Highlights from ALICE

Igor Altsybeev (TUM) for the collaboration

28 November CPOD2022

Pb-Pb@5.36 TeV
Nov 18, 2022
## ALICE detector and datasets in Run 1&2

### Inner Tracking System (ITS)
- \(|\eta| < 0.9\), tracking + triggering + particle identification (PID)

### Time Projection Chamber (TPC)
- \(|\eta| < 0.8\), tracking + PID

### Time Of Flight (TOF)
- \(|\eta| < 0.8\), PID

### V0 detector
- two forward scintillator arrays, triggering + centrality

### Zero Degree Calorimeters
- centrality + triggering
  - minimum bias triggers
  - rare triggers (muons, EMCAL, PHOS, high mult pp, etc.)

### Runs 1&2 (2009-2018):

<table>
<thead>
<tr>
<th>System</th>
<th>Energy</th>
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<tbody>
<tr>
<td>pp</td>
<td>0.9, 2.76, 7, 8, 13 TeV</td>
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<tr>
<td>p–Pb</td>
<td>5.02, 8 TeV</td>
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<tr>
<td>Pb–Pb</td>
<td>2.76, 5.02 TeV</td>
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<tr>
<td>Xe–Xe</td>
<td>5.44 TeV</td>
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</table>
ALICE detector in Run 3 (2022-2025)

- **TPC**: new readout chambers with Gas Electron Multipliers (GEMs)
- **New Inner Tracking System (ITS-2)**: 7 layers, 10 m² silicon tracker based on MAPS (12 G pixels)
- **New Muon Forward Tracker (MFT)**: 5 planes of MAPS, forward vertexing for muons
- **New beampipe**: smaller diameter (36.4 mm), first detection layer at 20 mm
- **New Fast Integration Trigger (FIT)**: interaction trigger, online luminometer, forward multiplicity

- Better **vertexing** (central and forward)
- **Continuous readout** with Pb–Pb@50 kHz
- Statistics up to x50
News from ALICE at LHC Run 3

- **July 2022** – first pp collisions, operation at 10 kHz @13.6 TeV
- Later, ALICE was taking pp physics data at ~500 kHz
- pp 1-4 MHz tests (pp@4.5 MHz is equivalent to Pb–Pb@50 kHz)

1 time frame ~100 collisions
News from ALICE at LHC Run 3

13.6 pb\(^{-1}\) by Nov 1

\(~10^{10}\) pp events collected

300x increase wrt Run 2!

LHC RF down + TS2

Selection of high-multiplicity and rare events using software triggers with a selection factor of \(~10^{-3}\)

- Due to earlier shutdown of LHC in 2022, planned Pb–Pb run postponed to 2023
- But: Pb–Pb test beam 17-18 November

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Nov 18, 2022
first Pb–Pb collisions
at top energy 5.36 TeV!

Event displays: https://cds.cern.ch/record/2841865
Moving on to the results...

LHC operates at $\mu_B \approx 0$ MeV
$T_{pc} \approx T_{fo} = 156.5 \pm 3$ MeV
2\textsuperscript{nd} order cumulants of net-protons

- **baryon number conservation** leads to deviation from the Skellam baseline
- ALICE data suggest **long-range correlations** $\Delta y \sim \pm 2.5$ unit or longer $\rightarrow$ earlier in time
- EPOS-LHC agrees with ALICE data but HIJING deviates significantly
  - string fragmentation in HIJING conserves baryon number over $\Delta y \sim \pm 1$ unit
3rd order cumulants of net-protons

- Data agree with Skellam baseline “0” since $\mu_B$ is very close to 0 at LHC energies
- EPOS-LHC and HIJING deviate from 0 since $p/\bar{p}$ deviates from unity:
  - $1.025 \pm 0.004$ (EPOS-LHC), $1.008 \pm 0.002$ (HIJING)
Antideuteron number fluctuations

Coalescence vs Thermal model:
Both qualitatively describe deuteron production
→ New observables needed to distinguish nuclei synthesis

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Antideuteron number fluctuations

