Correlations of the velocities and of the vorticities for nucleons and pions in PHSD model

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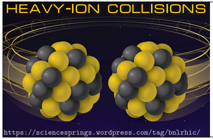
MOTIVATION



NICA
FAIR
RHIC

- Knowledge on vorticity $\Rightarrow$ knowledge on polarization

For fermions with spin 1/2

$$\Pi_\mu(x,p) = -\frac{1}{8}\varepsilon_{\mu\rho\sigma\tau}(1-n_F)\varpi^{\rho\sigma}\frac{p^\tau}{m}.$$

[F. Becattini et al., "A study of vorticity formation in high energy nuclear collisions", EPJ C 75 (2015)]

For Λ hyperons:

$$\langle \Pi_\Lambda \rangle = \frac{1}{\langle N_\Lambda \rangle} \cdot \frac{N_c}{2\pi^2} \int \mathrm{d}^3 x \mu^2(x)\vec{v}(x) \cdot \vec{\omega}(x)$$

[M. Baznat, K. Gudima, A. Sorin, O. Teryaev, "Helicity separation in heavy-ion collisions", Phys.Rev C 88 (2013)]

- Knowledge on correlations of kinematic characteristics of particles $\Rightarrow$ applicability of the hydrodynamical approach to description of the fireball.

- Correlations of the kinematic quantities are related to the thermodynamical equilibrium

- In axial vortical mechanism:

Correlation of vorticities for different types of particles $\Longleftrightarrow$ Correlation of polarizations for different types of particles

Relevant quantities and features of PHSD

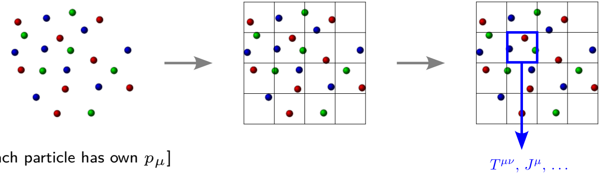
The relevant correlations:

$$\mathcal{D}[\vec{v}] = \mathcal{D}[\vec{v}_\pi, \vec{v}_N] = \int \vec{v}_\pi \cdot \vec{v}_N \, \mathrm{d}V \Bigg/ \sqrt{\int (\vec{v}_\pi)^2 \, \mathrm{d}V \cdot \int (\vec{v}_N)^2 \, \mathrm{d}V} \tag{1}$$

$$\mathcal{D}[\vec{\omega}] = \mathcal{D}[\vec{\omega}_\pi, \vec{\omega}_N] = \int \vec{\omega}_\pi \cdot \vec{\omega}_N \, \mathrm{d}V \Bigg/ \sqrt{\int (\vec{\omega}_\pi)^2 \, \mathrm{d}V \cdot \int (\vec{\omega}_N)^2 \, \mathrm{d}V} \tag{2}$$

Parton-Hadron-String Dynamics (PHSD) transport approach, based on solution of the Kadanoff–Baym equations in first-order gradient expansion in phase space [http://theory.gsi.de/~ebratkov/phsd-project/PHSD/].

Fluidization:



[Each particle has own p_μ]

Velocity ('Eckart definition'):

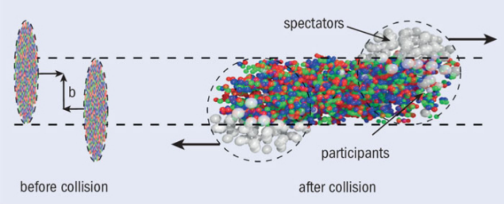
$$\vec{v} = \langle \vec{p}/E \rangle; \tag{3}$$

Vorticity (non-relativistic choice):

$$\vec{\omega} = \frac{1}{2} \operatorname{rot} \vec{v}. \tag{4}$$

Collision system

- Au + Au
- $\sqrt{s_{NN}} = 7.8$ GeV
- $b = 7.5$ fm



From https://cerncourier.com/a/participants-and-spectators-at-the-heavy-ion-fireball/

