Heavy Ion Physics with ALICE

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Les Rencontres de Physique de la Vallée d’Aoste
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Collisions of relativistic heavy nuclei create the conditions for the phase transition from ordinary matter to the Quark Gluon Plasma (QGP).
Nuclear collision and QGP expansion

- Pre-thermal processes: scattering of incoming quarks and gluons

Collision overlap zone:
- Full overlap -> “central” collisions
- Non-complete overlap -> “peripheral” collisions
Nuclear collision and QGP expansion

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- Thermalization
  Equilibrium is established ($t \sim 1 \text{ fm}/c = 3 \times 10^{-24} \text{s}$)

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Same conditions of the Universe ~10μs after the Big Bang
Nuclear collision and QGP expansion

- **Pre-thermal processes**: scattering of incoming quarks and gluons

- **Thermalization**
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- **QGP expansion and cooling** (t ~ 10 fm/c)
  Described by an almost perfect fluid dynamics

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  Inelastic interactions cease, particle abundances frozen

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- **Kinetic freeze-out**
  Elastic interactions cease, particle dynamics (spectra) frozen

Same conditions of the Universe $\sim 10 \mu$s after the Big Bang

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Collision systems

- Heavy-Ion collisions
  - Study the QCD phase diagram in the laboratory
  - Create and characterize the Quark Gluon Plasma
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- **pp collisions**
  - Provide reference data to check differences wrt to heavy-ion collisions

- **p-Pb collisions**
  - Control experiment, “Cold Nuclear Matter” effects
Collision systems

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  - Study the QCD phase diagram in the laboratory
  - Create and **characterize the Quark Gluon Plasma**

• **pp collisions**
  - Provide **reference data** to check differences wrt to heavy-ion collisions

• **p-Pb collisions**
  - Control experiment, “Cold Nuclear Matter” effects

**Intriguing similarities between pp /p-Pb/Pb-Pb collisions:**

traditional signatures of Quark Gluon Plasma formation in heavy-ion collisions observed also in smaller systems (pp, and p-Pb)

**Collectivity in small systems?**
ALICE Detector

A Large Ion Collider Experiment

THE ALICE DETECTOR

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14. Muon Trigger
15. Dipole Magnet
16. PMD
17. AD
18. ZDC
19. ACORDE

Run-1 (2009-2013)

Pb-Pb @ $\sqrt{s_{NN}} = 2.76$ TeV
p-Pb @ $\sqrt{s_{NN}} = 5.02$ TeV
pp @ $\sqrt{s} = 0.9, 2.76, 7, 8$ TeV

Run-2 (2015-2018)

Pb-Pb @ $\sqrt{s_{NN}} = 5.02$ TeV
p-Pb @ $\sqrt{s_{NN}} = 5.02, 8.16$ TeV
pp @ $\sqrt{s} = 5, 13$ TeV
Light particle production

- High precision $p_T$ distributions of $\pi, K, p$
  - ITS, TPC, TOF and HMPID for particle identification

- Random thermal + collective motion driven by pressure gradient
- Particles move in a common velocity field

Hardening of the spectra consistent with a radial collective flow: common velocity gives larger momentum boost to heavier particles $p = \gamma m \beta$
Collective expansion

- Random thermal + collective motion driven by pressure gradient
- Particles move in a common velocity field

**Common radial velocity** $\langle \beta_T \rangle$ and kinetic freeze-out temperature $(T_{\text{kin}})$ extracted via a simultaneous fit to the $\pi$, K, p spectra with the Blast-Wave model

**Particle spectra consistent with collective expansion**
Collective expansion

- Random thermal + collective motion driven by pressure gradient
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Global Blast-Wave fit to π (0.5-1 GeV/c), K (0.2-1.5 GeV/c), p (0.3-3.0 GeV/c)
- ALICE Preliminary, pp, $\sqrt{s} = 7$ TeV
- ALICE, p-Pb, $\sqrt{s} = 5.02$ TeV
- ALICE, Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
- ALICE Preliminary, Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV

