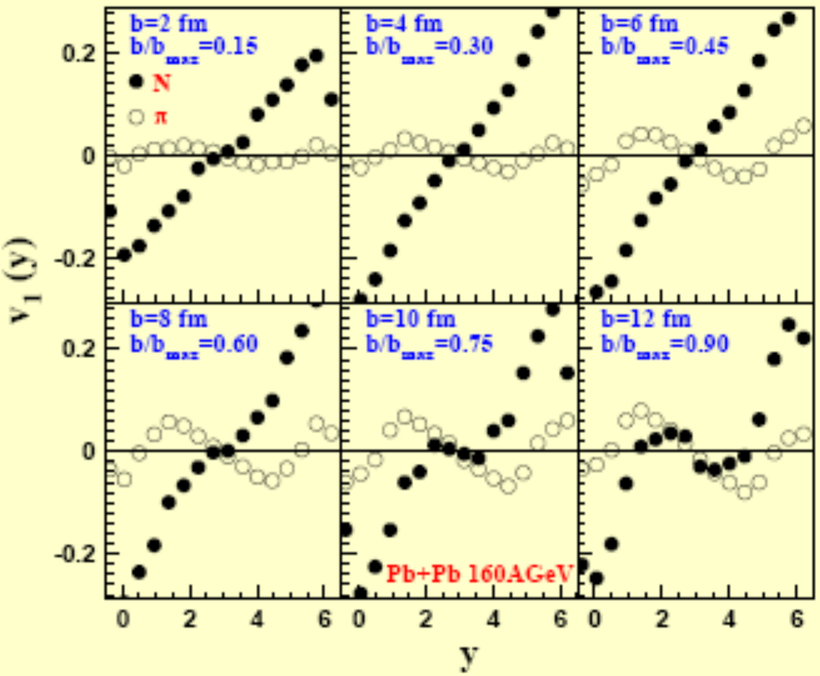
SOFTENING OF DIRECTED FLOW

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

Directed flow
at FAIR and NICA

Beam energy scan results for v_1 (STAR)

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

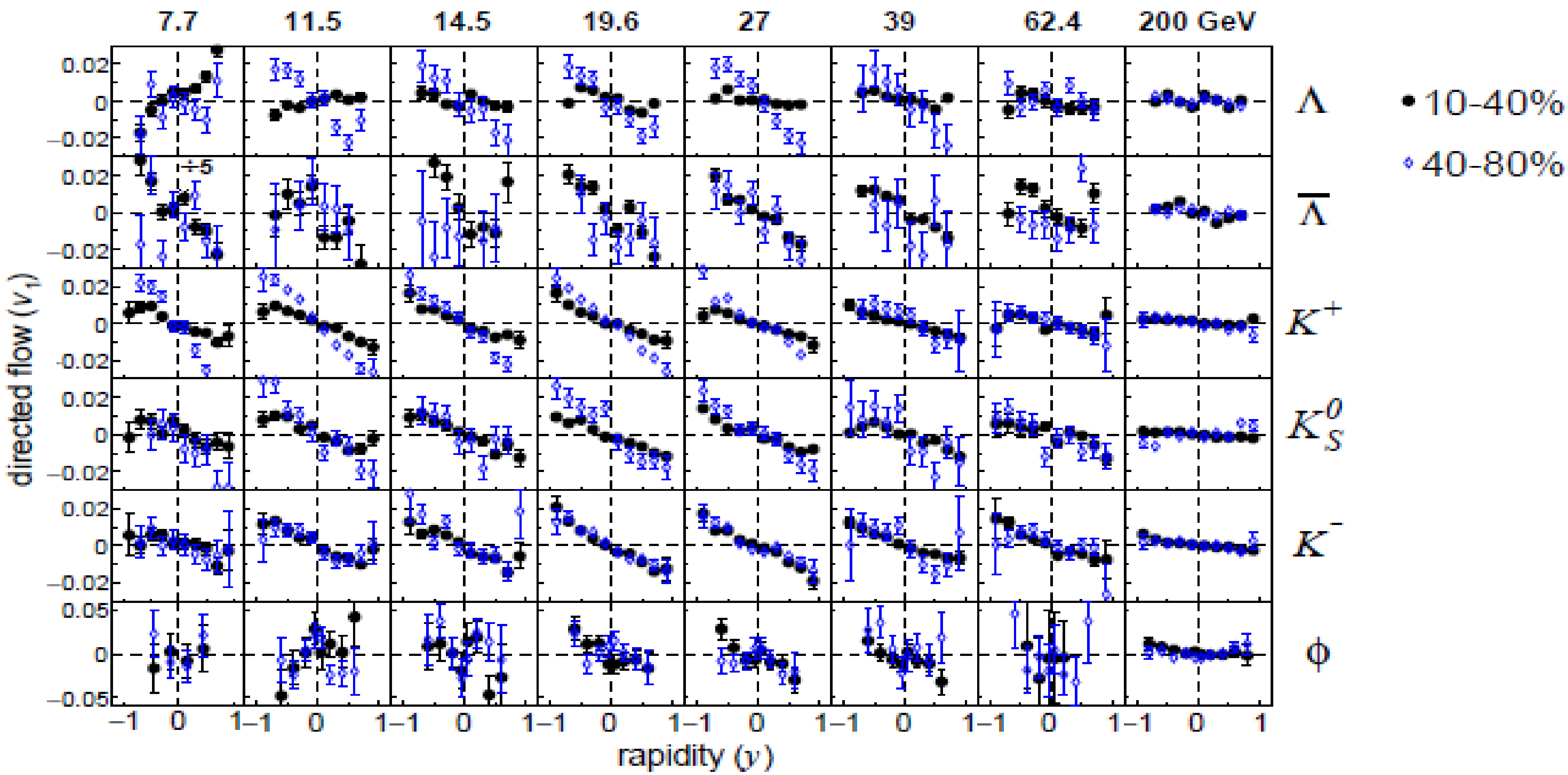
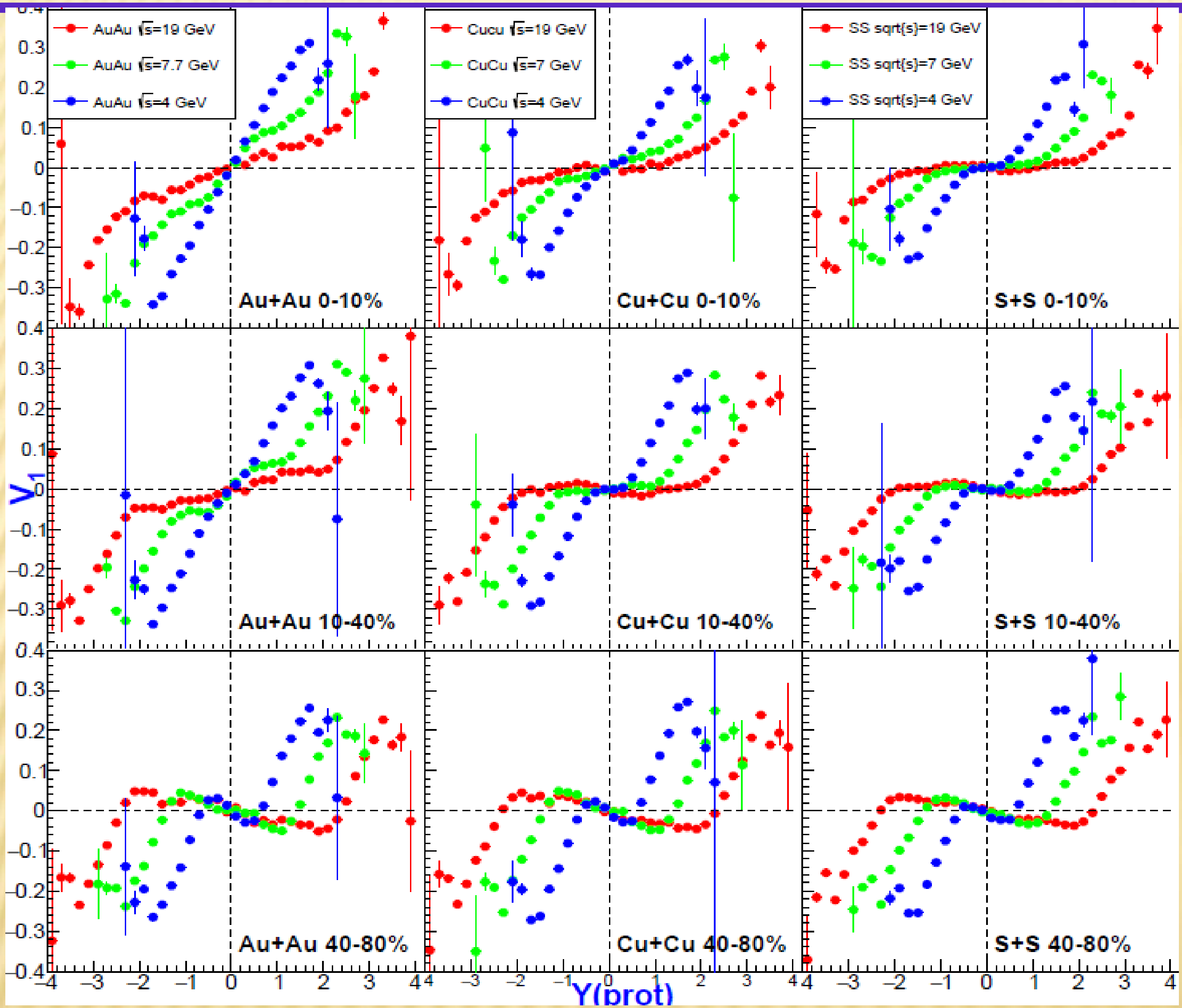


Figure 1: (Color online) Rapidity dependence of directed flow (v_1) for Λ, $\overline{\Lambda}$, K^+, K_s^0, K^- and ϕ in 10-40% and 40-80% Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 and 200 GeV.

