Measurement of the deuteron coalescence probability in jets with ALICE

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Physics motivation

- Light (anti)nuclei are produced in high-energy hadronic collisions at the LHC
- Matter and antimatter are produced in (almost) the same amount at midrapidity
- Their production mechanism is still not understood
- Two phenomenological models:
  - Statistical hadronization
  - Coalescence
Physics motivation

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Focus on it
Coalescence model

S. T. Butler et al., Phys. Rev. 129 (1963) 836

- If (anti)nucleons are close in phase space and match the spin state, they can form an (anti)nucleus

- Coalescence parameter $B_A$ is the key observable:

\[
E_A \frac{d^3N_A}{dp_A^3} = B_A \left( E_p \frac{d^3N_p}{dp_p^3} \right)^A \quad p_p = p_A/A
\]

- Coalescence parameter depends on both the source size and radial extension of the nucleus wave function:

Small source size $\rightarrow$ Large $B_A$

- pp $\sim$ 1 fm
- p–Pb $\sim$ 1.5 fm

Large source size $\rightarrow$ Small $B_A$

- Pb–Pb $\sim$ 3-6 fm
The study in small systems, such as pp and p–Pb, is interesting since the nucleons are closer in phase space wrt Pb–Pb.

Leading particle (highest $p_T$ and $p_T > 5 \text{ GeV/c}$) used as a proxy for the jet axis.

CDF technique used to find the three azimuthal regions:

- **Toward** ($|\Delta\phi| < 60^\circ$): contains JET and UE
- **Transverse** ($60^\circ < |\Delta\phi| < 120^\circ$): dominated by the Underlying Event (UE)
- **Away** ($|\Delta\phi| > 120^\circ$): contains recoil jet and UE

**Jet:** Toward – Transverse
The ALICE detector in Run 2

- Most suited LHC experiment to study light (anti)nuclei production
- Excellent PID capabilities

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The ALICE detector in Run 2

**Inner Tracking System (ITS)**
- Tracking, vertex, PID

**Time Of Flight (TOF)**
- Tracking, vertex, PID
- PID via time-of-flight

**Time Projection Chamber (TPC)**
- Tracking, PID via dE/dx

**V0**
- Trigger, multiplicity

- Most suited LHC experiment to study light (anti)nuclei production
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References:

- JINST 3 (2008) S08002
Deuteron identification

Low $p_T$ region (below 1 GeV/c): PID via $dE/dx$

$$\sigma_{dE/dx} \sim 5.5\% \text{ in } pp, \sim 7\% \text{ in } Pb-Pb$$

High $p_T$ region (over 1 GeV/c): PID via time-of-flight

$$\sigma_{\text{PID}} \sim 70 \text{ ps for } pp, \sim 60 \text{ ps for } Pb-Pb$$
(Anti)deuteron spectra: pp @ 13 TeV

Deuteron production in events with $p_T^{\text{lead}} > 5 \text{ GeV/c}$

The results are consistent with those obtained using the two-particle correlation method.

arXiv:2211.15204v1
Deuteron production in events with $p_T^{\text{lead}} > 5 \text{ GeV/c}$

$\frac{1}{N_{\text{evt}}} d^2N/dp_T dy$ (GeV/c)$^2$

Jet = Toward - Transverse

ALICE Preliminary

$p-$Pb, $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$

$\frac{(d+\bar{d})}{2}$

- Away
- Transverse $\times 2$
- Toward $\times 2$
- Lévy-Tsallis fit

ALICE Preliminary

$p-$Pb, $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$

$\frac{(d+\bar{d})}{2}$

- in-jet
- Lévy-Tsallis fit
Antiproton spectra: p–Pb @ 5.02 TeV

Antiproton production in events with $p_T^{\text{lead}} > 5$ GeV/c

$\text{Jet} = \text{Toward} - \text{Transverse}$

ALICE Preliminary
$p\text{-Pb, } \sqrt{s_{NN}} = 5.02 \text{ TeV}$

$1/N_{\text{ext}} (d^2N/dp_T dy)$ (GeV/c)$^2$
Enhancement of $B_2$ jet wrt $B_2$ UE in pp collisions

\[ B_2 = \left( \frac{1}{(2\pi/3)p_T^d} \left( \frac{d^2N}{dydp_T^d} \right)_d \right)^2 \left( \frac{1}{(2\pi/3)p_T^p} \left( \frac{d^2N}{dydp_T^p} \right)_p \right) \]

