Measurement of elliptic and triangular flow of light (anti-)nuclei with ALICE at the LHC

The 18th International Conference on Strangeness in Quark Matter (SQM 2019) - Bari (Italy)

June 13, 2019

Alberto Calivà for the ALICE Collaboration

GSI Helmholtzzentrum für Schwerionenforschung GmbH
Production mechanism of light (anti-)nuclei in high-energy heavy-ion collisions is still not understood

Two phenomenological models are typically used:

- **Statistical hadronization** model
- **Coalescence** approach
Production mechanism of light (anti-)nuclei in high-energy heavy-ion collisions is still not understood

Two phenomenological models are typically used:

- **Statistical hadronization** model
- **Coalescence** approach

**Azimuthal flow of light (anti-)nuclei is a key observable to study their production mechanism**

**Coalescence**: flow of light (anti-)nuclei connected to that of individual nucleons

- Mass number scaling (simplistic picture)
- Phase-space distributions of nucleons used to calculate flow of (anti-)nuclei in a more sophisticated approach
Production mechanism of light (anti-)nuclei in high-energy heavy-ion collisions is still not understood.

Two phenomenological models are typically used:

- **Statistical hadronization** model
- **Coalescence** approach

**Coalescence**: flow of light (anti-)nuclei connected to that of individual nucleons

- Mass number scaling (simplistic picture)
- Phase-space distributions of nucleons used to calculate flow of (anti-)nuclei in a more sophisticated approach

Flow of light (anti-)nuclei could be described by **hydrodynamics**

- Only simplified approach (Blast-Wave) is available
The ALICE setup and data sample

**ITS (Inner Tracking System)**
- Tracking, vertexing & PID (via dE/dx in silicon)

**TPC (Time Projection Chamber)**
- Tracking & PID (via dE/dx in the gas)

**TOF (Time Of Flight)**
- PID (via TOF measurement)

**V0**
- Centrality and event plane measurements

Data set:
Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

<table>
<thead>
<tr>
<th>Number of events ($\times 10^6$)</th>
<th>Observable</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>$\nu_2$ of (anti-)deuterons</td>
</tr>
<tr>
<td>48</td>
<td>$\nu_3$ of (anti-)deuterons</td>
</tr>
<tr>
<td>60</td>
<td>$\nu_2$ of (anti-)$^3$He</td>
</tr>
</tbody>
</table>
(Anti-)\(^3\)He identification based on the dE/dx measured by the TPC

Negligible contamination from (anti-)\(^4\)He

- \(^4\)He/\(^3\)He ~1/300 in Pb-Pb collisions at \(\sqrt{s_{NN}} = 2.76\) TeV (NPA 971 (2018) 1-20)
- Similar suppression is expected in Pb-Pb collisions at \(\sqrt{s_{NN}} = 5.02\) TeV

\((\text{anti-})\(^3\)H\) contamination relevant only for \(p_T < 3\) GeV/c

\((\text{anti-})\(^3\)H\) contribution estimated using a Gaussian fit

Signal extraction in the range \(|dE/dx - \langle dE/dx \rangle_{\text{He}}| < 3\sigma\)
\( p_T < 1 \text{ GeV}/c: \)

The dE/dx measured by the TPC is used requiring \(|dE/dx - <dE/dx>_d| < 3\sigma\)
(Anti-)deuteron identification

\[ p_T < 1 \text{ GeV}/c: \]
The \( dE/dx \) measured by the TPC is used requiring \(|dE/dx - <dE/dx>_d| < 3\sigma\)

\[ p_T > 1 \text{ GeV}/c: \]
- TPC pre-selection (\(|dE/dx - <dE/dx>_d| < 3\sigma\))
- Signal extraction using the \( \Delta M = M - M_d \) measured by TOF (background from TPC-TOF mismatch)
Analysis technique for the (anti-)\(^3\)He \(v_2\)

Elliptic flow of \(^3\)He measured using the Event Plane (EP) method

\[
v_2\{\text{EP, } |\Delta \eta| > 0.9\} (p_T) = \frac{\pi}{4R_{\psi_2}} \frac{N_{\text{in-plane}} (p_T) - N_{\text{out-of-plane}} (p_T)}{N_{\text{in-plane}} (p_T) + N_{\text{out-of-plane}} (p_T)}
\]

