Recent results from the ALICE Experiment at LHC

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QCD predicts at high temperature/density the Quark-Gluon Plasma (a deconfined system of quarks and gluons)
  ○ Achieved in the laboratory by colliding heavy ions
Why study QGP?

QGP might have existed in the expanding Universe in the first μs after the Big Bang

Neutron stars: a more likely place for QGP to exist → mass controlled by the equation of state (EoS) of nuclear matter
The goal is to understand the hard partonic and the QGP stages using the measured particles.
## Dedicated heavy-ion experiment at the LHC

**State of the art particle identification**

<table>
<thead>
<tr>
<th>System</th>
<th>pp</th>
<th>p-Pb / Pb-p</th>
<th>Xe-Xe</th>
<th>Pb-Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (TeV)</td>
<td>0.9, 2.76, 7, 8, 5.02, 13</td>
<td>5.02, 8.16</td>
<td>5.44</td>
<td>2.76, 5.02</td>
</tr>
<tr>
<td>( L_{\text{int}} )</td>
<td>200( \mu b^{-1} ), 100nb(^{-1} ), 1.5pb(^{-1} ), 2.5pb(^{-1} ), 1.3pb(^{-1} ), 36pb(^{-1} )</td>
<td>18 nb(^{-1} ), 25 nb(^{-1} )</td>
<td>0.3 ( \mu b^{-1} )</td>
<td>75 ( \mu b^{-1} ), <strong>0.8 nb(^{-1} )</strong></td>
</tr>
</tbody>
</table>
Impact parameter $b$
Perpendicular to beam direction
Connects centers of colliding nuclei
*Not measured directly* $\rightarrow$ estimated by centrality
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Centrality
Determined from *particle multiplicities*
- Most central: 0-5% centrality
- Peripheral: 70-80% centrality
Particle production vs. centrality in Pb-Pb @ 5.02 TeV

ALICE, arxiv:1910.07678

Low and intermediate $p_T$: collective motion and particle production mechanisms

High $p_T$: path-length dependence of the quark energy loss

Clear sign of radial flow at low $p_T$ and power-law shape at high $p_T$ as expected from perturbative QCD calculations
Nuclear modification factor - $R_{AA}$

$R_{AA} = \frac{d^2 N_{AA}/dp_T dy}{\langle N_{bin} \rangle d^2 N_{NN}/dp_T dy}$

- $R_{AA}$ is expected to be different from 1 in case of nuclear effects that can modify the $p_T$ spectrum → initial and final states effects
- final-state effects such as in-medium energy loss (via collisional and radiative processes), the collective expansion and the in-medium hadronization via coalescence
- initial state effects (CNM - cold nuclear matter effects) like nuclear modification of PDFs / CGC, $k_T$-broadening (Cronin effect)

$R_{AA} < 1$ at high $p_T$ - the nuclear effects suppress the particle production.
$R_{AA} \approx 1$ at high $p_T$ (binary scaling) - no nuclear effects.

System size:
- $pp \rightarrow$ test pQCD properties
- $p$-$Pb \rightarrow$ CNM effects
- $Pb$-$Pb \rightarrow$ QGP properties
Measured $R_{AA}$ - highlights

- Similar suppression in Pb-Pb and Xe-Xe at the same multiplicity ~ similar medium density
- New input to constrain path length dependence of energy loss
Measured $R_{AA}$ – highlights

**Charged hadrons**

**Identified hadrons**


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- New input to constrain path length dependence of energy loss

ALICE, arxiv:1910.07678

**Intermediate $p_T$:** The large difference between the suppression of different species
  → consistent with a mass ordering related to the radial flow

**High $p_T$:** No dependence on particle type
  → indicates partonic origin of energy loss
Significant quenching in central Pb-Pb collisions → Pushing down in $p_T$ and to larger jet $R$

Dead cone effect

$E_{\text{loss}} (g) > E_{\text{loss}} (u,d) > E_{\text{loss}} (c) > E_{\text{loss}} (b)$

$R_{AA}(g) < R_{AA}(c) < R_{AA}(b)$

Improved precision:
First direct view on interplay between melting and regeneration?

Low $p_T$ yields increase towards mid-rapidity: Qualitatively consistent with regeneration/coalescence

Quarkonia

Open charm

Jets

...more in J. Norman’s talk
Anisotropic flow

Anisotropic flow: initial spatial anisotropy → final momentum anisotropy via collective interactions
- $v_n$ quantify the event anisotropy

Anisotropic flow is sensitive to the system evolution
- Constrains initial conditions, EOS, transport properties (e.g. shear viscosity over entropy density ratio ($\eta/s$) and bulk viscosity over entropy density ratio ($\zeta/s$)), particle production mechanisms

Pressure gradients (larger in the x directions) push bulk "out" → "flow"
More, faster particles seen in the x-direction

$$E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \int d\phi d\rho d\rho_T dy \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_n)) \right)$$
Elliptic flow across the systems