- Consistent with Poisson baseline and SHM
- Overpredicted by simple Coalescence model

\[ \rho_{\bar{d}d} = \frac{\langle n_{\bar{d}} - \langle n_{\bar{d}} \rangle \rangle \langle n_{d} - \langle n_{d} \rangle \rangle}{\sqrt{\kappa_{2\bar{d}}} \sqrt{\kappa_{2d}}} \]

- Negative correlation observed
- Rules out Coalescence with correlated production of nucleons (A)
- Qualitatively described by Coalescence with independent nucleons (B)
- Explained by Canonical Ensemble SHM
  - but smaller correlation volume compared to \( \kappa_{2}/\kappa_{1} \) of net-protons

Accepted by PRL
arXiv.2204.10166

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Centrality dependence of $\mu_B$ in Pb–Pb 5.02 TeV

Using particle-antiparticle ratios:

$$\frac{\bar{h}}{h} \propto \exp \left[ -2 \left( B + \frac{S}{3} \right) \frac{\mu_B}{T} - 2I_3 \frac{\mu_{I_3}}{T} \right]$$

- $T = 156.5 \pm 1.5$ MeV, fixed from SHM studies
- $\mu_B$ and $\mu_{I_3}$ as free fit parameters


- Most precise measurement in Pb–Pb at LHC
  - taking ratios allows to cancel uncertainties
  - 6x improvement in precision with respect to Run 1 estimate
- Small but non-zero $\mu_B \approx 0.7$ MeV at LHC energies

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Higher-order mean-\(p_T\) fluctuations in pp and Pb–Pb

Intensive skewness \(\sim\) independent of \(\langle N_{ch}\rangle\)

\[ \Gamma_{\langle p_T \rangle} = \frac{\langle \Delta p_i \Delta p_j \Delta p_k \rangle \langle \langle p_T \rangle \rangle}{\langle \Delta p_i \Delta p_j \rangle^2} \]


Kurtosis \(\sim 1/\langle N_{ch}\rangle\)

\[ \kappa_{\langle p_T \rangle} = \frac{\langle \Delta p_i \Delta p_j \Delta p_k \Delta p_l \rangle \langle \Delta p_i \Delta p_j \rangle^2}{\langle \Delta p_i \Delta p_j \rangle^4} \]

ALICE Preliminary

- Pb-Pb, \(\sqrt{s_{NN}} = 5.02\) TeV
- Xe-Xe, \(\sqrt{s_{NN}} = 5.44\) TeV
- pp, \(\sqrt{s} = 5.02\) TeV

Uncertainties: stat. (bars), sys. (boxes)

baselines: random sampling the \(p_T\) spectrum

- First measurement of skewness and kurtosis of \(\langle p_T \rangle\) in pp, Pb-Pb and Xe-Xe collision at LHC energies
- Values remain above the baselines indicating the correlations in the system, however, HIJING and PYTHIA seem to reproduce data

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Strongly intensive quantity $\Sigma$

- $\Sigma$ in Pb–Pb decreases with centrality, while $\Sigma$ in pp grows with multiplicity.
Strongly intensive quantity $\Sigma$

**Strongly intensive quantity $\Sigma$ does not depend on system volume and V.F.**

- $\Sigma$ in Pb–Pb decreases with centrality, while $\Sigma$ in pp grows with multiplicity
- The behavior in Pb-Pb is not reproduced by HIJING and EPOS-LHC
Longitudinal fluctuations in A–A

- probing asymmetric density of the fireball along $\eta$

First measurement of longitudinal coefficient in ALICE, qualitatively comparable to ATLAS

Universal multiplicity scaling $\sim 1/(dN_{ch}/d\eta)^\alpha$, $\alpha \sim 0.5$
Accessing the initial state via $v_n$ – mean $p_T$ correlations

$v_n \sim$ initial shape (eccentricity)
$[p_T] \sim$ initial size

Correlations:

$\rho(v_n^2, [p_T]) = \frac{\text{cov}(v_n^2, [p_T])}{\sqrt{\text{var}(v_n^2)\text{var}([p_T])}}$