The symmetry plane of the collision is measured using the V0 detectors:
- V0A: \(-3.7 < \eta < -1.7\)
- V0C: \(2.8 < \eta < 5.1\)

Event plane resolution of the 2\(^{\text{nd}}\) harmonic measured using the three sub-events method

\[
R_{\psi_2} = \sqrt{\left< \cos \left( 2 \left( \psi_2^A - \psi_2^B \right) \right) \right> \cdot \left< \cos \left( 2 \left( \psi_2^A - \psi_2^C \right) \right) \right> \over \left< \cos \left( 2 \left( \psi_2^B - \psi_2^C \right) \right) \right>}
\]

\[
\begin{align*}
A & = \text{V0} \\
B & = \text{TPC (}\eta > 0\text{)} \\
C & = \text{TPC (}\eta < 0\text{)}
\end{align*}
\]
Analysis technique for the (anti-)d $v_2$ & $v_3$

Elliptic and triangular flow of (anti-)deuterons measured using the Scalar Product (SP) method

$$v_n\{SP\} = \frac{\langle \langle u_n,k Q_n^* \rangle \rangle}{\sqrt{\langle Q_n^A Q_n^B \rangle \langle Q_n^A Q_n^B \rangle}}$$

$$v_n^{tot}(\Delta M) = \frac{v_n^{sig}(\Delta M) N^{sig}(\Delta M) + v_n^{bkg}(\Delta M) N^{bkg}(\Delta M)}{N^{sig}(\Delta M) + N^{bkg}(\Delta M)}$$

Signal extraction:

- $N_{sig}$ and $N_{bkg}$ extracted from the fit of (anti-)deuteron yield vs. $\Delta M = M - M_d$
- $v_n^{bkg}$ described using a linear function
- $v_n^{sig}$ extracted from the fit of $v_n^{tot}$
Centrality & $p_T$ dependence of $v_2$ and $v_3$

$v_2$ of (anti-)deuterons and (anti-)$^3$He:

- Centrality & $p_T$ dependence as expected from relativistic hydrodynamics
Centrality & $p_T$ dependence of $v_2$ and $v_3$

- $v_2$ of (anti-)deuterons and (anti-)$^3$He:
  - Centrality & $p_T$ dependence as expected from relativistic hydrodynamics

- $v_3$ of (anti-)deuterons:
  - First measurement
  - Effects of initial state fluctuations of energy density in the colliding nuclei visible also for (anti-)deuterons
Mass ordering at low $p_T$ & slower rise for heavier particles

➢ as expected from relativistic hydrodynamics
$v_3$ of (anti-)deuterons vs. $v_3$ of $\pi$, $K$ and $p$

(Anti-)deuteron $v_3$ increases with $p_T$ and going from central to peripheral collisions

Centrality & $p_T$ dependence of the (anti-)deuteron $v_3$ consistent with expectations based on the $v_3$ of identified hadrons

- Mass ordering is observed at low $p_T$
Scaling of $v_2$ with the number of constituent quarks ($n_q$):

- Baryons show an approximate scaling vs. $p_T/n_q$
  - However, deviations up to 50% are observed
- Mesons and baryons show approximate scaling vs. $E_T^{\text{kin}}/n_q$
Scaling of $v_2$ with the mass number $A$ (simple coalescence approach) is violated in all centrality ranges.

The measured $v_2$ is overestimated by the predictions from simple coalescence.

- smaller deviations in more peripheral collisions
A-scaling of \( v_3 \) of (anti-)deuterons

Mass number scaling seems to be approximately valid for \( v_3 \)
The uncertainties are larger however …
Blast-Wave (BW) predictions for the (anti-)deuteron $v_2$ from combined fits of $v_2$ and $p_T$-spectra of $\pi, K, p$ in the $p_T$ ranges:

- Closer to the data in more central collisions
- Deviations in more peripheral collisions

\[
\begin{align*}
\pi: & \quad p_T \in [0.7, 1.5] \text{ GeV/c} \\
K: & \quad p_T \in [0.7, 2.0] \text{ GeV/c} \\
p: & \quad p_T \in [1.0, 2.5] \text{ GeV/c}
\end{align*}
\]
$v_2$ of (anti-)deuterons vs. Blast-Wave