- Pronounced $v_2$ in peripheral Pb-Pb and at similar multiplicities in p-Pb/pp
- $v_2$ extends to small systems $\rightarrow$ it’s enough to have few scatterings in order to build flow
- Multi-particle cumulants $\rightarrow$ non-flow contributions are suppressed
System size dependence Pb-Pb vs. Xe-Xe

Inclusive charged hadrons
Similar $v_2$ for both systems, but
Xe nucleus deformation
→ larger $v_2$ in Xe-Xe for most central collisions

Constrain initial conditions and medium properties
System size dependence

Constrain initial geometry and transport coefficients (e.g. $\eta/s$)
- $0$-$5\%$: $v_2^{\text{Xe}} > v_2^{\text{Pb}} \rightarrow \text{Xe}$ deformation

ALICE Preliminary
0$-$5$\%$, $|y| < 0.5$

$\text{Xe} - \text{Xe}$: $\sqrt{s_{\text{NN}}} = 5.44$ TeV
$\text{Pb} - \text{Pb}$: $\sqrt{s_{\text{NN}}} = 5.02$ TeV
ALICE, JHEP 1807 (2018) 103
System size dependence

Constrain initial geometry and transport coefficients (e.g., $\eta/s$)

- 0-5%: $v_2^{Xe} > v_2^{Pb} \rightarrow Xe$ deformation
- 20-30%: $v_2^{Pb} > v_2^{Xe}$ for $p_T > 2$ GeV/c
Heavy-flavor flow

c-quarks → produced isotropically in the early stages and pick up $v_2$ by interacting with QGP

- D meson $v_2$ similar to light meson $v_2$ → strong collectivity/thermalisation → strong c-quark coupling to the medium
Heavy-flavor flow

c-quarks $\rightarrow$ produced isotropically in the early stages and pick up $v_2$ by interacting with QGP

- D meson $v_2$ similar to light meson $v_2$ $\rightarrow$ strong collectivity/thermalisation $\rightarrow$ strong c-quark coupling to the medium
- Large $J/\psi$ $v_2$ up to $p_T \sim 8$ GeV/$c$ $\rightarrow$ charm recombination and thermalisation
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- Large $J/\psi$ $v_2$ up to $p_T \sim 8$ GeV/$c$ $\rightarrow$ charm recombination and thermalisation
- $v_2$ of $\Upsilon(1S)$ consistent with 0 (small values from theory)
Charm quark energy loss

Combine $v_2$ and $R_{AA}$ in order to constrain models
Event-shape-engineering

- Select events with similar centralities and different shapes based on the event-by-event flow/eccentricity fluctuations

Flow vector

\[ Q_{n,x} = \sum_i \cos(n \varphi_i) \]

\[ Q_{n,y} = \sum_i \sin(n \varphi_i) \]

\[ q_n \text{ distribution} \]

\[ Q_n = Q_{n,x}, iQ_{n,y} \]

\[ q_n = |Q_n|/\sqrt{M} \]
Charged hadrons ESE

- \( q_2 \) selects events up to 30% larger or smaller \( v_2 \) than the average
- \( p_T > 3 \text{ GeV/c} \): ratios almost flat \( \rightarrow \) same source of flow fluctuations
- \( p_T < 3 \text{ GeV/c} \): weak \( p_T \) dependence \( \rightarrow \) different ellipticity for various \( q_2 \) classes
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Identified particle ESE

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- $p_T < 3 \text{ GeV}/c$: weak $p_T$ dependence $\rightarrow$ different ellipticity for $q_2$ classes
- Same values for inclusive and PID
  - No dependence on particle species
Charm ESE

D mesons are sensitive to the light-hadron bulk collectivity and event-by-event fluctuations in the initial stage.

Ratio (ESE/unbiased) of J/ψ $v_2$ consistent with those of single muons within uncertainties.

$\rightarrow$ J/ψ $v_2$ compatible with the expected variations of the eccentricity.
Chiral magnetic effect

- Domains with different topological charge + strong magnetic field → charge separation along the magnetic field (Chiral Magnetic Effect)

- 3-particle correlator sensitive to CME → splitting of same and opposite sign correlator
  → Main question: background?
Chiral magnetic effect

- First measurement in Xe-Xe collisions
- Expected weaker magnetic field
  → Smaller splitting

→ Splitting in Xe-Xe and Pb-Pb similar
→ Indicates large background contribution (coupled to $v_2$, local charge conservation)
Charm quarks are produced early in the collision

→ powerful probe to **quantify** the initial magnetic field **directly**

Positive slope \( d\Delta v_1/d\eta \) for \( D^0 \) and \( \bar{D}^0 \)

- Quantify the effect of charge separation

→ Larger than that of charged hadrons by about three orders of magnitude
Magnetic field and angular momentum

1) large $L$ + spin-orbit coupling $\rightarrow$ (global) polarization (probing early/late stages)

