Recent results
from the ALICE Experiment at LHC

Catalin Ristea* on behalf of the ALICE Collaboration
*Institute of Space Science, Romania
By changing the energy available in the collision and the projectile-target combinations, one can obtain systems characterized by various temperatures and baryon chemical potentials → different regions on the phase diagram can be investigated.
Dedicated detector to exploit the unique physics potential of nucleus-nucleus collisions at LHC
Study the physics of strongly interacting matter at the highest energy densities reached so far in laboratory
Comprehensive studies of hadrons, electrons, muons and photons to understand and describe QGP formation in heavy ion collisions

<table>
<thead>
<tr>
<th>System</th>
<th>p-p</th>
<th>p-Pb / Pb-p</th>
<th>Xe-Xe</th>
<th>Pb-Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s_{NN}}$ (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>
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<tr>
<td>$L_{int}$</td>
<td>200μb$^{-1}$, 100nb$^{-1}$, 1.5pb$^{-1}$, 2.5pb$^{-1}$, 1.3pb$^{-1}$, 25pb$^{-1}$</td>
<td>18 nb$^{-1}$, 25 nb$^{-1}$</td>
<td>30 μb$^{-1}$</td>
<td>75 μb$^{-1}$, 250 μb$^{-1}$</td>
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</table>
ALICE Performance

- Excellent PID for hadrons, leptons and photons
- Good tracking resolution in TPC & EmCal detectors to resolve the inner structure of (copiously produced) jets @ LHC
- Excellent vertex capability (HF, V^0s, cascades, conversions)
- Efficient low-momentum tracking down to 150 MeV/c

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For most central collisions, Xe-Xe results are higher than Pb-Pb results at similar $N_{\text{part}}$ → $N_{\text{part}}$. - scaling violation for 0-5% Xe-Xe.

RHIC data showed the same behaviour (CuCu vs. AuAu)

- Xe–Xe result in agreement with the previous AA power-law trend

- a stronger rise with $\sqrt{s_{NN}}$ in AA than for pp and pA collisions
90% of the particles are produced in low $p_T$ and intermediate $p_T$ regions
Exponential/Boltzmann behaviour at low $p_T$ and power law shape at high $p_T$
Proton $p_T$ spectra shape change from central $\rightarrow$ peripheral $\Rightarrow$ radial flow
Strangeness production

New results from LHC-Run2
- pp 13 TeV
- Xe-Xe 5.44 TeV
- Pb-Pb 5.02 TeV

→ smooth increasing trend vs. multiplicity

At similar multiplicity, no dependence on system nor energy

Pb-Pb ratios → good agreement with the statistical hadronization model, for a grand-canonical ensemble $T_{ch} \sim 150$-160 MeV
\[ \langle p_T \rangle \text{ for identified particles} \]

→ the mass dependence of \( \langle p_T \rangle \) reflects collective expansion in the radial direction.

→ the differences in central values of \( \langle p_T \rangle \) between protons and pions/kaons are smaller at lower multiplicities.
  → smaller average collective velocity in the radial direction in peripheral collisions.

→ \( \Phi \) meson behaviour is the same as the proton (similar mass) for higher multiplicities.
Blast-Wave fits to particle spectra

- $\beta_T$ increases with centrality in AA collisions
  - Central Pb-Pb 5.02 TeV → largest $\beta_T$
- $T_{\text{kin}}$ is lower in central collisions
- in p-p and p-Pb, similar evolution of the BW fit parameters towards high multiplicity

Simultaneous fit to the pi, K, p spectra:

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

$T_{\text{kin}}$ – kinetic freeze-out temperature

$\beta$ – transverse radial flow velocity
Baryon-to-meson ratio

Low to intermediate $p_T < 7$ GeV/c

Baryon-to-meson ratios are important tools to study
  ● hydrodynamic behavior
  ● recombination/coalescence

Different behaviour between $p/\Phi$ and $p/\pi$, $\Lambda/K^0_S$ ratios

→ radial flow/expansion affects the particle ratios and $p_T$ spectra ⇒ similar spectra for $p/\Phi$
→ recombination role?

