ALICE Overview

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University of Torino and I.N.F.N. (Italy)
for the ALICE Collaboration
A Large Ion Collider Experiment

Introduction

• After a short introduction, a selection of ALICE results will be presented
  ➡ Emphasis will be given to recent Run 2 analyses
  ➡ Selection means that several topics will be left out, but several ALICE talks have been scheduled in this conference: they will help to fill the gaps!

• ALICE talks:

  Aug, 22 ➡ A. Isakov, Heavy-flavour jets in ALICE
              ➡ M. Gagliardi, Detector and Trigger performance in ALICE during Run2

  Aug, 24 ➡ F. Catalano, Measurement of D-meson production and flow in Pb-Pb collisions with ALICE at the LHC
            ➡ D. Hatzifotiadou, Outreach activities of the ALICE experiment

  Aug, 26 ➡ A. Fantoni, Upgrade of the ALICE inner tracking: construction and commissioning
            ➡ K. Gulbrandsen, The ALICE Upgrade: Future Prospects
            ➡ M. Toppi, Multiplicity and energy dependence of light charged particle production in ALICE at the LHC
            ➡ M. Vasileiou, Strangeness production with ALICE at the LHC.

  Aug, 27 ➡ B.Lim, Recent Measurements Hadronic Resonances with ALICE at the LHC
            ➡ S. Bufalino, Production of light (anti-)(hyper-)nuclei at LHC energies with ALICE
Why ALICE?

- **ALICE**: A Large Ion Collider Experiment
- **Main goal**: Study the properties of strongly-interacting matter at extreme conditions of temperature and energy density
  - The QCD phase diagram at high temperature and vanishing baryochemical potential is accessible in collisions of heavy nuclei at the highest energies
  - The transition to a state in which partons and gluons are deconfined (Quark Gluon Plasma, QGP) can be created in the laboratory
  - Early Universe: QGP-hadron transition at $t \sim 10^{-6}$ s after the Big Bang
- **Lattice QCD**: cross-over from hadrons to QGP at
  - Critical temperature $T_c \approx 145 - 160$ MeV
  - Energy density $\epsilon_c \approx 0.5$ GeV/fm$^3$

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A. Bazarov et al, PRD 90 (2014) 094503
S. Borsanyi et al, JHEP 1009 (2010) 073
Space-time evolution of a Heavy-Ion collision

**Initial state**
- Collision: Hard probes generation
- QGP: thermalization and expansion

**Final state**
- Chemical freeze-out
- Bulk production
- Kinetic freeze-out: Particles stream to the detector

**Collision time**
- Formation time (charm quark):
  \[
  \frac{1}{2m_c} = 0.08 \text{ fm/c} \approx 3 \times 10^{-25} \text{ s}
  \]
- Collision time:
  \[
  \frac{2R}{\gamma} = 0.005 \text{ fm/c} \approx 2 \times 10^{-26} \text{ s}
  \]

**QGP life time**
- \(10 \text{ fm/c} \approx 3 \times 10^{-23} \text{ s}\)

**Thermalization time**
- \(0.2 \text{ fm/c} \approx 7 \times 10^{-25} \text{ s}\)
ALICE

- **Inner Tracking System**: vertexing, tracking and PID
- **Time Projection Chamber**: tracking and PID
- **Time-Of-Flight**: PID
- **Material budget**: 0.08 % $X_0$
- **Particle ID**: 0.1 ÷ 20 GeV/c
- **Momentum resolution**: $\sim 1 - 7\%$ for $p_T = 0.1 - 20$ GeV/c

Muon spectrometer
ALICE

• **V0**: multiplicity/centrality classification

• **EMCAL**: e.m. calorimeter

• **PHOS**: photon spectrometer

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Much more on ALICE apparatus in M. Gagliardi’s talk on August, 22nd.
Data sets - Run 1 & Run 2

- **In Run 2**: significant increase of integrated luminosity:
  - Higher precision
  - Rare probes
- Different collisions systems and energies:
  - Energy and system dependence studies of particle production are possible

<table>
<thead>
<tr>
<th>System</th>
<th>Year</th>
<th>$v_{sNN}$ (TeV)</th>
<th>$L_{int}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb-Pb</td>
<td>2010-2011</td>
<td>2.76</td>
<td>~75 µb⁻¹</td>
</tr>
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<td>~250 µb⁻¹</td>
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<tr>
<td>Xe-Xe</td>
<td>2017</td>
<td>5.44</td>
<td>~0.3 µb⁻¹</td>
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<td>pp</td>
<td>2009-2013</td>
<td>0.9, 2.76, 7, 8</td>
<td>~200 µb⁻¹, ~100 µb⁻¹, ~1.5 pb⁻¹, ~2.5 pb⁻¹</td>
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<td></td>
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- **pp 13 TeV**
  - High multiplicity triggers
  - Reference for rare probes
- **pp 5.02 TeV**
  - Reference data sample for Pb-Pb

