Studies of quark-gluon plasma and beyond with ALICE

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CERN
on behalf of the ALICE Collaboration

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05.09.2022, online
Relativistic heavy-ion collisions and QGP

MADAI Collaboration

- Initial state
- Pre-equilibrium
- QGP and expansion
- Hadronization
- Hadronic phase and freeze-out

0.1 fm/c
~1 fm/c
~10 fm/c
~20-50 fm/c
Relativistic heavy-ion collisions and QGP

MADAI Collaboration

Pb–Pb collisions at LHC energies
- Hot and dense QGP with high $T$ and $\sim$zero $\mu_B$

Exploring the Phase Diagram of Strongly Interacting Matter, J. Stachel, Mon. 08:30
Relativistic heavy-ion collisions and QGP

Pb–Pb collisions at LHC energies
- Hot and dense QGP with high $T$ and $\sim$zero $\mu_B$

pp and p–Pb collisions
- Baseline for heavy-ion studies
- Cold nuclear matter effects
- Traces of QGP? (events with high multiplicities)
Initial stages

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Initial state Pre-equilibrium

- Initial state
- Pre-equilibrium
- QGP and expansion (~1 fm/c)
- Hadronization (~10 fm/c)
- Hadronic phase and freeze-out (~20-50 fm/c)
Anisotropic flow and its properties

Initial (elliptical) geometry of non-central collisions → azimuthal modulation in momentum

\[ \frac{dN}{Nd\phi} = 1 + 2v_2 \cos (2(\phi - \Psi_{RP})) + \text{higher harmonics} \ (v_3, v_4, \ldots) \]
Anisotropic flow and its properties

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\[
\frac{dN}{Nd\phi} = 1 + 2v_2 \cos \left(2\phi - \Psi_{RP}\right) + \text{higher harmonics} \ (v_3, v_4, \ldots)
\]

Flow of identified hadrons

Low \(p_T\): mass ordering described by hydro
High \(p_T\): quark-level flow + recombination
Anisotropic flow and its properties

Initial (elliptical) geometry of non-central collisions → azimuthal modulation in momentum

\[
\frac{dN}{d\phi} = 1 + 2v_2\cos(2(\phi - \Psi_{RP})) + \text{higher harmonics } (v_3, v_4, \ldots)
\]

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

Study of the correlation between the shape of the fireball ($v_n^2$) and its size ($[p_T]$)

- Access to the initial conditions through bulk observables
- No quantitative description of the data
- Slightly better agreement with models using IP-Glasma initial conditions

Access to initial conditions through bulk observables

Only qualitative description of data with models
Fluctuations of flow angle and magnitude

First measurements of flow angle and magnitude fluctuations with 4-particle correlations

- Novel insights into the initial conditions
- Unique sensitivity to the shear viscosity $\eta/s$, need for re-examination of existing models

\[
A^f = \frac{\langle v_n^2(p_T^a) v_n^2 \cos 2n [\Psi_n(p_T^a) - \Psi_n] \rangle}{\langle v_n^2(p_T^a) v_n^2 \rangle}
\]

\[
M^f = \frac{\langle v_n^2(p_T^a)^2 \rangle / \langle v_n^2(p_T^a) \rangle^2 \langle v_n^2 \rangle}{\langle v_n^2(p_T^a) \rangle / \langle v_n^2 \rangle^2}
\]
Polarisation of J/ψ in Pb–Pb collisions

Inclusive J/ψ polarisation with respect to the event plane at low $p_T$

Polar angular distribution of dilepton decay: $W(\theta) \propto \frac{1}{3 + \lambda_\theta} (1 + \lambda_\theta \cos^2 \theta)$

- First evidence of J/ψ polarisation in Pb–Pb collisions!
- Vanishes at higher momenta: sensitive to vorticity and magnetic field?
Properties of the medium

- **Initial state**
- **Pre-equilibrium**
- **QGP and expansion**
- **Hadronization**
- **Hadronic phase and freeze-out**
Electromagnetic probes: photons

First measurement of direct photons in Pb−Pb at $\sqrt{s_{NN}} = 5.02$ TeV
- 0−10% centrality: virtual photons via dielectrons
- Other centralities: real photons with conversion method