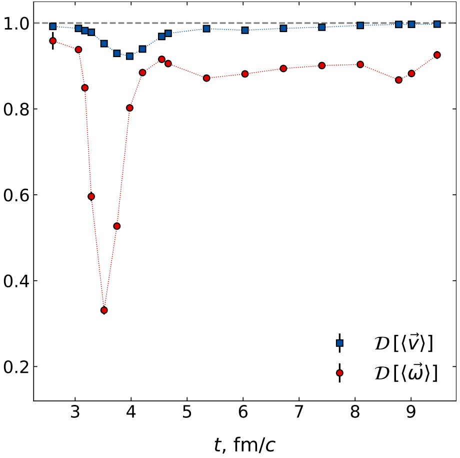
In practice, spectators and participants are splitted on rapidity:

```
if ||y| - y_beam| > 0.27:
    <participant>
else:
    <spectator>
```

$$y = \frac{1}{2} \ln \frac{1 + |\vec{p}/E|}{1 - |\vec{p}/E|} \quad (5)$$

We remove spectators from the consideration

CORRELATIONS



The velocities of pions and nucleons are correlated, the vorticities – not.

- $\mathcal{D}[\langle\vec{v}\rangle] \approx 1$.
- Decrease of $\mathcal{D}[\vec{v}]$ at $t \sim 3.5 - 4.5$ fm/$\mathbb{c}$.

  Will be considered in the talk

- $\mathcal{D}[\langle\vec{\omega}\rangle]$ is significantly lower than $\mathcal{D}[\langle\vec{v}\rangle]$, in particular at $t \sim 3 - 4$ fm/$\mathbb{c}$.

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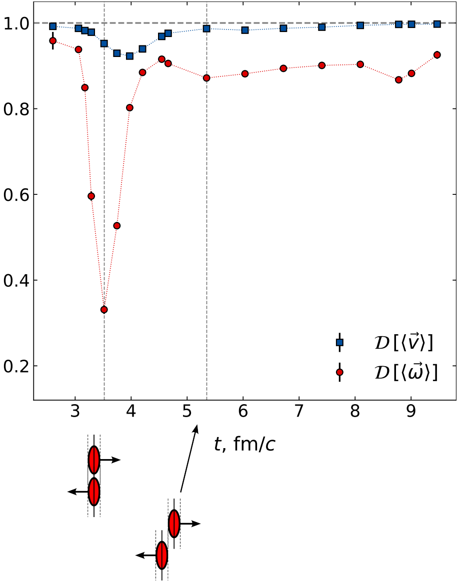
Correlations



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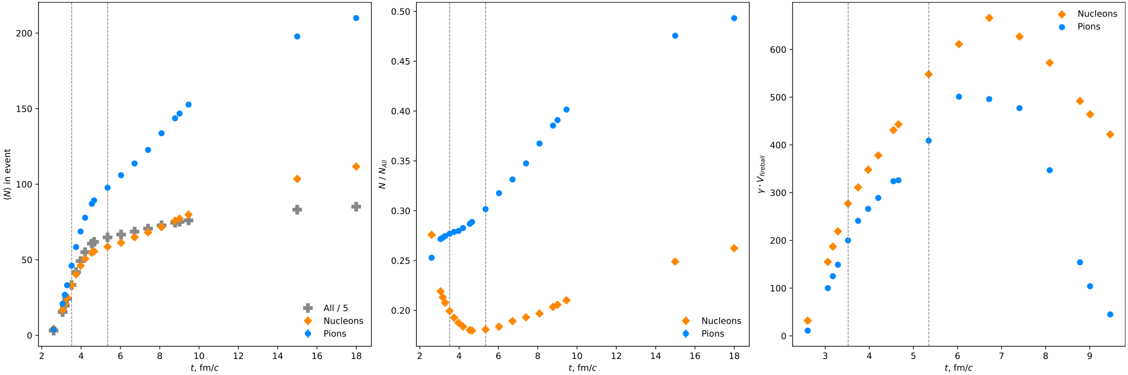
Evolution of multiplicities and volume of the fireball