- Enhancement of $B_2^{\text{jet}}$ wrt $B_2^{\text{UE}}$ in pp collisions

pp, $\sqrt{s} = 13$ TeV

$\rho_T^{\text{lead}} > 5$ GeV/c

ARICLE

arXiv:2211.15204v1

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Hard Probes 2023 - 28/03/2023
$B_2$ in jet and UE

$B_2 = \frac{1}{(2\pi/3)p_T^d} \left( \frac{d^2N}{dydp_T} \right)_{d} \frac{1}{(2\pi/3)p_T^p} \left( \frac{d^2N}{dydp_T} \right)_{p}$

- Enhancement of $B_2^{\text{jet}}$ wrt $B_2^{\text{UE}}$ in pp collisions
- What happens in p–Pb collisions?
\[ B_2 = \frac{1}{(2\pi/3)p_T^{\text{d}}}(\frac{d^2N}{dydp_T})_{\text{d}}^2 \]

- Enhancement of \( B_2^\text{jet} \) wrt \( B_2^\text{UE} \) in pp collisions
- What happens in p–Pb collisions?
- Enhancement factor is larger wrt pp collisions
\( B_2 \) in jet and UE

- Enhancement of \( B_2^{\text{jet}} \) wrt \( B_2^{\text{UE}} \) in pp collisions
- What happens in p–Pb collisions?
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\[ B_2 = \frac{1}{(2\pi/3)p_T^d} \left( \frac{d^2N}{dy dp_T} \right)_{d} \]

\( B_2^{\text{UE}}(p-Pb) < B_2^{\text{UE}}(pp) \) since p–Pb source size is larger than pp source size
$B_2$ in jet and UE

Assuming the same source size for nucleons in jet, nucleons are probably closer in momentum space in $p$–Pb wrt pp since $p$–Pb source size is larger than pp source size.

- Enhancement of $B_2^{\text{jet}}$ wrt $B_2^{\text{UE}}$ in pp collisions
- What happens in $p$–Pb collisions?
- Enhancement factor is larger wrt pp collisions

$B_2^{\text{jet}} (p$–$Pb) > B_2^{\text{jet}} (pp)$

$B_2^{\text{UE}} (p$–$Pb) < B_2^{\text{UE}} (pp)$ since $p$–Pb source size is larger than pp source size

Assuming the same source size for nucleons in jet, nucleons are probably closer in momentum space in $p$–Pb wrt pp

\[
B_2 = \frac{1}{(2\pi/3)p_T^d} \left( \frac{d^2N}{dydp_T} \right)_d \left( \frac{1}{(2\pi/3)p_T^p} \left( \frac{d^2N}{dydp_T} \right)_p \right)^2
\]
**$B_2$ in jet and UE**

For the first time, we see some differences between jets in pp and p–Pb collisions.

- Difference related to particle composition?

\[
B_2 = \frac{1}{(2\pi/3) p_T^d} \left( \frac{d^2N}{dydp_T} \right)_d^2
\]

- Enhancement of $B_2^{\text{jet}}$ wrt $B_2^{\text{UE}}$ in pp collisions

- What happens in p–Pb collisions?

- Enhancement factor is larger wrt pp collisions

\[B_2^{\text{jet}} (p–Pb) > B_2^{\text{jet}} (pp)\]

\[B_2^{\text{UE}} (p–Pb) < B_2^{\text{UE}} (pp)\] since p–Pb source size is larger than pp source size

For the first time, we see some differences between jets in pp and p–Pb collisions

Difference related to particle composition?

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d/p in jet and UE

- \(d/p\) calculated as ratio of normalized spectra
- \(d/p\) _jet_ is higher than \(d/p\) _UE_

Higher \(d/p\) _jet_ in p–Pb collisions wrt pp collisions
- Different particle composition \(\rightarrow\) could affect the coalescence probability

\(\text{ALICE Preliminary}\)
\(p–\text{Pb}, \sqrt{s_{NN}} = 5.02\ \text{TeV}\)
\(p_T^{\text{lead}} > 5\ \text{GeV/c}\)

\(\text{in-jet}\)
\(\text{underlying event}\)
$B_2$ in jet and UE – model comparison

- Two different models:
  - PYTHIA 8 Monash 13 + simple coalescence

![Graph showing $B_2$ vs $p_T/A$ for different models.](image)
$B_2$ in jet and UE – model comparison

- Two different models:
  - PYTHIA 8 Monash 13 + simple coalescence
  - PYTHIA 8.3 with reaction-based deuteron production (Bierlich et al., arXiv:2203.11601)
B₂ in jet and UE – model comparison