**Blast-Wave (BW)** predictions for the (anti-)deuteron $v_2$ from combined fits of $v_2$ and $p_T$-spectra of $\pi, K, p$ in the $p_T$ ranges:

- Closer to the data in more central collisions
- Deviations in more peripheral collisions

BW describes (anti-)deuteron $v_2$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in 0-40% collisions.

\[\begin{align*}
\pi: & \quad p_T \in [0.7, 1.5] \text{ GeV/c} \\
K: & \quad p_T \in [0.7, 2.0] \text{ GeV/c} \\
p: & \quad p_T \in [1.0, 2.5] \text{ GeV/c}
\end{align*}\]
$v_2$ of (anti-)$^3$He lies between the Blast-Wave and simple coalescence predictions in all centrality ranges

- Consistent with the deuteron $v_2$ measurement and RHIC results
$v_2$ & $v_3$ vs. iEBE-VISHNU + Coalescence

Coalescence model with phase space distributions of nucleons generated by iEBE-VISHNU (PRC 98, 054905 (2018)):

- AMPT initial conditions
- (1+2)d hydro (VISHNU) + UrQMD

- good description of the data in 0-40%
- no predictions for more peripheral collisions
First measurement of the (anti-)deuteron $v_3$

- Effects of initial-state fluctuations seen for (anti-)deuterons
- $p_T$ & centrality dependence consistent with identified hadrons
First measurement of the (anti-)deuteron $v_3$

- Effects of initial-state fluctuations seen for (anti-)deuterons
- $p_T$ & centrality dependence consistent with identified hadrons

- Simplified hydro (BW) underestimates $v_2$ of (anti-)deuterons and (anti-)${}^3$He
  - Closer to the data in more central collisions

- Classical coalescence (based on $A$-scaling) overestimates the $v_2$ of (anti-)deuterons and (anti-)${}^3$He
  - Closer to the data in more peripheral collisions
Summary

First measurement of the (anti-)deuteron $\nu_3$

- Effects of initial-state fluctuations seen for (anti-)deuterons
- $p_T$ & centrality dependence consistent with identified hadrons

- Simplified hydro (BW) underestimates $\nu_2$ of (anti-)deuterons and (anti-)${}^3$He
  - Closer to the data in more central collisions

- Classical coalescence (based on $A$-scaling) overestimates the $\nu_2$ of (anti-)deuterons and (anti-)${}^3$He
  - Closer to the data in more peripheral collisions

- State-of-the-art coalescence + iEBE-VISHNU describes our data in 0-40%
First measurement of the (anti-)deuteron $v_3$

- Effects of initial-state fluctuations seen for (anti-)deuterons
- $p_T$ & centrality dependence consistent with identified hadrons

- Simplified hydro (BW) underestimates $v_2$ of (anti-)deuterons and (anti-)${}^3$He
  - Closer to the data in more central collisions
- Classical coalescence (based on A-scaling) overestimates the $v_2$ of (anti-)deuterons and (anti-)${}^3$He
  - Closer to the data in more peripheral collisions

- State-of-the-art coalescence + iEBE-VISHNU describes our data in 0-40%
- What about full hydrodynamics? ....
Summary

First measurement of the (anti-)deuteron $v_3$

- Effects of initial-state fluctuations seen for (anti-)deuterons
- $p_T$ & centrality dependence consistent with identified hadrons

- Simplified hydro (BW) underestimates $v_2$ of (anti-)deuterons and (anti-)${}^3\text{He}$
  - Closer to the data in more central collisions

- Classical coalescence (based on $A$-scaling) overestimates the $v_2$ of (anti-)deuterons and (anti-)${}^3\text{He}$
  - Closer to the data in more peripheral collisions

- State-of-the-art coalescence + iEBE-VISHNU describes our data in 0-40%
- What about full hydrodynamics? ....

Thank you for your attention!
Backup slides
Blast-wave predictions of the (anti-)deuteron $p_T$-spectra

ALICE

$\text{Pb-Pb } \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$

0-10%

10-20%

20-40%

Blast-wave predictions of the (anti-)deuteron $v_2$