- Study of the correlation between the shape of the fireball ($v_2$) and its size ($[p_T]$)
- New constraints on the nucleon size
  - IP-Glasma $\sim 0.4$ fm; v-USPhydro $\sim 0.5$ fm; Trajectum $\sim 0.7$ fm; JETSCAPE (TRENTo) $\sim 1.1$ fm
  - ALICE data agrees better with width $\sim 0.4$ fm, or transverse radius of 0.56 fm
Flow angle and flow magnitude fluctuations in Pb–Pb

\[ \vec{V}_n = v_n e^{in\Psi_n} \]

\( v_n \): anisotropic flow

\( \Psi_n \): flow symmetry plane angle

Probe flow magnitude fluctuations \( M_f^2 \) and flow angle fluctuations \( A_f^2 \) with multi-particle correlations:

\[
M_f^2 = \frac{\langle v_n^2 (p_T^a) v_n^2 \rangle}{\langle v_n^2 \rangle^2} \frac{\langle v_n^2 \rangle}{\langle v_n^2 \rangle} \]

\[
A_f^2 = \frac{\langle \cos n [\phi^a_1 + \phi^a_2 - \phi^a_3 - \phi^a_4] \rangle}{\langle \cos n [\phi^a_1 + \phi^a_2 - \phi^a_3 - \phi^a_4] \rangle} \approx \langle \cos 2n [\Psi_n (p_T^a) - \Psi_n] \rangle_w
\]

- Large deviations from unity, effect most pronounced at high \( p_T \)
- Comparison with theoretical models: observables are sensitive to initial state and the QGP properties
Observation of partonic flow in small collision systems

- Mass ordering at low $p_T$ region
- Baryon-meson splitting at intermediate $p_T$ region
- Also in pp!
- Mass ordering at low $p_T$ region
- Baryon-meson splitting at intermediate $p_T$ region
- Also in pp!

- Model comparison indicates partonic flow + coalescence in p–Pb and pp

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3-body femtoscopy correlations

- Measured 3-particle correlation functions deviate from lower-order contributions → hint to three-body effects
- N-N-N and N-N-Λ interactions for the EoS of neutron stars *D. Lonardoni et al., PRL 114, 092301 (2015)*

Accepted by EPI A
ALICE, arXiv:2206.03344 (2022)
Absorption of $^3\text{He}$ nuclei in matter

Measurements of antinuclei provide important input for astrophysics and dark-matter studies

- One of dominant production mechanisms is **DM annihilation** (e.g. $\chi + \chi \rightarrow W^+W^- \rightarrow ^3\text{He} + X$)
- **Disappearance probability** of antinuclei (quantified by $\sigma_{\text{inel}}$) is crucial for studying the galaxy transparency

- ALICE: antinuclei factory + interaction in detector material $\rightarrow$ measurement of $\sigma_{\text{inel}}$ for $^3\text{He}$
- via baryon/antibaryon ratio (pp), or TOF-to-TPC ratio (Pb–Pb)

- **GEANT4 modeling consistent within 2$\sigma$ with data**

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**ALICE, arXiv.2202.01549 accepted by Nature Physics**

Igor Altsybeev, CPOD2022
More highlights from recent ALICE publications

- Observation of the dead-cone effect with D⁰-tagged jets
  - Nature 605 (2022) 7910, 440

- Prompt D⁰ vs b → D⁰
  - arXiv:2202.00815

- Production of K⁰, Λ, Ξ, Ω in jets and UE in pp & p–Pb
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- Large angle small angle
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# List of recent ALICE publications (since May 2022)

[https://twiki.cern.ch/twiki/bin/view/ALICEpublic/ALICEPublicResults](https://twiki.cern.ch/twiki/bin/view/ALICEpublic/ALICEPublicResults)