- Two different models:
  - PYTHIA 8 Monash 13 + simple coalescence
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- Both models qualitatively reproduce the data and the large difference between B₂^{jet} and B₂^{UE}
**$B_2$ in jet and UE – model comparison**

- Two different models:
  - PYTHIA 8 Monash 13 + simple coalescence
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- Both models qualitatively reproduce the data and the large difference between $B_2^{\text{jet}}$ and $B_2^{\text{UE}}$

- Further comparison with models

**Graphs:**

- **Graph 1:**
  - $B_2$ vs $p_T/A$ for jet and UE features
  - Data compared to PYTHIA 8 Monash 13 + simple coalescence

- **Graph 2:**
  - $B_2$ vs $p_T/A$ for PYTHIA 8.3 with reaction-based deuteron production

**Data/Model Comparison:**

- $B_2$ values compared to underlying event predictions
- ARXIV:2211.15204v1

**Note:**

- marika.rasa@cern.ch
- Hard Probes 2023 - 28/03/2023
Summary

• Light (anti)deuteron production in three azimuthal regions in pp and p–Pb collisions

• Coalescence parameter in-jet and underlying event
  • Enhancement of $B_2^{\text{jet}}$ wrt $B_2^{\text{UE}}$ of a factor 15 (24) in pp (p–Pb) collisions

• Higher $B_2^{\text{jet}}$ in p–Pb collisions wrt pp collisions
  • Nucleons are probably closer in momentum space in p–Pb wrt pp

• Higher d/p ratio in p–Pb collisions wrt pp collisions for jets

• Good agreement with model comparison in pp collisions

• New investigation in Run 3 data

Thank you for the attention!
Statistical models

- Hadrons emitted from a system in statistical and chemical equilibrium
- $T_{\text{chem}}$ is the key parameter
- $dN/dy \propto \exp(-m/T_{\text{chem}})$
- Nuclei binding energy $\sim$ few MeV → how they can survive?
- Particle yield well described with a common $T_{\text{chem}}$ of $\sim 156$ MeV

(Advanced) coalescence model

- Wigner function formalism

\[ N_A = g_a \cdot \int d^3x_1 \ldots d^3x_A \cdot d^3k_1 d^3k_A \cdot f_1(x_1, k_1) \cdot f_A(x_A, k_A) \cdot W_A(x_1, \ldots, x_A, k_1, \ldots, k_A) \]

- Different Wigner density functions available:
  - Gaussian: standard one
  - Double gaussian
  - Hulthén: Yukawa-like potential
  - \( \chi \text{EFT} \): Chiral effective field theory
Coalescence parameter

- $B_A$ is rather flat in all multiplicity classes, but increase at high $p_T/A$ in the MB class.

Smooth evolution from small to large source size.
The ALICE detector in Run 2

Inner Tracking System (ITS)

Six concentrical layer of silicon sensors:

- 2 layers of Silicon Pixel Detectors (SPD);
- 2 layers of Silicon Drift Detectors (SDD);
- 2 layers of Silicon micro-Strip Detectors (SSD).
The ALICE detector in Run 2

Time Projection Chamber (TPC)

Cylindrical gas detector, made by a field cage filled with Ne/CO$_2$/N$_2$ (90/10/5). The cage is closed with two endcaps made of Multi-Wire Proportional Chambers (MWPC).

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The ALICE detector in Run 2

Time Of Flight (TOF)

90 modules formed by a system of 10 gaps double stack Multigap Resistive Plate Chambers (MRPC). The resistive plates are made with commercially available soda-lime glass sheets with a gap of 250 μm.

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The ALICE detector in Run 2

Formed by two different modules, V0A and V0C, consisting of two arrays of scintillator counters and Wave-Length Shifting (WLS) fibres installed on either sides of the interaction point.
Pythia simulation

• **PYTHIA 8.3:**
  - d production via ordinary reactions
  - Energy dependent cross sections parametrized based on data
  - Reactions:
    - $p + n \rightarrow \gamma + d$
    - $p + n \rightarrow \pi^0 + d$
    - $p + n \rightarrow \pi^0 + \pi^0 + d$
    - $p + n \rightarrow \pi^+ + \pi^- + d$
    - $n + n \rightarrow \pi^- + d$
    - $n + n \rightarrow \pi^- + \pi^0 + d$

• **PYTHIA 8 Monash:**
  - Simple coalescence
  - d is formed if $\Delta p < p_0$, with $p_0 = 285$ MeV/c