Directed flow of protons in light and heavy systems



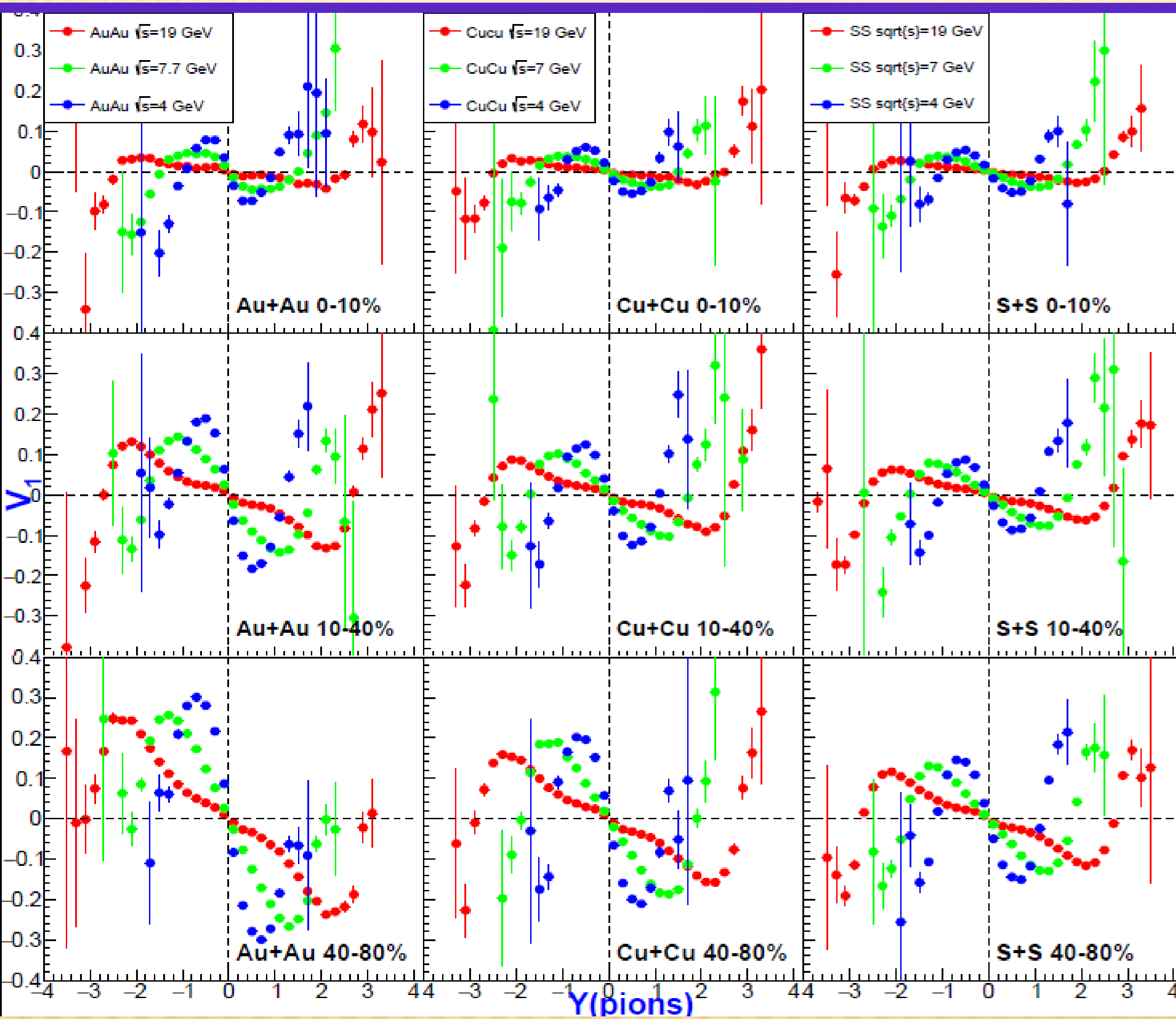
Au + Au   Cu + Cu   S + S

QGSM

Blue - √s = 4 GeV
Green – 7.7 GeV
Red – 19 GeV

- **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**

Directed flow of pions in light and heavy systems



Au + Au Cu + Cu S + S

QGSM

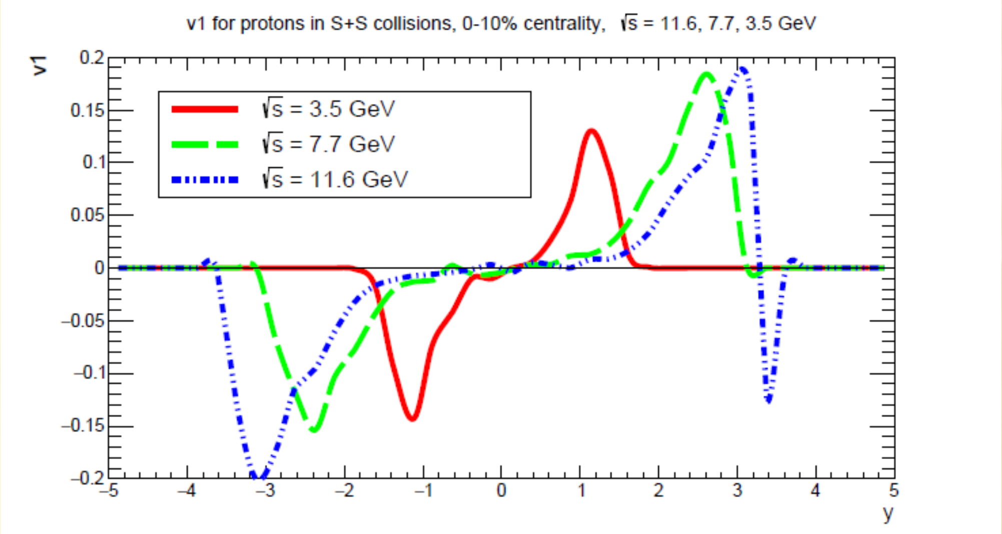
Blue - √s = 4 GeV
Green – 7.7 GeV
Red – 19 GeV

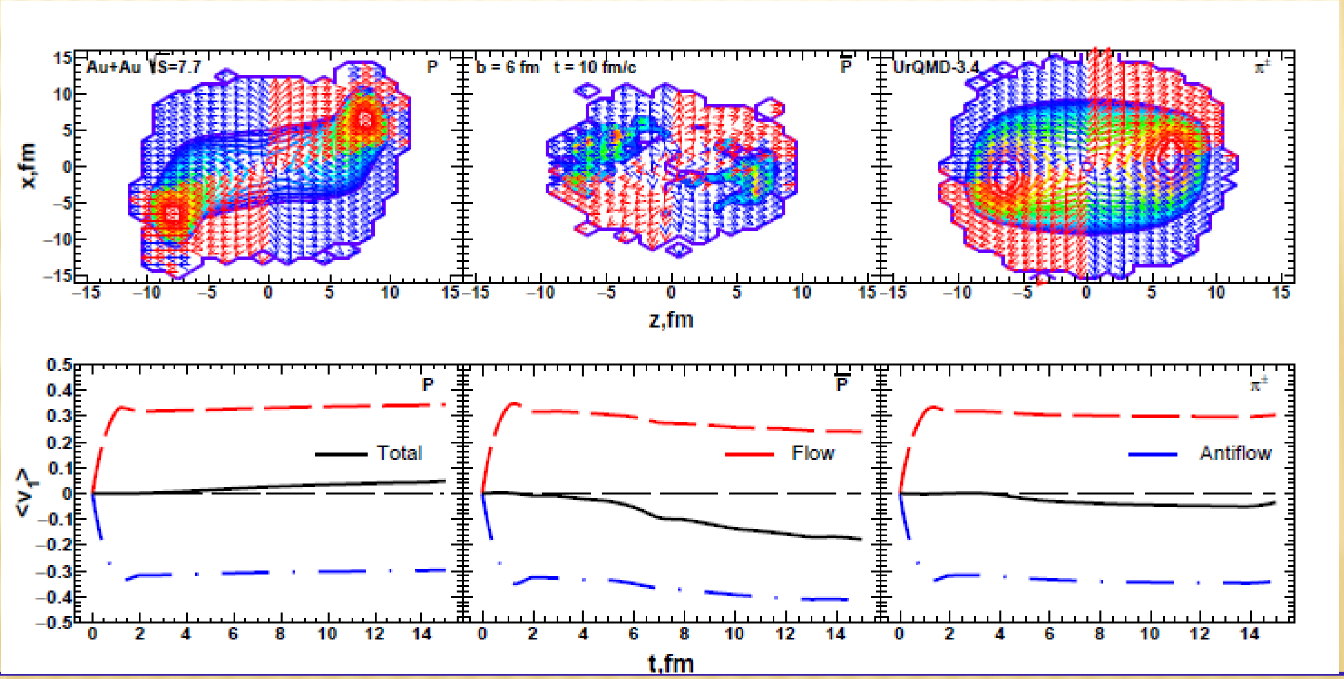
- **Development of antiflow at midrapidity at any impact parameters**
- **The antiflow slope at midrapidity is stronger for smaller colliding systems**
- **The slope decreases with rising CM energy of collisions**