- High $p_T$: consistent with pQCD expectations
- Low $p_T$: hint for an excess from thermal photons
Electromagnetic probes: photons and dielectrons

First measurement of direct photons in Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV
- 0–10% centrality: virtual photons via dielectrons
- Other centralities: real photons with conversion method

• High $p_T$: consistent with pQCD expectations
• Low $p_T$: hint for an excess from thermal photons

Analysis of dielectron ($e^+e^-$) invariant mass spectrum
• Hint for an excess at low $m_{ee}$ from thermal source
• Need to better control heavy-flavour background
**$R_{AA}$ of J/$\psi$ and D meson from beauty**

Unprecedented measurement of beauty hadron $R_{AA}$ down to low $p_T$ via non-prompt J/$\psi$ and D

- $R_{AA}$ (non-prompt)/$R_{AA}$ (prompt) > 1 for $p_T$ > 5 GeV/c
- Model description requires mass-dependent energy loss and coalescence

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dp_T|_{PbPb}}{dN/dp_T|_{pp}}$$

**Graphical Data**

- ALICE Preliminary
  - Non-prompt J/$\psi$, Pb–Pb: $\sqrt{s_{NN}}$ = 5.02 TeV, 0-10%
  - CMS, J/$\psi \rightarrow \mu^+\mu^-$, $|y| < 0.9$
  - ATLAS, J/$\psi \rightarrow \mu^+\mu^-$, $|y| < 2.0$ (EPJC 78 (2018) 509)
  - ALICE, J/$\psi \rightarrow e^+e^-$, $|y| < 0.9$

**Model Description**

- Mass-dependent energy loss and coalescence

**Model Descriptions**

i) $m_0$ set to $m_b$ (E-loss)

ii) $m_0$ set to $m_b$ (coalescence)

iii) w/o shadowing

iv) w/o coalescence

**Data Sources**

- ALICE, C. Cot, Wed. 16:40

**ArXiv**

2202.00815
ψ(2S) production in Pb–Pb

Extending the ψ(2S) measurement down to zero $p_T$

Clear hierarchy of suppression over all the $p_T$ and for all centralities

Hint for regeneration of ψ(2S) at low momentum

<table>
<thead>
<tr>
<th>J/ψ</th>
<th>ψ(2S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>3.07 GeV/c$^2$</td>
</tr>
<tr>
<td>Binding energy</td>
<td>0.64 GeV</td>
</tr>
</tbody>
</table>

Counts per 25 MeV/c$^2$

ALICE Preliminary
Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
$2.5 < y_{\text{cms}} < 4$
$p_T < 12$ GeV/c, 0-90%

ALICE Preliminary, $2.5 < y_{\text{cms}} < 4$, $0.3 < p_T < 12$ GeV/c

Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
NA50, $0 < y_{\text{lab}} < 1$ (EPJ C49(2007) 559)

Pb–Pb, $\sqrt{s_{NN}} = 17$ GeV

ALICE (pp ref: $f_s = 5.02$ TeV, arXiv:2109.15240)

NAS50 (pp ref: $f_s = 27$ GeV, from EPJC48 329(2006))
Medium-induced jet modifications

Jet studies with grooming: find first hard splitting
- Model comparisons indicate QGP resolves individual hard prongs that interact incoherently
- Jet core is more collimated in Pb–Pb than in pp

\[ R = \sqrt{\Delta \phi^2 + \Delta \eta^2} \]
\[ \theta_g = R_g / R \]
Jet modifications in PbPb

Jet studies with grooming: find first hard splitting
- Model comparisons indicate QGP resolves individual hard prongs that interact incoherently
- Jet core is more collimated in Pb–Pb than in pp

Jets with larger R are more suppressed in Pb–Pb collisions
- Hint of R-dependent suppression, not seen up to R = 0.4
- Consistent with narrower jet population

ALICE Preliminary, 0-10% Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV
Ch-particle jets, anti-$k_T$, $|\eta_{\text{jet}}| < 0.9-R$
Where does the energy go?

