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

• Directed Flow: connection to equation of state (EOS)

• Models at our disposal (UrQMD, DCM, QGSM)

• Directed flow at BES, FAIR and NICA energies:
  (i) Y-distributions; (ii) with $P_T$ cuts; (iii) development with time

• Directed flow and freeze-out

• Summary and perspectives
Motivation

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

soft physics regime

had (high-$p_T$) probes

$\tau_0 \leq 1 \text{ fm/c}$

Freeze-Out

Hadron Gas

$T_{fo}$ $T_{ch}$ $T_c$
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}

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

Elliptic flow:

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

Directed flow:

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

Rapidity dependence

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

Transverse momentum dependence

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

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
In case of first order phase transition

\[ \frac{dP}{d\varepsilon} = c_s^2 = 0 \]
Plastic Ball Collaboration introduced a slope parameter

\[ F = \frac{d\langle p_x \rangle/A}{dy_n}, \quad y_n = y/y_{\text{max}} \]

\[ F_y = \frac{d\langle p_x \rangle/A}{dy} \]

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

\[ \Rightarrow \text{normal flow} \]

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

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

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
Figure 1: (Color online) Rapidity dependence of directed flow ($v_1$) for $\Lambda$, $\bar{\Lambda}$, $K^+$, $K_S^0$, $K^-$ and $\phi$ 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
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
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 $P_T > 0.2 \text{ GeV/c}$ and $P_T > 0.9 \text{ GeV/c}$

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
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
Here $V_1$ of high-$p_T$ pions reveals normal flow already at 11.6 GeV
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
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
$V_1 \left( y, p_T \right)$ 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 Lambda's, 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 Lambda$_c$, UrQMD

Normal flow in central collisions at higher energies and (weak) antiflow at low energies.
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
It appears that $V_1$ of both pions and protons at midrapidity is formed not earlier than 5 – 6 fm/c
$V_1$ of mesons and baryons at midrapidity is formed at approximately $6 \text{–} 10 \text{ fm}/c$. 

Protons, $\text{Au+Au}, \sqrt{s}=11.6 \text{ GeV} \ b=6 \text{ fm}$

Pions, $\text{Au+Au}, \sqrt{s}=11.6 \text{ GeV} \ b=6 \text{ fm}$

Kaons, $\text{Au+Au}, \sqrt{s}=11.6 \text{ GeV} \ b=6 \text{ fm}$

Lambdas, $\text{Au+Au}, \sqrt{s}=11.6 \text{ GeV} \ b=6 \text{ fm}$

Time development of directed flow, QGSM
Time development of directed flow, UrQMD

Protons, Au+Au, $\sqrt{s}=11.6$, $b=6$

Pions, Au+Au, $\sqrt{s}=11.6$, $b=6$

Kaons, Au+Au, $\sqrt{s}=11.6$, $b=6$

Lambdas, Au+Au, $\sqrt{s}=11.6$, $b=6$

$V_1$ of mesons and baryons at midrapidity is formed at approximately 6 – 10 fm/c
Influence of resonances on the development of $V_1$

- Protons, Au+Au, $\sqrt{s}=11.6$, $b=6$, no resonance decays
- Kaons, Au+Au, $\sqrt{s}=11.6$, $b=6$, no resonance decays
- Pions, Au+Au, $\sqrt{s}=11.6$, $b=6$, no resonance decays
- Lambdas, Au+Au, $\sqrt{s}=11.6$, $b=6$, no resonance decays

Difference is seen only for Lambdas and for protons (not so distinct) at $t \approx 5$ 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 \((b = 2 \text{ fm})\), semicentral \((b = 6 \text{ fm})\) and peripheral \((b = 11 \text{ fm})\) Au+Au collisions at \(E_{\text{lab}} = 8 \text{ A GeV}\). 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
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

\[
\begin{align*}
\text{Au+Au @ 4 GeV ; 0 – 10\%}
\end{align*}
\]

Transverse radius distribution \( d^2N \cdot dR_T \cdot dt \)
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