Contributions of different components

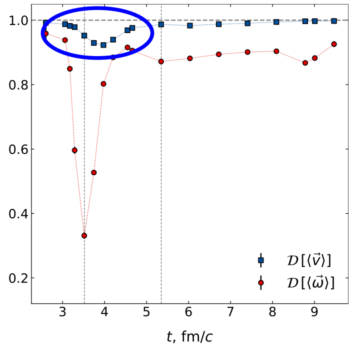
$$\mathcal{D}[\vec{v}_\pi, \vec{v}_N] = \frac{1}{G}\int \vec{v}_\pi \cdot \vec{v}_N \, \mathrm{d}V \qquad \mathcal{D}_i[\vec{v}_\pi, \vec{v}_N] = \frac{1}{G}\int (v_\pi)_i \cdot (v_N)_i \, \mathrm{d}V \qquad G = \sqrt{\int (\vec{v}_\pi)^2 \mathrm{d}V \cdot \int (\vec{v}_N)^2 \, \mathrm{d}V}$$

t, fm/c	$\mathcal{D}[\vec{v}]$	$\mathcal{D}_x[\vec{v}]$	$\mathcal{D}_y[\vec{v}]$	$\mathcal{D}_z[\vec{v}]$	$\mathcal{D}[\vec{\omega}]$	$\mathcal{D}_x[\vec{\omega}]$	$\mathcal{D}_y[\vec{\omega}]$	$\mathcal{D}_z[\vec{\omega}]$
2.6	0.9922	-0.0002	0.0054	0.9869	0.9586	0.0032	0.9559	-0.0006
3.06	0.9875	0.0046	0.0031	0.9798	0.9381	0.0319	0.9062	-0.00003
3.17	0.9823	0.0051	0.0027	0.9745	0.8492	0.0661	0.7828	0.0003
3.3	0.9785	0.0061	0.0037	0.9687	0.5961	0.1270	0.4686	0.0005
3.52	0.9522	0.0086	0.0064	0.9372	0.3563	0.2737	0.0824	0.0002
3.75	0.9293	0.0101	0.0064	0.9129	0.5270	0.2785	0.2483	0.0002
3.97	0.9228	0.0108	0.0065	0.9055	0.8024	0.2506	0.5517	0.0001
4.20	0.9395	0.0093	0.0059	0.9243	0.8846	0.1849	0.6998	-0.0001
4.55	0.9687	0.0091	0.0056	0.9540	0.9155	0.1197	0.7957	0.00004
4.66	0.9759	0.0093	0.0045	0.9621	0.9056	0.1068	0.7988	-0.0001
5.35	0.9868	0.0139	0.0074	0.9655	0.8717	0.1370	0.7335	0.0012
6.03	0.9832	0.0228	0.0163	0.9447	0.8815	0.2291	0.6594	0.0032
6.72	0.9876	0.0256	0.0150	0.9470	0.8941	0.2599	0.6318	0.0024
7.4	0.9902	0.0228	0.0155	0.9519	0.9010	0.2079	0.6917	0.0014
8.09	0.9944	0.0109	0.0075	0.9759	0.9035	0.2440	0.6596	-0.0001
8.78	0.9967	0.0055	0.0023	0.9889	0.8674	0.1936	0.6755	-0.0017
9.01	0.9970	0.0048	0.0014	0.9908	0.8824	0.1524	0.7325	-0.0024
9.47	0.9974	0.0028	0.0008	0.9938	0.9256	0.1374	0.7911	-0.0029

$\mathcal{D}[\vec{v}] \approx \mathcal{D}_z[\vec{v}]$

$\mathcal{D}_z[\vec{\omega}] \approx 0$; proportion $\mathcal{D}_y[\vec{\omega}]/\mathcal{D}_x[\vec{\omega}]$ changes with time

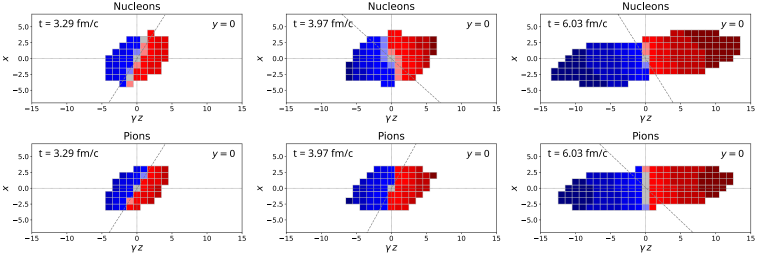
The dip in D[V] (qualitatively)