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

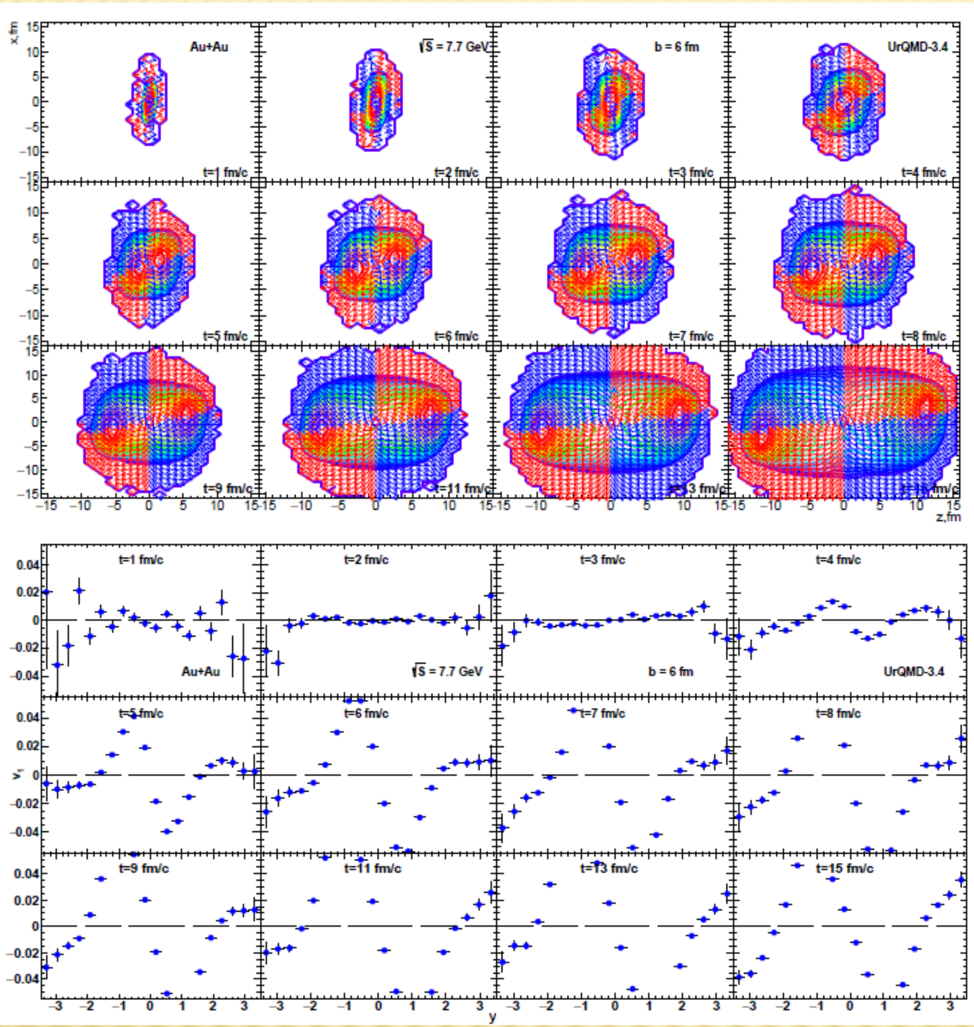
See poster by O.Vityuk

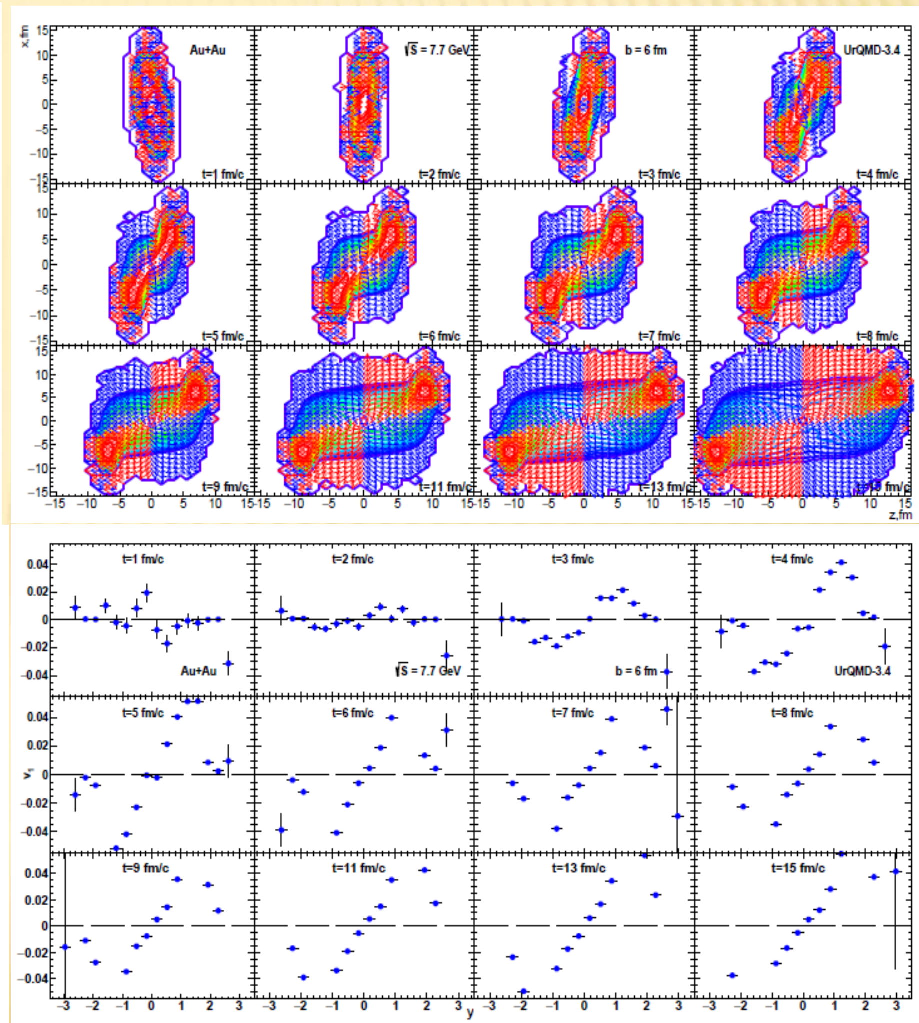




- **Directed flow = Normal flow – Antiflow**

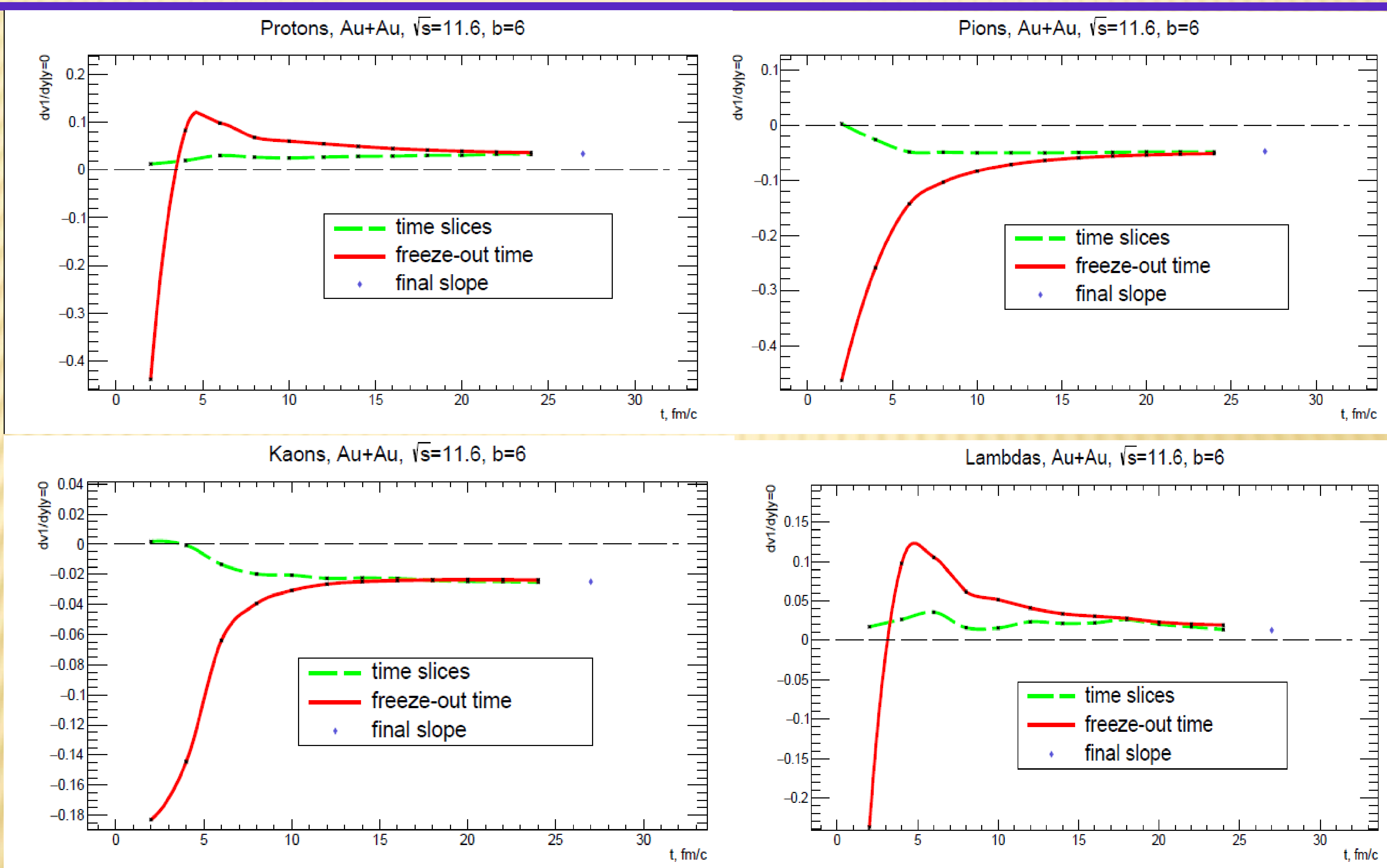
Time development of directed flow