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<th>ASTRO</th>
<th>Title</th>
<th>System 1</th>
<th>System 2</th>
<th>ArXiv</th>
<th>INSPIRE</th>
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<td>CF</td>
<td>Two-particle transverse momentum correlations in pp and p-Pb collisions at LHC energies</td>
<td>pp, pPb</td>
<td>221108979</td>
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<td>The ALICE experiment – A journey through QCD</td>
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<td>Measurement of the lifetime and Λ separation energy of Λ,H</td>
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<td>Multiplicity dependence of Υ production at forward rapidity in pp collisions at 13 TeV</td>
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<td>Performance of the ALICE Electromagnetic Calorimeter</td>
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<td>Measurements of groomed-jet substructure of charm jets tagged by D± mesons in proton-proton collisions at 13 TeV</td>
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<td>+ papers appeared on arXiv today:</td>
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<td>1) Measurement of electrons from beauty-hadron decays in pp and Pb-Pb at 5.02 TeV</td>
<td><a href="http://arxiv.org/abs/2211.13985">http://arxiv.org/abs/2211.13985</a></td>
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<td>2) J/ψ production at midrapidity in p-Pb collisions at 8.16 TeV</td>
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<td>4) First measurement of Λc+ production down to p_T = 0 in pp and p-Pb at 5.02 TeV</td>
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ALICE review paper: physics results of Run 1+2

> 400 papers on 2009-2018 data

Abstract

The ALICE experiment was proposed in 1993, to study strongly-interacting matter at extreme energy densities and temperatures. This proposal entailed a comprehensive investigation of nuclear collisions at the LHC. Its physics programme initially focused on the determination of the properties of the quark–gluon plasma (QGP), a deconfined state of quarks and gluons, created in such collisions. The ALICE physics programme has been extended to cover a broader ensemble of observables related to Quantum Chromodynamics (QCD), the theory of strong interactions. The experiment has studied Pb–Pb, Xe–Xe, p–Pb and pp collisions in the multi-TeV centre of mass energy range, during the Run 1–2 data-taking periods at the LHC (2009–2018). The aim of this review is to summarise the key ALICE physics results in this endeavor, and to discuss their implications on the current understanding of the macroscopic and microscopic properties of strongly-interacting matter at the highest temperatures reached in the laboratory. It will review the latest findings on the properties of the QGP created by heavy-ion collisions at LHC energies, and describe the surprising QGP-like effects in pp and p–Pb collisions. Measurements of few-body QCD interactions, and their impact in unraveling the structure of hadrons and hadronic interactions, will be discussed. Finally, prospects for future measurements with the ALICE detector in the context of its planned upgrades will also be briefly described.
ALICE upgrades

Goals: direct photon detection to probe gluon density at small $x$, forward $\pi^0$
Currently: prototype development, beam tests

**FoCal = ECal+HCal**

$3.4 < \eta < 5.8$

**ITS3**
- truly cylindrical inner layers
- closer to the interaction point, reduced material budget
- Improved vertexing for heavy flavour probes, thermal dielectrons

Letter-of-Intent: CERN-LHCC-2020-009


Igor Altsybeev, CPOD2022
Letter of intent for ALICE 3

Detector concept:
- compact low-mass all-silicon tracker
- excellent vertex reconstruction
- wide acceptance $|\eta| < 4$
- PID in $0.3 < p_T < 7$ GeV/c

Key objectives:
- precision measurements of dileptons
- systematic measurements of (multi-) heavy flavour hadrons
- hadron long-range correlations

Updated version released Nov 2022 - arxiv.2211.02491
Conserved charge fluctuations with ALICE 3

- high PID purity in large kinematic acceptance
- long-range correlations in a very wide acceptance
- constraining effects from baryon number conservation, hydro evolution

\[ \frac{\kappa_2(p - \bar{p})}{\langle p + \bar{p} \rangle} \]

- net-protons

ALICE LoI, arXiv.2211.02491

Igor Altsybeev, CPOD2022
Higher-order cumulants

Simulation of the Critical Fluctuations (CF) is based on PQM model

- Net-baryon and net-strangeness fluctuations for $|\eta| \leq 4$ and for 6th order

\[ \frac{\kappa_6}{\kappa_2} \]

0-5%, 0.6 < $p$ < 1.5 GeV/c, |$\eta$|<0.8

ALICE LoI, arXiv.2211.02491

Igor Altsybeev, CPOD2022
Summary

- Investigations with **new types of observables** provide more insights and additional constraints on our models
- A lot of **new results from Runs 1+2**, many are still to come
- Harvest of physics results from Run 1 and 2 is summarized in the **ALICE review paper**
- ALICE is successfully taking **data in LHC Run 3**
- Preparations for the **future ALICE upgrades** are ongoing, where many observables will benefit from even more statistics and larger ALICE acceptance

*Thank you for your attention!*