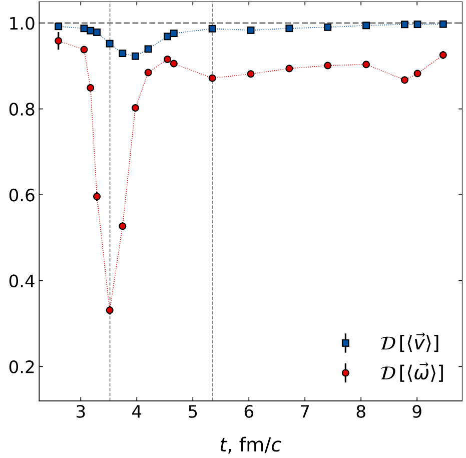
About the time of the maximal overlap,
the surface $v_z = 0$ rotates around y axis.

This happens asynchronously for pions and nucleons.

Spatial distribution of v_z:



DIFFERENCE IN DEPENDENCIES



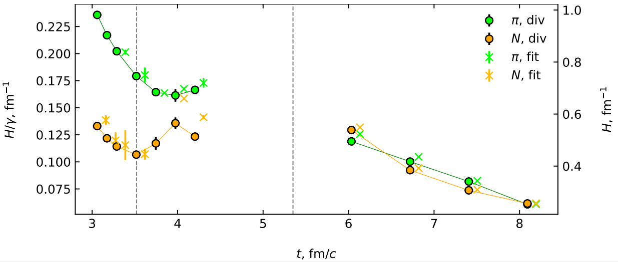
A guess: there is a contribution in $\vec{v}$ not influencing $\mathrm{rot}\,\vec{v}$

$\Downarrow$

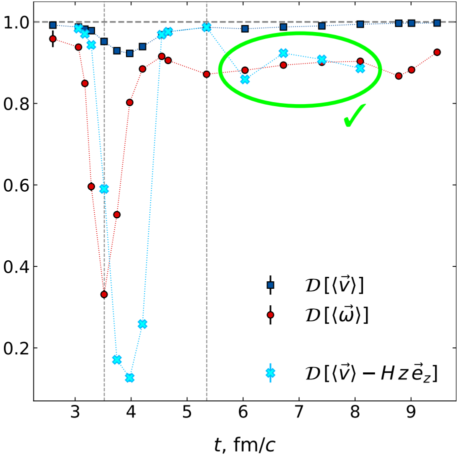
'microscopic' Hubble flow

The idea: subtract the Hubble contribution from $\vec{v}$ and look at the correlations of the residuals

[Just v_z components are considered]



Difference in dependencies: subtraction of H



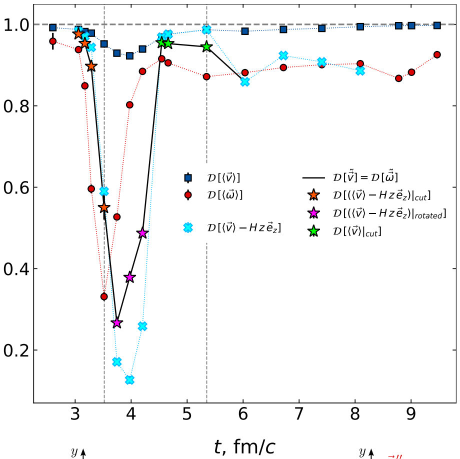
For $t > 6$ fm/c

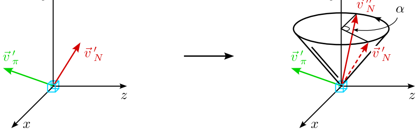
$$\mathcal{D}[\vec{v} - H\, z\vec{e}_z] \approx \mathcal{D}[\vec{\omega}]$$

$$\Downarrow$$

At $t > 6$ fm/c the enhancement of $\mathcal{D}[\vec{v}]$ is due to the Hubble contribution to the velocities