Common radial velocity $\langle \beta_T \rangle$ and kinetic freeze-out temperature ($T_{\text{kin}}$) extracted via a simultaneous fit to the π, K, p spectra with the Blast-Wave model

Particle spectra consistent with collective expansion
• \( v_2 \) elliptic flow: related to the geometry of the overlap zone, sensitive to the thermalization of the system

Quantified via the Fourier expansion:

\[
\frac{dN}{d\varphi} = \frac{N}{2\pi} \left[ 1 + \sum_{n=1}^{\infty} 2v_n \cos (n (\varphi - \Psi_R)) \right]
\]
Elliptic flow

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Mass ordering consistent with hydrodynamic expansion
Elliptic flow

- $v_2$ elliptic flow: related to the geometry of the overlap zone, sensitive to the thermalization of the system

$$\frac{dN}{d\phi} = \frac{N}{2\pi} \left[ 1 + \sum_{n=1}^{\infty} 2v_n \cos (n(\phi - \Psi_R)) \right]$$

Significant $v_2$ in p–Pb collisions
- Mass ordering just as in Pb–Pb
- Collectivity in high-multiplicity pp and p–Pb collisions?
Strangeness production in Pb-Pb collisions

- Strangeness enhancement originally proposed as a signature of QGP formation in nuclear collisions
  
  Rafelski & Muller, PRL 48 (1982) 1066

- Hyperon-to-pion ratio larger in Pb-Pb than in pp collisions and in agreement with thermal model expectations

- Enhancement increases with strangeness content
Strangeness production: new results @ 5 TeV

- Ratio of $p_T$-integrated yields to pions measured at both 2.76 TeV (not shown) and 5.02 TeV
- Strangeness increase compatible at the two energies
  - Apparently produced near thermal and chemical equilibrium
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Increase of strangeness observed also in high multiplicity \( pp/p-Pb \) events:
- At high multiplicity pp events the ratio reaches values similar to the ones in Pb-Pb

No evident dependence on center-of-mass energy
- Driven by final state rather than collision system or energy

Traditional models (e.g. Pythia) fail to reproduce the data
- Qualitative description only by models that introduce extra-mechanism providing ‘coherence’ (e.g DIPSY)

See also Nature Phys. 13 (2017) 535-539

27/02/2018
Heavy-flavor production: D mesons

A Large Ion Collider Experiment

• Heavy quarks are produced in parton hard scatterings in the initial phases of the heavy-ion collision
• Flavor is conserved in strong interactions
  – Transported through the full system evolution -> Probe properties (opacity, transport) of the medium

Nuclear modification factor:
(if $R_{AA}=1$ no medium effects)

$$R_{AA} = \frac{1}{N_{\text{coll}}} \frac{dN_{AA}/dp_T}{dN_{PP}/dp_T}$$
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- **Strong suppression of D mesons in Pb–Pb collisions**
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- Strong suppression of D mesons in Pb–Pb collisions
- No modification in p-Pb collisions

Strong energy loss of charm quarks in the medium
Heavy-flavor production: D mesons

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Nuclear modification factor: 
(if $R_{AA} = 1$ no medium effects)

$$R_{AA} = \frac{1}{N_{coll}} \frac{dN_{AA}/dP_T}{dN_{pp}/dP_T}$$

- Comparison of $D_s^+$ with non-strange D mesons hints a lower $D_s^+$ suppression
- Coalescence + strangeness enhancement?

Strong energy loss of charm quarks in the medium

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27/02/2018
Heavy-flavor production: quarkonia

- Binding energy dependent quarkonium \textbf{suppression} \rightarrow QGP thermometer
  \textit{Matzui and Satz, PLB 178 (1986) 416}