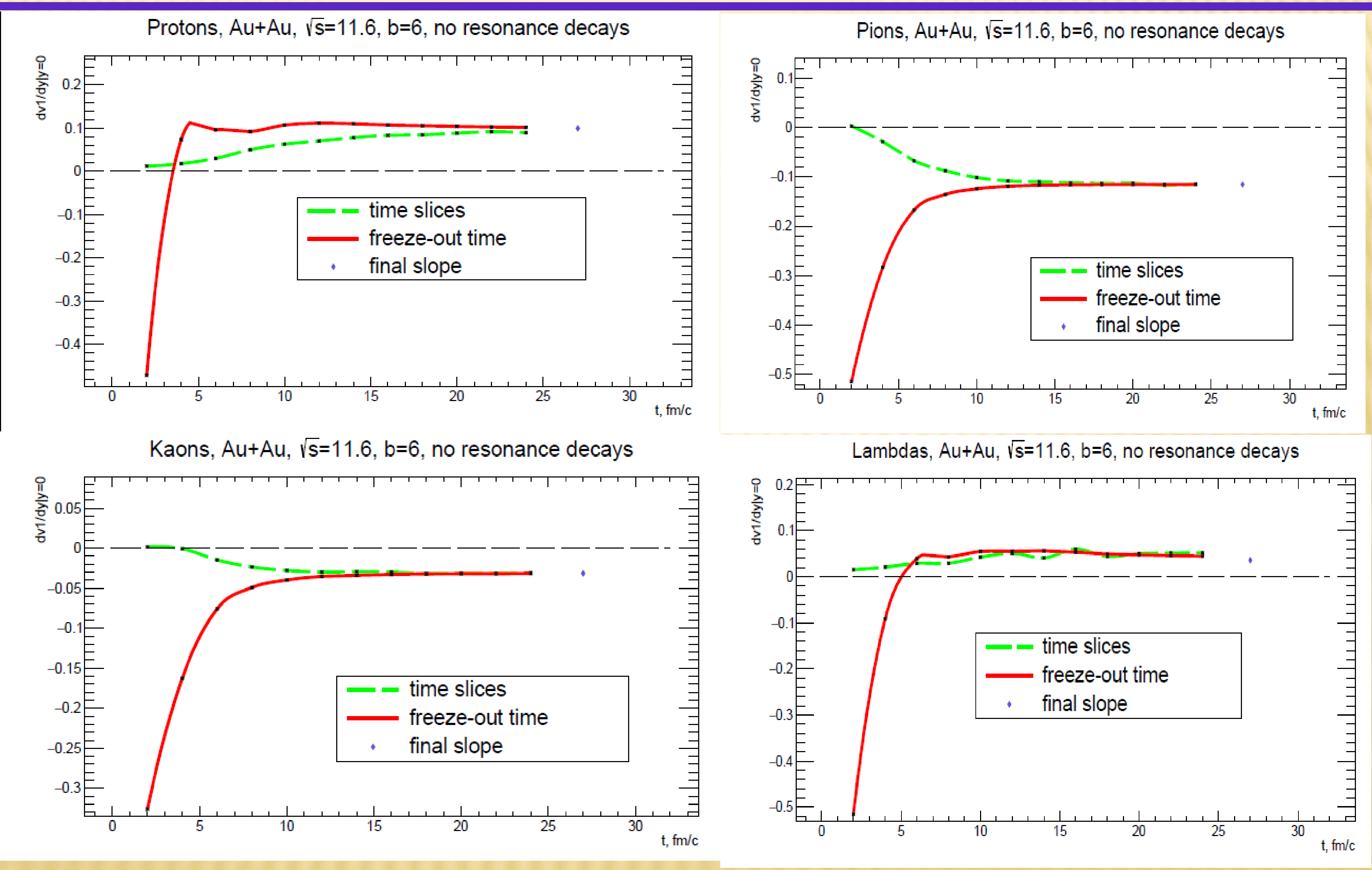
- It appears that V_1 of both pions and protons at midrapidity is formed not earlier than 5 – 6 fm/c

Time development of directed flow



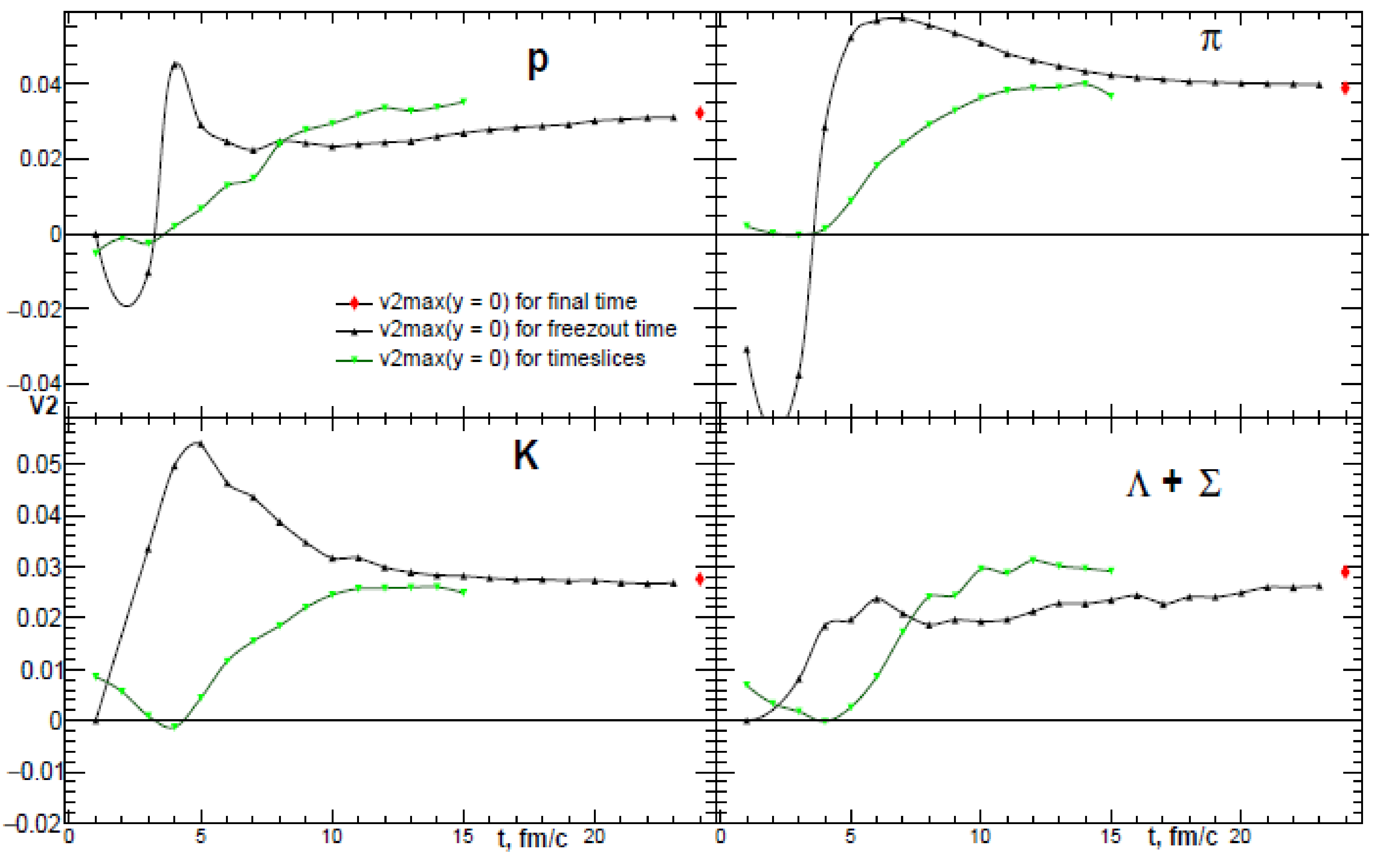
- V_1 of both mesons and baryons at midrapidity is formed at approximately 6 – 10 fm/c

