Multiplicity fluctuations and collective flow in small colliding systems

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Collectivity in small systems

Purpose of this study

Analysis of collectivity in small colliding systems from an integrated dynamical model

Mass ordering for identified hadrons

Consistent with hydrodynamic flow picture


P. Bozek, W. Broniowski, P. Romatschke, K. Werner, B. Schenke, R. Venugopalan, G. Y. Qin, ....

*Caveat: Mass ordering without flow

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1. Initial state
   MC Glauber model + PYTHIA

2. QGP fluid
   Fully (3+1) dimensional viscous hydrodynamics

3. Particlization
   Cooper-Frye formula

4. Hadron gas
   Hadron cascade (JAM)

Integrated dynamical model

Integrated dynamical model

- **1. Initial state**
  - MC Glauber model + PYTHIA

- **2. QGP fluid**
  - Fully (3+1) dimensional viscous hydrodynamics

- **3. Particlization**
  - Cooper-Frye formula

- **4. Hadron gas**
  - Hadron cascade (JAM)

Asymmetric longitudinal profile

Rapidity triangle/trapezoid clearly observed in d+Au collision at RHIC

Modified BGK model

Number of participants \((N_A, N_B)\) from MC-Glauber model

Hadronic string formation

\(-Y_{\text{beam}} \leftrightarrow \text{rapidity} \rightarrow Y_{\text{beam}}\)


Rapidity dependence

One string formation

\[ Y \]
Rapidity dependence

Rapidity distribution in a pp collision at 200 GeV

PYTHIA
Rapidity dependence

Rapidity distribution in a pp collision at 200 GeV

\( \frac{dN_{pp}}{dY} \)

\(-Y_{\text{beam}} \leftrightarrow \text{rapidity} \rightarrow Y_{\text{beam}}\)
Rapidity dependence

Rapidity distribution in a pp collision at 200 GeV

Fluctuations of multiplicity and longitudinal profile
Initial profile

Particles generated by PYTHIA

Each particle associated with Gaussian function

Initial entropy density distributions

Transverse profile \((\eta_s = 0)\)
Setting

◆ Collision systems: p/d/\(^3\)He+Au at \(\sqrt{s_{NN}} = 200\) GeV (RHIC)
  p+Pb at \(\sqrt{s_{NN}} = 5.02\) TeV (LHC)

◆ Initial conditions: MC Glauber model + PYTHIA

◆ Viscous hydrodynamics:
  - EoS: s95p-v1.1
    \[
    \begin{align*}
    \text{Lattice QCD (HotQCD)} \\
    \text{Resonance gas (JAM)}
    \end{align*}
    \]
  - Shear viscosity: \(\eta/s = 1/4\pi\)  
    - Initial time: \(\tau_0 = 0.6\) [fm]

◆ Cooper-Frye formula:
  Switching temperature \(T_{sw} = 155\) [MeV]

◆ Hadron cascade: JAM
Viscous hydrodynamic simulations

$d+Au$ 200 GeV

$T = 155$ MeV

$^3He+Au$ 200 GeV

$T = 155$ MeV
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Multiplicity distributions

The larger colliding nucleus, the higher multiplicity

- Fluctuations of multiplicity
- Utilization for centrality cut
Pseudorapidity distributions

**LHC**

- min. bias

**ALICE**

- \( p+Pb \)

**RHIC**

- PHOBOS \( p+Au \)
- \( d+Au \)
- \( ^3He+Au \)

**Rapidity triangle/trapezoid picture works quite well**

$p_T$ distributions

Reasonable description of transverse dynamics

Flow harmonics vs $p_T$ in $d/^{3}\text{He}+\text{Au}$

QGP fluid + hadronic gas picture works in $d/^{3}\text{He}+\text{Au}$ collisions

$v_2$ vs $p_T$ in p+A

Smaller than experimental results

Need a sophisticated model in p+A collisions

$v_2$ vs pseudorapidity

Asymmetric shape of $v_2(\eta)$
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Summary

◆ Analysis of flow observables in small colliding systems at LHC and RHIC energy

◆ Development of a new hydrodynamic initialization model based on MC-Glauber + PYTHIA

QGP fluid + hadronic gas picture works in d/$^{3}$He+Au collisions

Our results smaller than experimental data in p+A collisions
Back up
Event generator PYTHIA8

\[
\frac{dN_{\text{ch}}}{d\eta} \\
\eta
\]

\[
N_{\text{event}} \\
N_{\text{ch}}
\]

PYTHIA work very well at the RHIC energy

Initial entropy density

\[ s_0(\tau_0, \eta_s, x_\perp) = \frac{K}{\tau_0} \sum_i \frac{1}{\sqrt{2\pi \sigma_\eta^2}} \frac{1}{2\pi \sigma_\perp^2} \exp \left[ -\frac{(x - x^i)^2 + (y - y^i)^2}{2\sigma_\perp^2} - \frac{(\eta_s - \eta_s^i)^2}{2\sigma_\eta^2} \right] \]

\[ \tau_0 = 0.6 \text{ [fm]} \]

\[ \sigma_\perp = 0.1 \text{ [fm]} \]

\[ \sigma_\eta = 0.3 \]

\[ \eta_s^i \text{ from MC Glauber + PYTHIA} \]

\[ K = 5.6 \text{ for RHIC energy} \]

\[ = 5.0 \text{ for LHC energy} \]

\[ x^i, y^i, \eta_s^i \]
Rejection sampling

One AA event
\[ \rightarrow N_A \times N_B \text{ PYTHIA events} \]

Weight in one PYTHIA event
\[ w(\eta) = \frac{1}{2} \left( \frac{Y_b + \eta}{Y_b} \frac{1}{N_A} + \frac{Y_b - \eta}{Y_b} \frac{1}{N_B} \right) \]

\[ N_A N_B w(\eta) = \begin{cases} N_A & (\eta = -Y_b) \\ N_B & (\eta = Y_b) \end{cases} \]
Initial profile at RHIC

Transverse profile \((\eta_s = 0)\)

Longitudinal profile \((x = 0 \text{ [fm]})\)
$\nu_2$ vs centrality

Increase of $\nu_2$ with multiplicity
Hadron cascade effects in d+Au

Large fraction of $v_2$ generated in QGP fluid
Hadron cascade effects in $^3\text{He}+\text{Au}$

Large fraction of $v_2$ generated in QGP fluid