- Enhancement via \textbf{(re)generation} due to large c quark multiplicity at LHC

\begin{itemize}
  \item RHIC energy
  \begin{itemize}
    \item Start of collision
    \item Development of quark-gluon plasma
    \item Hadronization
  \end{itemize}

  \begin{itemize}
    \item \(J/\psi\) production probability
    \item Statistical regeneration
    \item Sequential suppression
  \end{itemize}

  \begin{itemize}
    \item Energy Density
  \end{itemize}

  \begin{itemize}
    \item LHC energy
  \end{itemize}
\end{itemize}
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- Enhancement via (re)generation due to large c quark multiplicity at LHC

\[ R_{AA} = \frac{1}{N_{\text{coll}}} \frac{dN_{AA}/d\eta}{dN_{\text{nn}}/d\eta} \]

- Larger suppression at RHIC than at LHC

-Compatible with regeneration scenario
Heavy-flavor elliptic flow $v_2$

- Non-zero $v_2$ for D mesons and $J/\psi$, and comparable with that for $\pi$

Further signs of charm thermalization and recombination
Heavy-flavor elliptic flow $v_2$

- Non-zero $v_2$ for D mesons and $J/\psi$, and comparable with that for $\pi$

In p-Pb collisions:
- At $p_T<3$ GeV/$c$ $v_2$ compatible with 0 (No recombination expected)
- At $p_T>3$ GeV/$c$ $v_2>0$
- Values compatible with $J/\psi$ $v_2$ in central Pb-Pb collisions

Suggest that charm quarks participate in collective effects also in p-Pb? other mechanism?
Charmed baryons

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- First mid-rapidity measurement of $\Lambda_c$ in pp and p-Pb collisions at the LHC
  - Charmed baryon-to-meson ratio not reproduced by event generators
- Measurement of $\Xi_c$ in pp collisions
- Constrains charm hadronization
- Benchmark for measurements in heavy-ion collisions
Major upgrade of ALICE apparatus during Long Shutdown 2 (2019-2020)

**Goals:** study rare low $p_T$ probes (heavy flavour and quarkonia, low mass dielectrons, nuclei)
- Non triggerable probes -> Need continuous readout at 50 kHz (x50 faster)
- Improve tracking resolutions at low $p_T$ and vertexing -> increase granularity and reduce material thickness
- Secondary vertex for measurements in the forward region

• **Data taking during Run 3-4** (2021-2029) : aim at 10 nb$^{-1}$
Conclusions

Progress in the **characterization of the QGP created in heavy-ion collisions**
Run 2 (Pb–Pb at 5 TeV): similar trends, more data ⇒ **precise** characterization

Early thermalization and strong collective behavior consistently described by hydrodynamic models

Strangeness enhancement as predicted in a QGP medium

Suppression of heavy flavor and high $p_T$ particle production wrt to binary scaled pp collisions

Evidence of collective behaviour in p-Pb and high-multiplicity pp collisions

Smooth strangeness enhancement from pp to p-Pb driven by event multiplicity

Heavy flavors are **NOT** suppressed

More to come with the **upgrade**: high Pb-Pb luminosity and improved tracking
Nuclei production

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- Heavy-ion collisions are also factory for nuclei
- Production mechanism of compound objects inside the fireball
  - Coalescence or thermal production?

\[
\frac{2d}{(p+p)} \times 10^{-3}
\]

ALICE Preliminary

- Increase of d/p ratio with multiplicity expected from coalescence model
- Saturation at high multiplicities expected for thermal production

\[
\langle dN_{ch} / d\eta_{lab} \rangle_{|\eta_{lab}| < 0.5}
\]

ALICE—PUBLIC-2017-007

- Yield compatible with exponential fall predicted by the thermal model with \( T_{chem} \sim 156 \text{ MeV} \)

Mechanism of nuclei production not yet fully understood

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27/02/2018
Hyper-Nuclei production

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- Heavy-ion collisions are also factory for hyper-nuclei
- Hypernucleus: nucleus containing at least an hyperon
- Hypertriton \((^3\Lambda\text{He})\) is the lightest hypernucleus formed by \((p,n,\Lambda)\)

\[
^3\Lambda\text{H} \rightarrow ^3\text{He} + \pi^-
\]

Most precise measurement of hypertriton lifetime

\[
\tau = 223^{+41}_{-33} \text{(stat.)} \pm 20 \text{(syst.) ps}
\]