Influence of resonances on the development of V_1



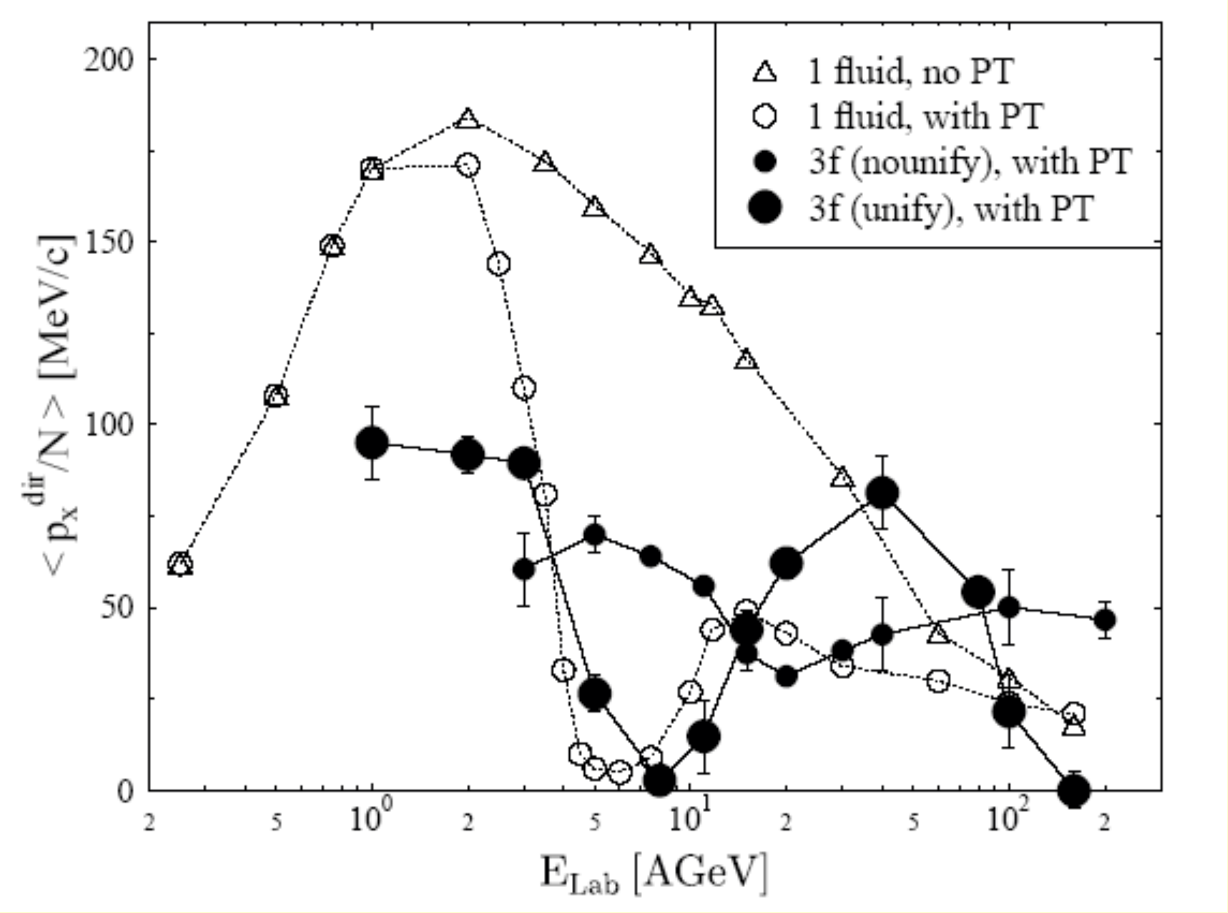
- Difference is seen only for Lambdas and for protons (not so distinct) at t ≈ 5 fm/c

(for comparison): Time development of elliptic flow



- V_2 of both mesons and baryons at midrapidity is formed after 10 fm/c

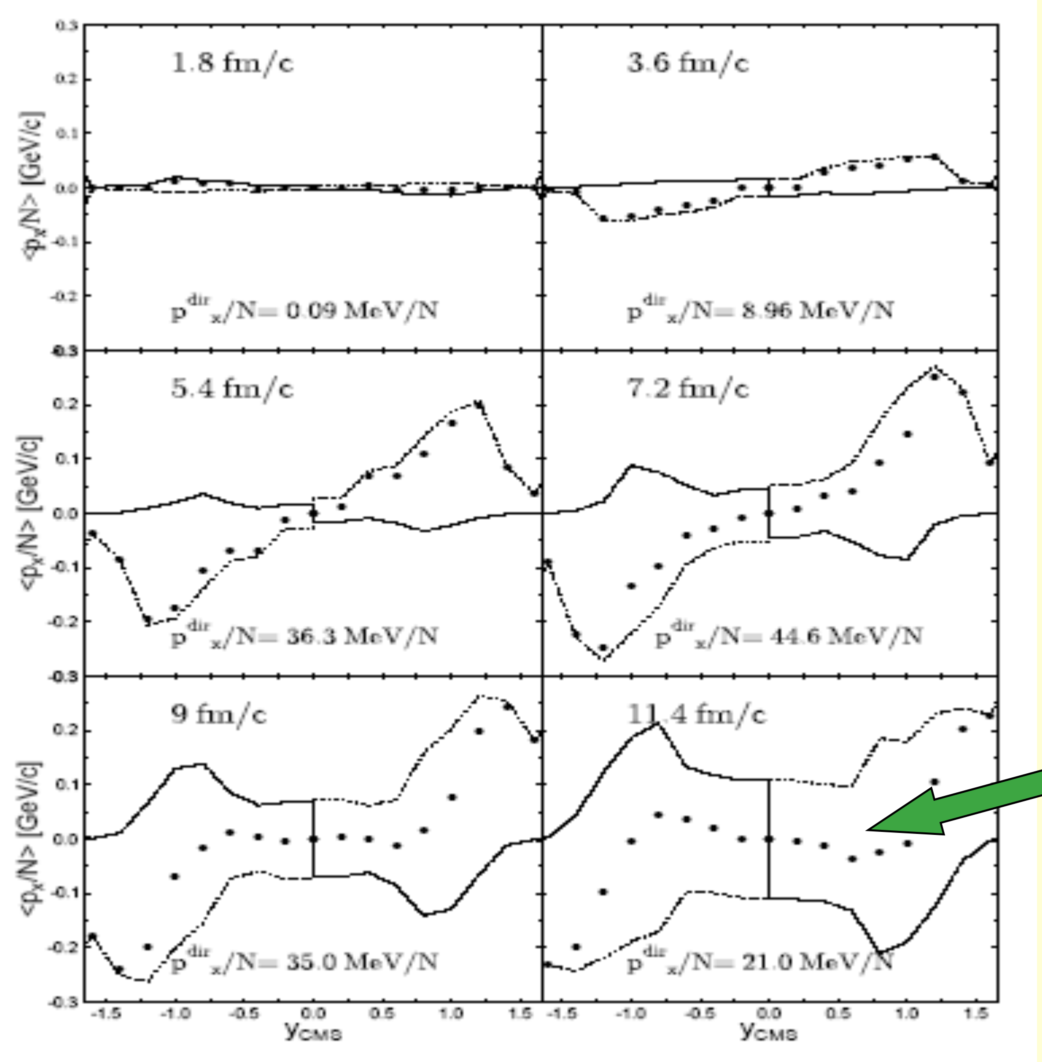
Directed flow of nucleons. 3-fluid hydro



The model predicts a local minimum in the excitation function of directed flow at energies between 10 and 20 AGeV (so far not been observed)

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

Directed flow of nucleons. 3-fluid hydro



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

The antiflow component is a source of the reduction of directed flow at midrapidity

NB! This is a very rare case when the antiflow behavior is reproduced in hydrodynamic model