$I_{AA}$ measurement: how the jet energy is redistributed in heavy-ion collisions

$$I_{AA} = \frac{\Delta_{recoil}(Pb - Pb)}{\Delta_{recoil}(pp)}$$

Hint for an energy recovery at low jet momentum

- In association with azimuthal broadening
- Good description of results with JETSCAPE
Hadronization and hadronic phase

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0.1 fm/c

~1 fm/c

~10 fm/c

Initial state

Pre-equilibrium

QGP and expansion

Hadronization

~20-50 fm/c

Hadronic phase and freeze-out
Antimatter/matter imbalance and $\mu_B$

Baryochemical potential $\mu_B \rightarrow$ antimatter/matter imbalance
Can be obtained from the statistical hadronisation model:

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

where $T = 156.2 \pm 2$ MeV and

<table>
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<tr>
<th></th>
<th>$\pi^+$</th>
<th>p</th>
<th>$^3$He</th>
<th>$^\Lambda^3$H</th>
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<tr>
<td>$B + S/3$</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>8/9</td>
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<tr>
<td>$I_3$</td>
<td>1</td>
<td>1/2</td>
<td>1/2</td>
<td>0</td>
</tr>
</tbody>
</table>

ALICE Preliminary
Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV
$\chi^2$/NDF = 1.72/2

data - fit

ALI-PREL-503451
Antimatter/matter imbalance and $\mu_B$

Baryochemical potential $\mu_B \rightarrow$ antimatter/matter imbalance
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Most precise measurement of $\mu_B$ at TeV scale!
- Cancellation of uncertainties in the ratio
- Consistent with previous results, but with x6 smaller errors
Antinucleosynthesis beyond the average

New observable based on event-by-event fluctuations to distinguish between hadron coalescence and statistical hadronisation [1]:

\[
\frac{\kappa_2}{\kappa_1} = \frac{\langle (n - \langle n \rangle)^2 \rangle}{\langle n \rangle}
\]

\* SHM is clearly favoured by the cumulant ratio

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• SHM is clearly favoured by the cumulant ratio

Pearson correlation to constrain the correlation volume for baryon number:

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

• Coalescence model A: full correlation among p and n
• Coalescence model B: independent p and n production

Production of (anti)(hyper)nuclei

(Anti)(hyper)nuclei production in small systems is of particular interest
- System size smaller or compatible to the one of the nucleus
- Allows for the study of coalescence since nucleons are created close to each other
- Very different model predictions, ideal environment to constrain production mechanism

Measurements in pp and p–Pb collisions:
- In good agreement with 2-body coalescence
- Tension with SHM at low charged-particle multiplicities
Collisions of small systems: pp, p–Pb
Flow of identified particles in small systems

Baryon-meson splitting at intermediate $p_T$ in both pp and p–Pb collisions

*Comparison of p–Pb results with models indicates partonic flow + coalescence*

(No J/$\psi$ flow within uncertainties in high-multiplicity pp collisions)
Strangeness enhancement in pp collisions

Large enhancement of (multi-)strange particle production in high-multiplicity pp collisions at $\sqrt{s} = 7$ TeV

- In remarkable agreement with results from p–Pb collisions
- In high-multiplicity events strangeness production reaches values similar to those observed in Pb–Pb collisions!

*How are these multi-strange particles produced, and in which direction?*
Investigating the enhancement in more details

- Both Full and Transverse to leading particle yields increase with multiplicity
- Toward leading particle yield shows almost flat dependence with multiplicity
- No collision energy dependence

Strange hadrons in pp collisions are dominantly produced in the transverse direction to the leading particles
Dead-cone effect exposed by ALICE

Suppression of gluon radiation from heavy quarks at small angles [1]

$$R(\theta) = \frac{1}{N_{D^0_{jets}}} \frac{dn^{D^0_{jets}}}{d\ln(1/\theta)} / \frac{1}{N^{\text{inclusive jets}}} \frac{dn^{\text{inclusive jets}}}{d\ln(1/\theta)}$$

First direct observation using iterative jet declustering and Lund plane analysis of jets with a soft $D^0$ meson