Difference in dependencies: the final result





※ Subtraction of the linear contribution + simultaneous cut on ω_x and ω_y:

$$|\omega_x| > \varkappa_x \langle|\omega_x|\rangle \text{ and} |\omega_y| > \varkappa_y \langle|\omega_y|\rangle \quad (6)$$

t, fm/c	3.06	3.17	3.30	3.52
$\varkappa_x$	0	0.001	0.01	0.96
$\varkappa_y$	0.97	1.11	0.82	0
$V_{\text{used}}/V_{\text{total}}$	0.48	0.30	0.42	0.29

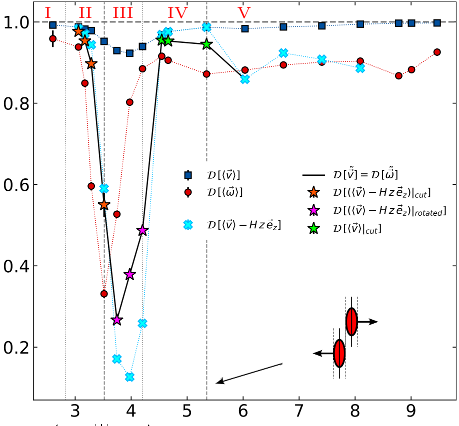
※ The cut Eq. (6) (the Hubble constant couldn't be got here)

t, fm/c	4.55	4.66	5.35
$\varkappa_x$	0.02	0	0
$\varkappa_y$	0.58	0.64	0.98
$V_{\text{used}}/V_{\text{total}}$	0.66	0.65	0.35

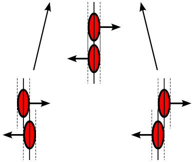
※ Subtraction of the linear contribution + rotation of the field $\vec{v}_N$ around y-axis until $\mathcal{D}[\langle\vec{v}'_N\rangle, \langle\vec{v}_\pi\rangle] = \mathcal{D}[\langle\vec{\omega}'_N\rangle, \langle\vec{\omega}_\pi\rangle]$

t, fm/c	3.75	3.97	4.20
α	0.26	0.57	0.52

DIFFERENCE IN DEPENDENCIES: THE FINAL RESULT



t, fm/c



- In accordance with the origin of the difference between $\mathcal{D}[\vec{v}_\pi, \vec{v}_N]$ and $\mathcal{D}[\vec{\omega}_\pi, \vec{\omega}_N]$, the considered time interval may be divided by 5 stages. They correspond to the different stages of the collision.

- For the all stages, except of IV-th one, the influence of the Hubble expansion is significant.

  For the V-th stage, the Hubble expansion is only one reason of the difference.

- In the III-rd stage, the influence of non-parallelism of $\vec{v}_\pi$ and $\vec{v}_N$ is noticeable.

- At the stages II and IV, the regions with small values of the vorticity significantly decrease $\mathcal{D}[\vec{\omega}_\pi, \vec{\omega}_N]$.

Note: the intermediate states I-II and III-IV are also useful

CONCLUSIONS

- The high correlation of velocities of pions and nucleons is obtained.
- The main contribution to the $\mathcal{D}[\vec{v}]$ comes from the longitudinal components of the velocities.
- The lowering of $\mathcal{D}[\vec{v}]$ at times around the moment of maximal overlapping of the nuclei is connected with rotation of the surface $v_z = 0$ around the y-axes.
- The significant difference between time dependencies of $\mathcal{D}[\vec{v}]$ and $\mathcal{D}[\vec{\omega}]$ is explained:
  - $\mathcal{D}[\vec{v}]$ is highly enhanced with the Hubble contribution to the velocity.
  - the regions with small vorticity decrease $\mathcal{D}[\vec{\omega}]$.
  - around the time of the maximal overlapping, the different orientation of the $v_z = 0$ surfaces for pions and nucleons significantly influences $\mathcal{D}[\vec{v}]$.

After the time of the last touch of nuclei, the standard hydrodynamics is applicable, before that moment more sophisticated approaches should be used