High $p_T$ → constant ratios (due to jet fragmentation)
Anisotropic flow

Non-central collisions: overlap region is not symmetric in coordinate space
- spatial anisotropy $\rightarrow$ pressure gradients lead to momentum anisotropy

Quantify anisotropy: Fourier decomposition of particle azimuthal distribution relative to the reaction plane ($\Psi_{RP}$) — coefficients $v_2, v_3, v_4, \ldots v_n$

Anisotropic flow is sensitive to the system evolution
- Constraints 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, freeze-out conditions

$$ v_n = \langle \cos n(\varphi - \Psi_{RP}) \rangle $$

$v_n$ quantify the event anisotropy
- $v_2$ elliptic flow, $v_3$ triangular flow, $\ldots$
Elliptic flow across the systems

- Pronounced $v_2$ in peripheral Pb-Pb and at similar multiplicities in p-Pb/p-p
- $v_2$ extends to small systems → it’s enough to have few scatterings in order to build flow
Flow of identified hadrons in Pb-Pb at 5.02 TeV

- for $p_T < 2-3$ GeV/c, $v_2$ of the different particle species is mass-ordered $\rightarrow$ indicative of strong radial flow
- for $3 < p_T < 8-10$ GeV/c, particles are grouped according to their number of constituent quarks $\rightarrow$ quark coalescence
- the $\Phi$ meson $v_2$ follows proton $v_2$ at low $p_T$ (similar masses), but $\pi v_2$ at intermediate $p_T$ in all centrality classes.
Nuclear modification factor - $R_{AA}$

\[ R_{AA} = \frac{d^2N_{AA}^A}{dp_T dy} \frac{\langle N_{bin} \rangle d^2N_{NN}^A}{dp_T dy} \]

- $R_{AA}$ 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, kT-broadening (Cronin effect)

$R_{AA} < 1$ at high $p_T$ - the nuclear effects suppress the particle production.

$R_{AA} \sim 1$ at high $p_T$ (binary scaling) – no nuclear effects.
Charged hadrons $R_{AA}$

Compared with $N_{\text{coll}}$ scaled p-p collisions,

- Large suppression of high $p_T$ particles in most central A-A collisions
  - Described by models including parton energy loss in the QGP medium
- No suppression in peripheral A-A and MB p-A collisions
Centrality dependence

- Multiple hard scatterings $\rightarrow$ power-law shape spectra for all centralities
- From central to peripheral A-A collisions $\rightarrow$ less suppression
- Increased suppression with increasing centrality $\rightarrow$ larger and hotter medium produced in central collisions as compared to peripheral
Most Peripheral AA Collisions

First ever measurements to such peripheral centrality

\[ R_{AA} \text{ in Pb-Pb decreasing with centrality } < 80\% \Rightarrow \text{agreement with HG-PYTHIA (no energy loss)} \]

- HG-PYTHIA (HIJING Glauber PYTHIA) based on the HIJING Glauber model for the initial state and PYTHIA

Progressive reduction of medium induced parton energy loss

1805.05212
Small Systems

- Significant change of underlying p-p reference spectra with multiplicity
- $p_T$ dependent
- the multiplicity of the most peripheral class (95-100% centrality) is lower than pp (because the nucleon-nucleon collisions that occur in a very peripheral Pb-Pb collision are not MB collisions) and therefore the $R_{AA}$ could be influenced by the fact that MB pp is no longer a good reference
**Xe-Xe $R_{AA}$**

1805.04399

- Similar suppression pattern in both Pb-Pb and Xe-Xe at the same multiplicity ~ similar medium density
- New input to constrain path length dependence of energy loss
Different $R_{AA}$ at intermediate $p_T$ due to radial flow (mass dependent push to higher $p_T$) in addition to recombination

In Pb-Pb collisions all three species are equally suppressed for all centralities at $p_T > 8$ GeV/$c$

(Light)flavor independent energy loss at high $p_T$ as observed at 2.76 TeV
Energy Dependence of $R_{AA}$

- First measurement of $R_{AA}$ for $\eta$ meson @ LHC
- High $p_T$ particle suppression gradually sets in with increasing energy
Jets $R_{AA}$

In jets multiple partons lose energy → more partons in high energy jets → more $E_{loss}$

Jet core not affected
Corona effect softens $p_T$ of jet constituents,
Slight increase of $R_{aa}(R)$ → more soft contributions to jets

Pb-Pb 0-10% $\sqrt{s_{NN}} = 5.02$ TeV
ALICE Preliminary
POWHEG+Pythia8 reference

Anti-$k_T$ $R = 0.3 \mid \eta_{jet} < 0.4$
$p_{T,lead,ch}^{ch} > 5 \text{ GeV/c}$