Beyond the QGP studies
Hadron-hadron interactions

ALICE is pioneering the study of strong interactions using femtoscopic correlations

- Emission source is constrained from pairs for which the interaction is well-known
- By measuring correlation function we can study the interactions among hadron pairs!
Hadron-hadron interactions

ALICE is pioneering the study of strong interactions using femtoscopic correlations

\[ C(k^*) = \int S(r^*) |\Psi(k^*, r^*)|^2 d^3r^* = \xi(k^*) \cdot \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)} \]

- Emission source is constrained from pairs for which the interaction is well-known
- \( \rightarrow \) by measuring correlation function we can study the interactions among hadron pairs!
Hadron-hadron interactions: few highlights

First studies of residual strong interaction between charm and light-flavour hadrons

• Results compatible with Coulomb interaction and with shallow attractive strong interaction
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First studies of three-body interactions
  • Important role in the structure of (hyper)nuclei and in models to describe dense baryonic matter (e.g. neutron stars)
Hadron-hadron interactions: few highlights

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First studies of three-body interactions
• Important role in the structure of (hyper)nuclei and in models to describe dense baryonic matter (e.g. neutron stars)

First measurement of proton-deuteron interaction at the LHC
• Valuable input for models, insight into light nuclei formation
On the transparency of our Galaxy to $^3\text{He}$ nuclei

Pioneering studies of antinuclei inelastic interactions with matter at low kinetic energies

- Fixed-target experiment within ALICE: LHC as an antimatter factory, ALICE detector material as a target

$\sigma_{\text{inel}}^{^3\text{He}} = 5.02 \text{ TeV}$

$\langle A \rangle = 34.7$

Data

GEANT4

arXiv:2202.01549
On the transparency of our Galaxy to $^3\text{He}$ nuclei

Pioneering studies of antinuclei inelastic interactions with matter at low kinetic energies
• Fixed-target experiment within ALICE: LHC as an antimatter factory, ALICE detector material as a target

Essential input for indirect searches of dark matter in space with antinuclei!
• High transparency of our Galaxy to $^3\text{He}$ nuclei from a DM source
“ALICE 1” (2010’s) → “ALICE 2” (2020’s)

Run: 244918
Time: 2015-11-25 10:36:18
Colliding system: Pb-Pb
Collision energy: 5.02 TeV
Detector and software upgrades for Run 3

New Inner Tracking System (ITS)
- 7 barrels, 10 m² silicon tracker based on MAPS (12.5 G pixels)''

New GEM-based TPC
with continuous readout

New Muon Forward Tracker (MFT) - 5 disks based on MAPS

New Trigger and Readout
Upgrade of readout electronics of all detector, new Central Trigger Processor

New Fast Interaction Trigger (FIT)
- 3 detector technologies: interaction trigger, online luminometer, forward multiplicity

New Beampipe
smaller diameter (36.4 mm), first detection layer at 20 mm

About x3 better tracking precision
Pb–Pb collisions rate x50 higher
Results from first collisions (pilot beam 2021)

Full PID capabilities from TPC and TOF are available
First look at the charged-particle multiplicity and pp correlation function

Detector, simulation, reconstruction and analysis software are ready for physics! ✅
Already preparing for Run 4 and beyond!
Summary
Fruitful harvest of ALICE results from Run 1 and Run 2 campaigns
• Detailed insights into the QGP properties
• Broad programme of the studies in pp and p–Pb collisions
• Unique and novel studies beyond the QGP physics

ALICE completed the Phase I upgrade and is ready for Run 3
• Significantly enhanced capabilities
In preparation for Run 4 and beyond

Thank you for your attention!
Back-up slides
The ALICE Detector during Run1 and Run2

Central Barrel \(|\eta| < 0.9\)
- Tracking
- PID
- EM-Calorimeters

ACORDE (cosmics)
Forward detectors:
- AD (diffraction selection)
- V0 (trigger, centrality)
- T0 (timing, luminosity)
- ZDC (centrality, ev. sel.)
- FMD \((N_{ch})\)
- PMD \((N_\gamma, N_{ch})\)

Muon Spectrometer
\(-4 < \eta < -2.5\)