Directed flow of hadrons in 3-fluid hydro THESEUS

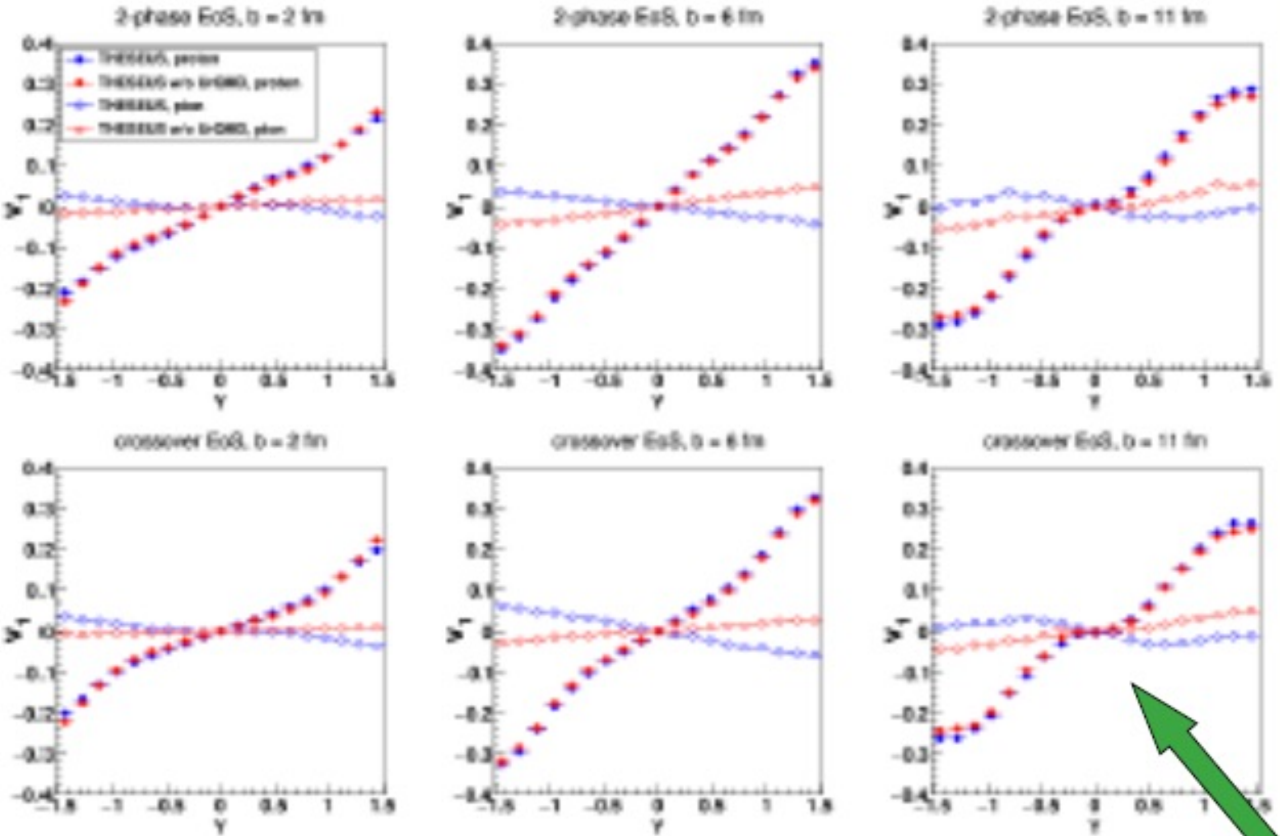


Figure 5. Two upper rows: Directed flow (v_1) of protons (full symbols) and pions (open symbols) for central (b = 2 fm), semicentral (b = 6 fm) and peripheral (b = 11 fm) Au+Au collisions at E_{lab} = 8 A GeV. The upper row is for the 2-phase EoS while the lower row shows results for the crossover EoS. 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

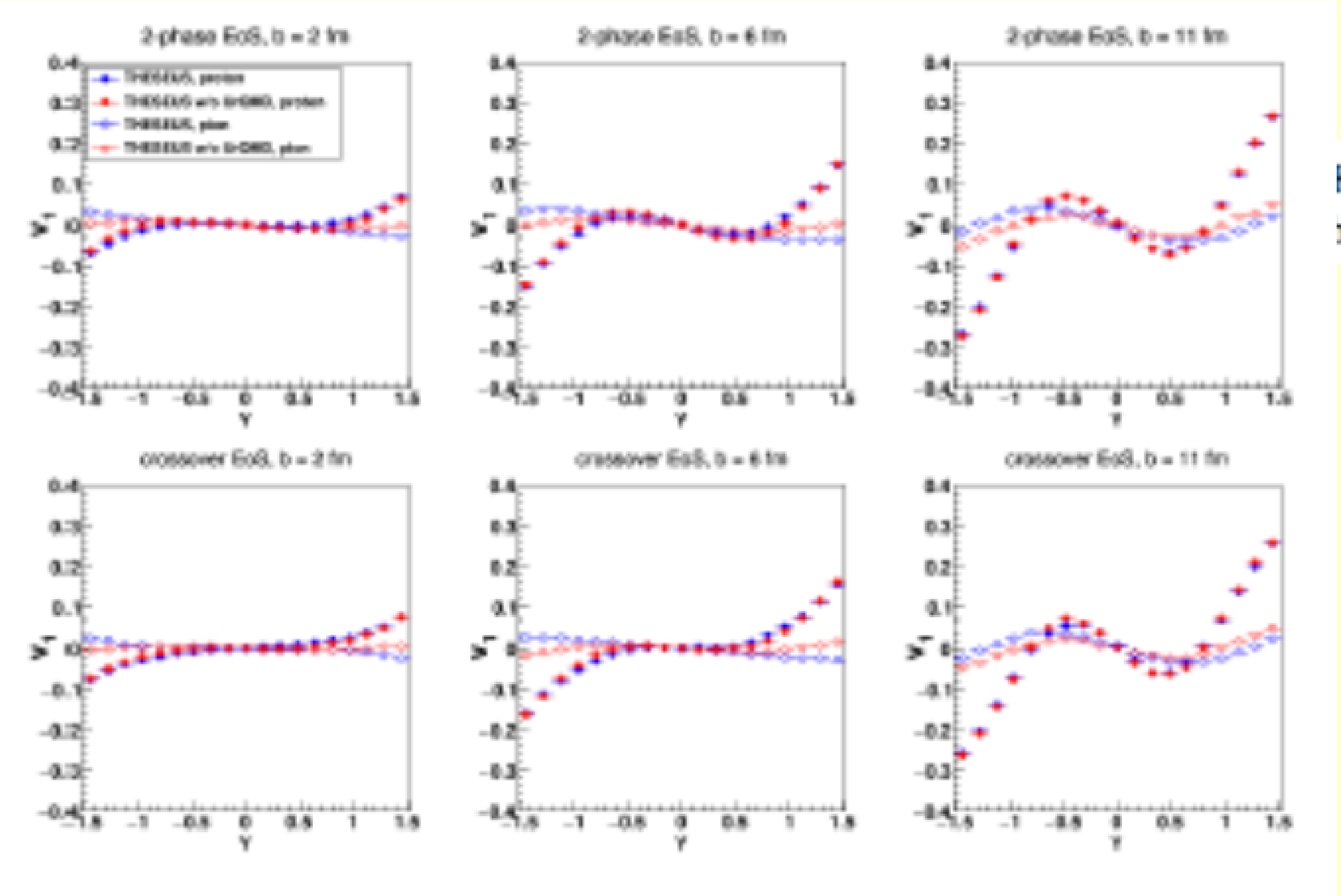
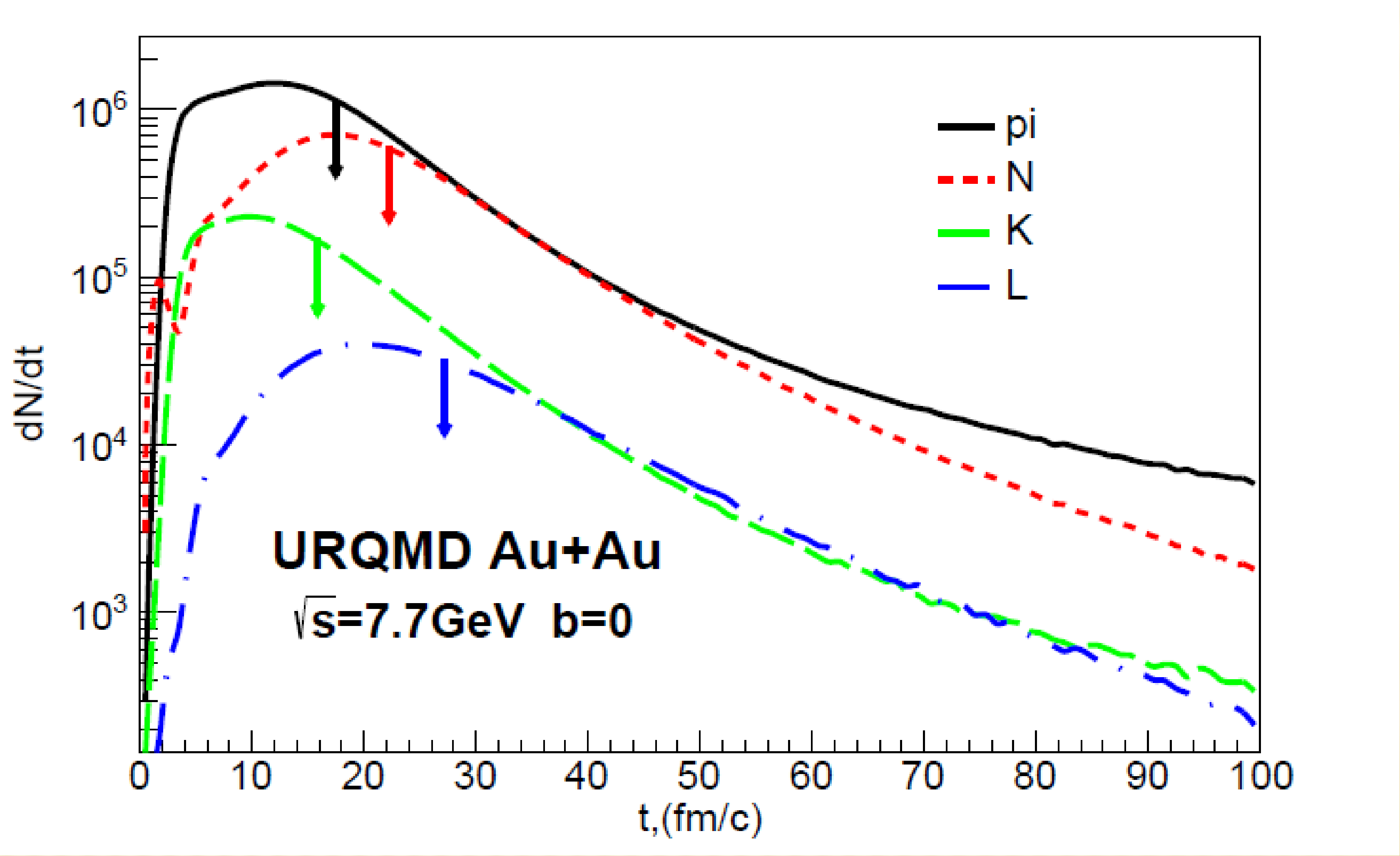


Figure 6. Same as in Fig. 5 but for E_{lab} = 30 A GeV.