No $p_T$ dependence

K. Zapp, QM'18
Heavy flavor in heavy ion collisions

Heavy quarks in Pb-Pb collisions at LHC

- Produced early in collision time, through large $Q^2$, small formation time → experience the system full evolution

Open heavy flavors

- $c$ and $b$ quarks lose energy in the medium via collisional and radiative energy loss (dead cone effect) → smaller energy loss for heavy than for light quarks

\[ E_{\text{loss}}(g) > E_{\text{loss}}(u,d) > E_{\text{loss}}(c) > E_{\text{loss}}(b) \]
\[ R_{AA}(g) < R_{AA}(c) < R_{AA}(b) \]

- Medium creates a competition between fragmentation (one quark producing a jet) and recombination (the $c$ quark picks up a light quark from the medium)
- Low $p_T$ $c$-quark thermalization → push from large collective flow, transport models

Quarkonia

- Presence of the medium modifies the yield of $J/\psi$, $\psi'$, $\Upsilon$
- Different binding energies and radii → melting (Debye screening) in the QGP at different temperatures → thermometer of QGP
- QGP, $c$ (cbar) + cbar(c) → quarkonium → recombination
**$R_{AA}$ in p-Pb for J/$\psi$**

**p-Pb allows for CNM and initial conditions testing**

- Contribution of hot-matter effects are thought to be negligible
- J/$\psi$ suppression observed at positive rapidity
- For negative $y$, an increasing trend in RAA is present at low $p_T$ and the data are compatible with unity

**Initial conditions in p-Pb forward/backward rapidity:**

Various combinations of CNM effects (pure shadowing, nPDF, CGC) give rather good description for the data
### J/ψ $R_{AA}$ in Heavy Ion Collisions

**RHIC → LHC**

Evidence for increasing recombination for Pb-Pb

At RHIC top energy:
- J/Psi production is strongly suppressed
- RAA suppression increases with collision centrality

At LHC energies:
- smaller suppression for central collisions compared to PHENIX results
- weaker centrality dependence
J/ψ flow in p-Pb/Pb-Pb collisions

Similar mechanism responsible for the behavior in both systems

- Transport models
- Thermalization implications
- Collective effects in small systems
- Constraints the $R_{AA}/v_2$ for models

• $R_{p\text{Pb}} \sim 1 \& v_2$ in pPb $> 0 = \text{not a contradiction}$

$R_{AA} \chi(1S)$ in Pb-Pb

- Extreme precision measurement
- Slight increased suppression with centrality
- Weak $p_T/y$ dependence
- More suppressed than $J/\psi$
- Models w/ or w/o recombination are able to reproduce data → no clear sign of recombination
- CNM effects?
Open Heavy Flavor - $R_{AA}$ and $v_2$ in Pb-Pb

First measurements of $D_s^+$ @ LHC
- Different suppression of $D_s$ with respect to $D \to$ due to the recombination of the c quark in the QGP where s quarks are abundant
- Mass ordering at intermediate $p_T$
- Slow/low $p_T$ $D^0$ thermalized with QGP and largely affected by collective flow
- Measurement precision with potential to constrain transport models, current $D_s^+(2\pi T) \sim 1.5 - 7$

Beauty-decay electrons $R_{AA}$

- $E_{\text{loss}}(c) > E_{\text{loss}}(b) \Rightarrow R_{AA}(c) < R_{AA}(b)$
- Data described by models with $E_{\text{loss}}$ dependence on quark mass
- $R_{pPb}(b\rightarrow c\rightarrow e) \sim 1$ - (ALICE, JHEP) $\Rightarrow$ rules out CNM effects
Conclusions

ALICE provides plethora of precision measurements for many hadron types

Allowing better understanding and validation of QCD description for LHC collisions

Universality of strangeness production across different systems

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

Large suppression of high $p_T$ particles investigations to continue
Access to more and more rarer probes
BACKUP
Spectra comparison:

Harder spectra @5.02 for both AA (more parton energy loss) and pp reference

⇒ similar $R_{AA}$ suppression

Factor ~2 decrease of system. uncertainties wrt previous published results
\textbf{ATLAS Preliminary}

Pb+Pb $\sqrt{s_{NN}} = 5.02\ \text{TeV},\ 0.49\ \text{nb}^{-1}$

$p p\ \sqrt{s} = 5.02\ \text{TeV},\ 25\ \text{pb}^{-1}\ \text{anti-}\kappa_i\ R=0.4$

$126 < p_T^{\text{jet}} < 158\ \text{GeV}$

0 - 10%

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