2) $B$ along $L$ $\rightarrow$ opposite direction effect for particles/antiparticles $\rightarrow$ sensitive to magnetic field

- $\Lambda$ results confirm earlier observed trend of the global polarization $\rightarrow$ decrease with increasing collision energy
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- $\Lambda$ results confirm the observed earlier trend of the global polarization $\rightarrow$ decrease with increasing collision energy
- Larger effect for $K^*0$ and $\Phi$ than observed in $\Lambda$ polarization

ALICE, arxiv:1910.14408

At low momenta: deviation from 1/3 (maximum in semi-central collisions)
Hadron interactions

The LHC provides a unique and precise testing of the hadron-hadron interaction at distances lower than 1 fm:

- Search for bound states
- Strong constraints to low-energy QCD effective theories
- More precise equation of state (NS)

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

Source function \( S(\mathbf{r}) \)

Emission source

Two-particle wave function

Modelling/fitting performed using CATS

Hadron interactions

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  - More precise equation of state (NS)
- Large set of particle pairs studied in ALICE in small collisions systems, pp and p-Pb collisions

ALICE, PRL 123 (2019) 112002, p-Ξ^-
ALICE, arXiv:1905.13470, p-K^-
ALICE, arXiv:1910.14407, p-Σ^0
Light nuclei production

Production mechanism of A=3 nuclei
→ Thermal, coalescence, ...?

Yields and ratios
→ First (anti-)triton spectra in Pb-Pb collisions
→ $^3$He/p increases by one order of magnitude

Smooth evolution with multiplicity
Two regimes:
- Flat trend at low multiplicity: the system size is smaller than the nucleus size
- Decreasing trend at high multiplicity: the system size is larger than the nucleus size
Hyper-matter investigation

Pb-Pb 2015 dataset published in September
2018 Pb-Pb dataset + Machine Learning methods (in red)

- Single measurement same relative error as world average
- Precision is crucial to test of different models with different hypertriton structure and final state interaction

Hyper-triton lifetime close to free \( \Lambda \), in agreement with expectations
Photonuclear reactions

Probe nPDFs with quasi-real photon in ultra-peripheral Pb-Pb collisions → in agreement with nuclear gluon shadowing

ALICE, arxiv:1904.06272
ALICE Upgrade Program

Better vertexing

Faster TPC

TPC

ITS2
ALICE Upgrade Program

- Better vertexing
- Faster TPC
- ITS2
- ITS3

 Miami-2019, Fort Lauderdale, Dec, 14
Future “all-silicon” heavy-ion detector at the LHC (beyond 2030)

Physics potential

- **Heavy flavours, quarkonia**
  - Multi-heavy flavoured hadrons ($\Xi_{cc}$, $\Omega_{cc}$, $\Omega_{ccc}$)
  - $\chi_c$ states

- **Thermal radiation**
  - Dileptons and photons

- **Soft hadronic and electromagnetic radiation**
  - Hadrons down to tens of MeV/c
  - Photons down to ~50 MeV/c

- **BSM**
  - Dark photons

EoI document (arXiv:1902.01211) signed by ~400 physicists
→ submitted to European Strategy for Particle Physics Preparatory group
Conclusions

Collective behaviour across systems in high multiplicity pp, p-Pb and A-A collisions

Precision measurements
- To understand system evolution and QGP properties (initial effects, parton energy loss and medium response, spin interactions and magnetic field, CME, flow)
- Hadron Physics (hyper-triton, hadron-hadron interactions)
Allowing better understanding and validation of QCD

ALICE upgrade: order(s) of magnitude more events, with improved detectors
Backup
Blast-Wave fits to particle spectra

Simultaneous fit to the pi, K, p spectra:

\[
\frac{dN}{p_{\perp}dp_{\perp}} \propto \int_0^R rdr m_{\perp} I_0 \left( \frac{p_{\perp} \sinh \rho}{T_{\text{kin}}} \right) K_1 \left( \frac{m_{\perp} \cosh \rho}{T_{\text{kin}}} \right)
\]

- \(T_{\text{kin}}\) – kinetic freeze-out temperature
- \(\beta_T\) – transverse radial flow velocity

- \(\beta_T\) increases with centrality in AA collisions
  - Central Pb-Pb 5.02 TeV → largest \(\beta_T\)
- \(T_{\text{kin}}\) is lower in central collisions → longer system lifetime to develop collective effects
- in pp and p-Pb, similar evolution of the BW fit parameters towards high multiplicity
- higher \(T_{\text{kin}}\) in pp and p-Pb with respect to heavy-ion collisions
Strangeness production

- The integrated particle yields exhibit a continuous evolution with the charged particle multiplicity independent of the collision system.
- Abundances of strange hadrons are invariant with the collision energy at similar multiplicities.
- At large multiplicities small systems reach the values observed in heavy-ions.
- Chemical composition seems to be driven by $\langle dN_{\text{ch}}/d\eta \rangle$ and not by the collision system.