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

Directed flow and freeze-out

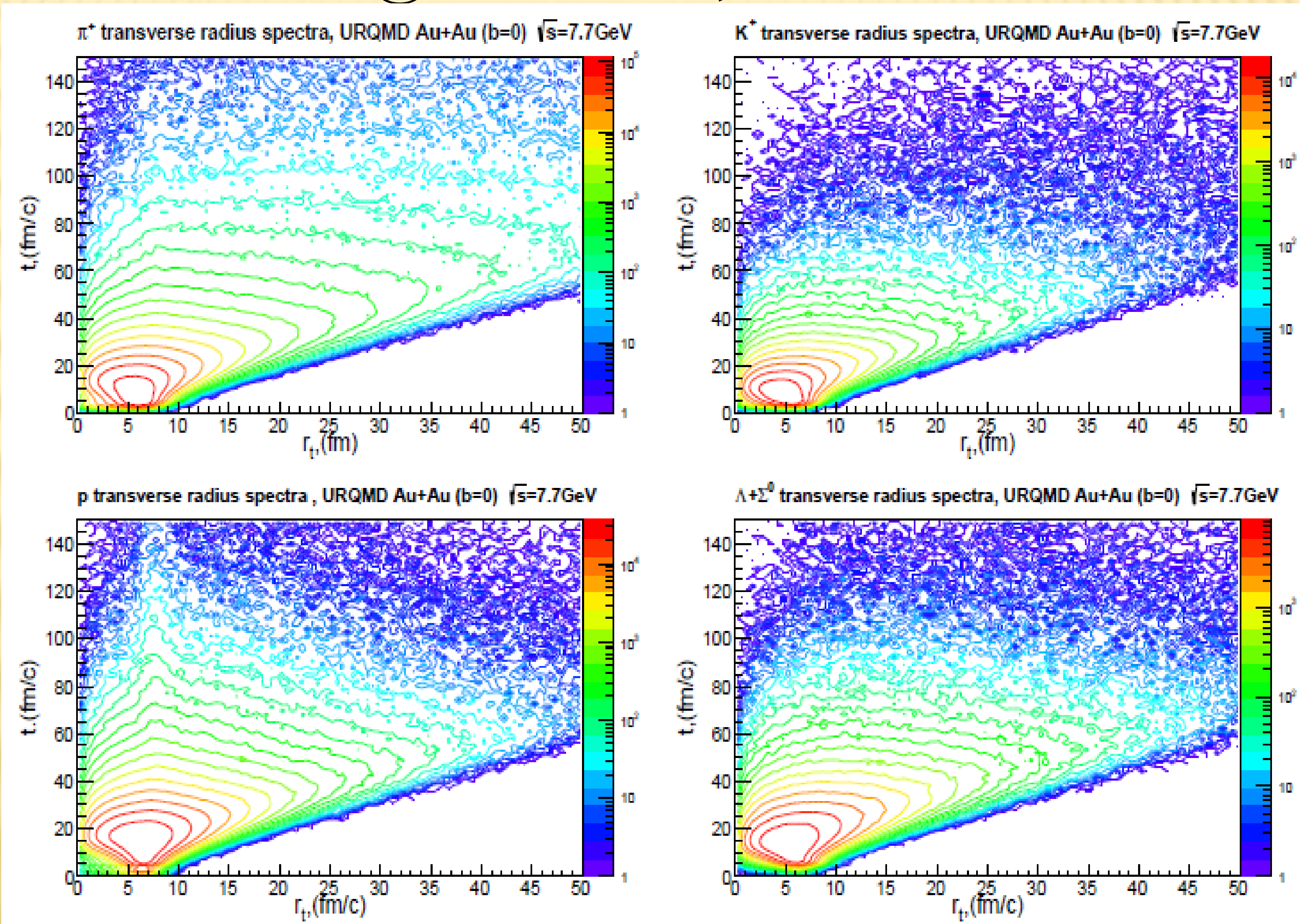
Sequential freeze-out of hadrons at NICA energies



- There is no sharp freeze-out for different hadrons
- The order of freeze-out is as follows: mesons (kaons and pions), nucleons and lambdas

Freeze-out of hadrons at NICA energies

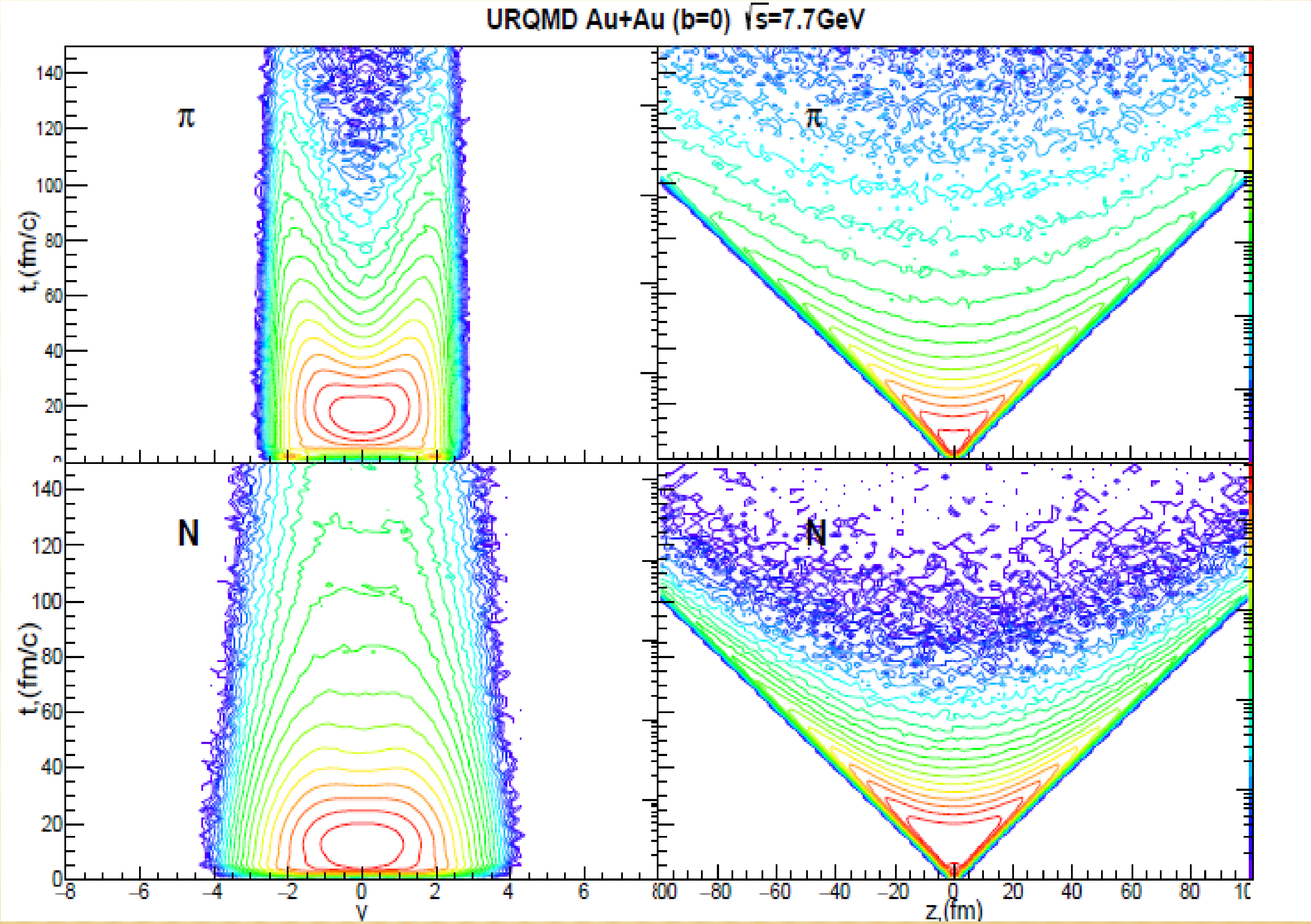
Au+Au @ 7.7 GeV ; b = 0 fm



- Baryons are emitted longer and from larger areas than mesons

Freeze-out of hadrons at NICA energies

Au+Au @ 7.7 GeV ; b = 0 fm



- Baryons are emitted longer and from larger areas than mesons

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:

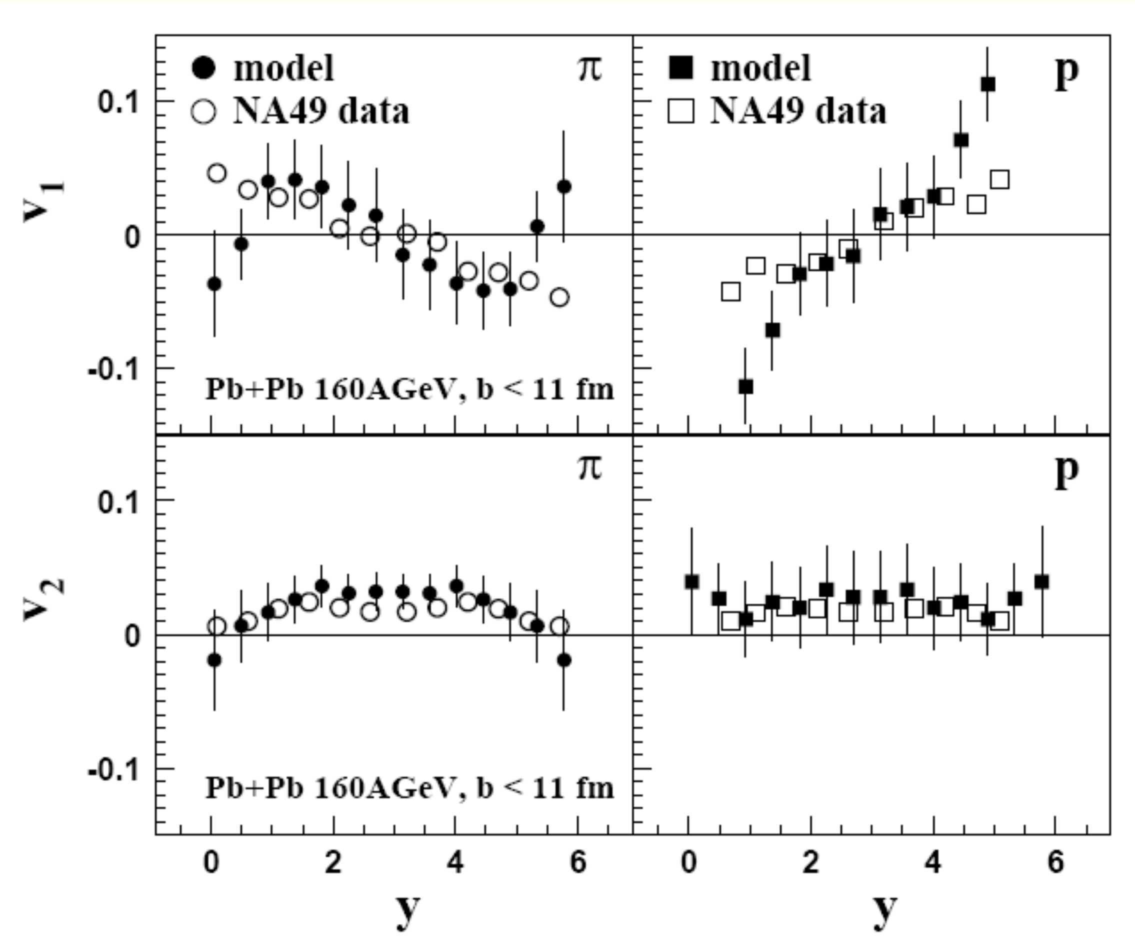
QGP ➔ the effect is stronger for semi-central collisions

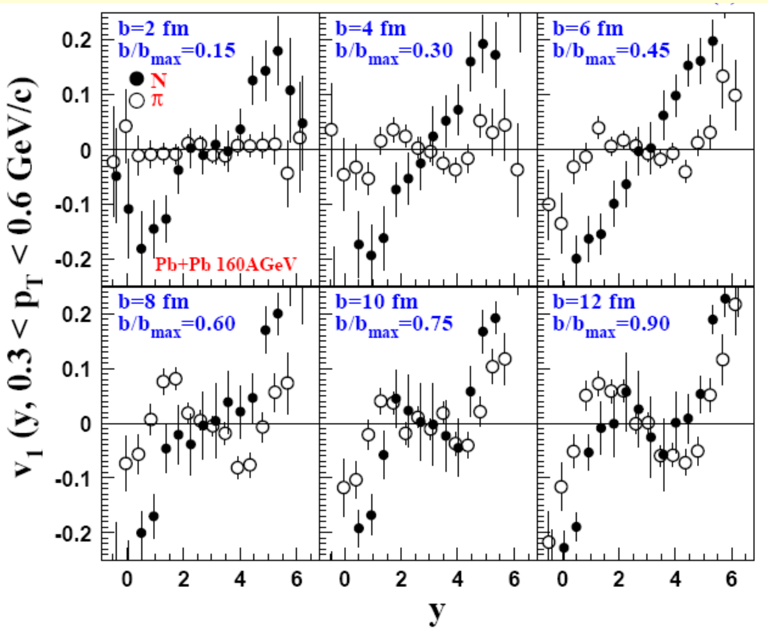
Cascade ➔ the effect is stronger for semi-peripheral and peripheral ones

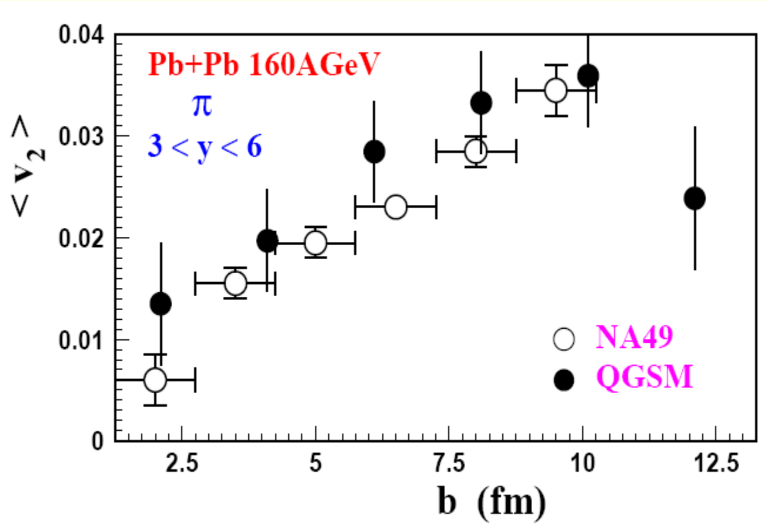
- At energies about few GeV: normal directed flow of protons at midrapidity in central collisions and antiflow in peripheral ones. Mesons – antiflow for all centralities.
- The directed flow of high-P_T is elongated in normal direction
- Development of both directed and elliptic flow of hadrons at midrapidity in transport models takes about 6-8 fm/c (or longer)
- Collective phenomena, such as anisotropic flow, should be studied together with the freeze-out conditions

Back-up Slides

Comparison with QGSM calculations

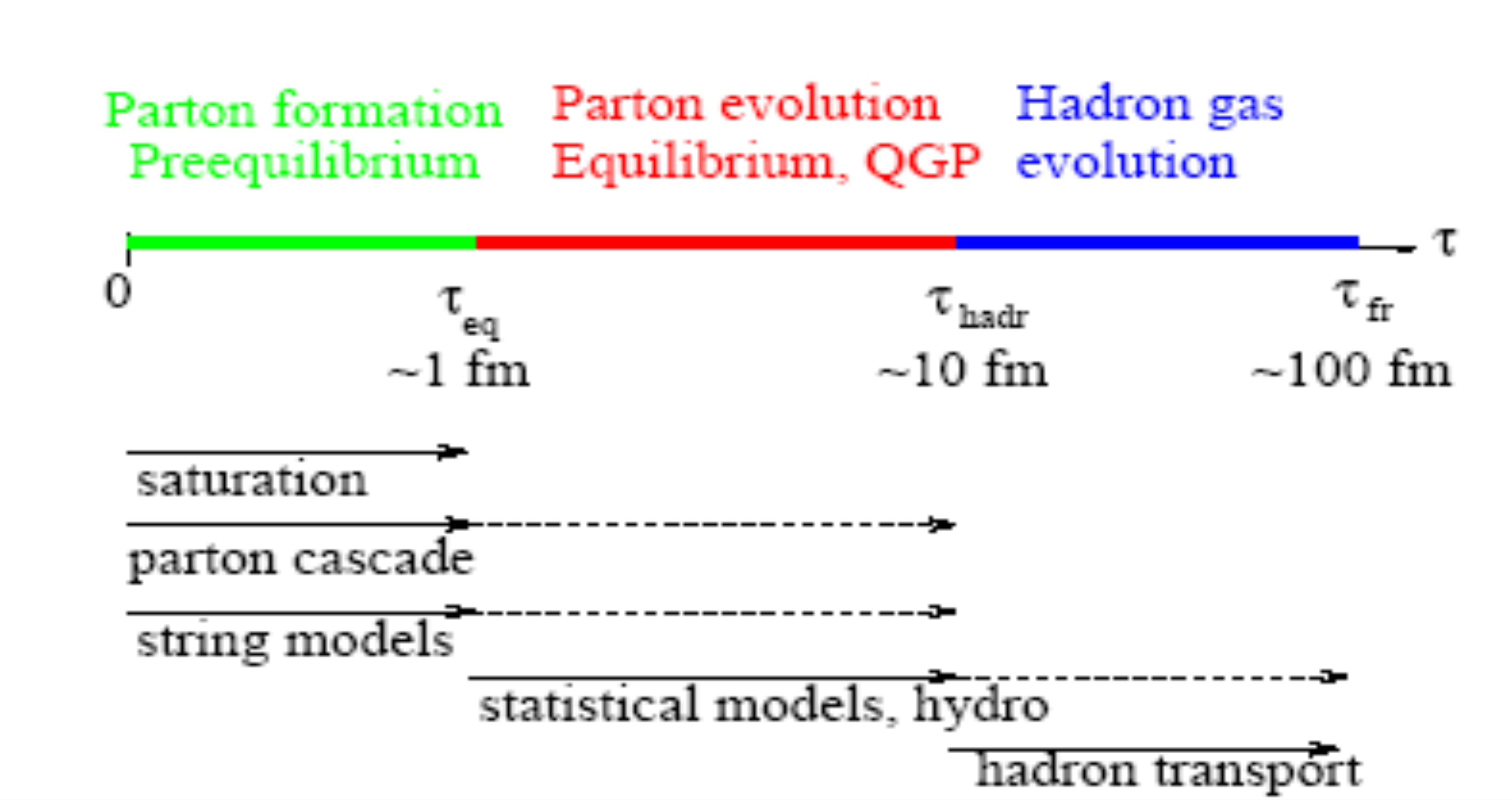






E. Zabrodin et al. , PRC 63 (2003) 034902;
L. Bravina et al., PRC 61 (2000) 064802

Applicability of different models



Predictions for A+A at 200 and 5500 GEV