- **Pb-Pb 2018**
  - Central (0-10%): 9x2015
  - Mid-Central (30-50%): 4x2015
ALICE performance in Pb-Pb 2018

- Fast reconstruction for calorimeters and muon spectrometer synchronous with data taking.
- Improved data quality with respect to 2015
  - Reduced space charge distortions in the TPC
- Analysis is ongoing, but several results are already available

\[ Y(1S) \rightarrow \mu^+\mu^- \]

\[ J/\psi \rightarrow \mu^+\mu^- \]

Ultra Peripheral Collisions
The initial state of the collision

• What is the structure of the colliding objects?
  ➤ Spatial and momentum distribution of incoming partons
  ➤ Modification of the PDFs in bound nucleons (nPDF)
  ➤ Gluon saturation at small Bjorken-x / Color Glass condensate

• Insight into initial state via:
  ➤ p-Pb collisions
  ➤ Ultra-Peripheral Pb-Pb collisions
    ✓ Impact parameter $b > 2R_2$
    ✓ Hadronic interactions are suppressed
Ultra-Peripheral Pb-Pb collisions

- Coherent $J/\psi$ photo production
  - $\gamma$ coupling coherently to the nucleus
  - Low $p_T$ $J/\psi$, target nucleus not breaking up
  - Sensitive to gluon PDFs at low Bjorken-$x$
    ($\sim 10^{-5} \div 10^{-2}$)
  - ✓ shadowing region

Models without gluon shadowing overpredict the data

Moderate shadowing in the nucleus necessary to describe the measurements
The final state of the collision

- Up to ~21000 charged particles are produced in a central Pb-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV.
- The kinematics of the produced particles is frozen at the kinetic freeze-out.
- ALICE measurements of these bulk particles provide information on the geometry of the collision and on the evolution of the created fireball:
  - charged particle multiplicity
  - transverse momentum spectra of identified particles
  - collective phenomena
  - correlations
Multiplicity in pp, p-Pb, Xe-Xe and Pb-Pb

- Charged multiplicity expressed either as $\langle dN_{ch}/d\eta \rangle$ or $N_{ch}^{tot}$ scaled by the number of participant pairs.
- $\sqrt{s}$ dependence in A-A collisions differs from pp and p-Pb
  - No universal scaling
- In central Xe-Xe: multiplicity per part. pair follows the same power-law fit with energy found with previous A-A measurements.
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- In central Xe-Xe: multiplicity per part. pair follows the same power-law fit with energy found with previous A-A measurements.

- As a function of centrality:
  - Deviations from \( N_{\text{part}} \) scaling in all A-A available data
  - Steeper rise in most central A-A collisions possibly due to upward fluctuations

- The underlying mechanism to describe the increase with energy and centrality is still not completely understood
ALICE has measured $p_T$ spectra for identified hadron in the central rapidity region.

- Even at LHC energy, 95% of produced particles have $p_T < 2$ GeV/c.
- Bulk of particle production associated with "soft" physics in non-perturbative regime of QCD.

Hardening of the spectral shapes with increasing centrality and particle mass.
The flowing “bulk” of soft particles

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- For p-Pb (and pp) modifications mostly for $p_T < 3 \text{ GeV/c}$
- New: p-Pb sample at 8.16 TeV (2018)
The flowing “bulk” of soft particles

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Radial flow

- The hardening of the $p_T$ spectra is described by hydrodynamic expansion of the medium (radial flow) with transverse velocity $\beta_T$

- Simultaneous blast-wave fits to $\pi^\pm$, $K^\pm$ and $p + \bar{p}$ spectra with $T_{\text{kin}}$ (kinetic freeze-out temperature) and $\langle \beta_T \rangle$ as parameters

- **Pb-Pb collisions**: $T_{\text{kin}}$ decreases and $\langle \beta_T \rangle$ increases with centrality

- **Small systems**: $\langle \beta_T \rangle$ increases with multiplicity
  - $T_{\text{kin}}$ higher w.r.t. Pb-Pb
  - At the same multiplicity $\langle \beta_T \rangle$ larger in smaller systems

- **Simplified approach** more complete modeling: hydrodynamical model + freeze-out and resonance decays.

Anisotropic transverse flow

• Reaction plane: it contains the beam direction and the centers of the colliding nuclei

• **Hydrodynamic description**: the initial spatial anisotropy of the overlap region becomes a momentum anisotropy:
  ➤ Larger pressure gradients imply more particles emitted in-plane

• The anisotropy is:
  ➤ quantified through a Fourier decomposition of the azimuthal distribution, w.r.t. reaction plane
  ➤ expressed via the $v_n$ coefficients
  ➤ $v_2$ (elliptic flow) is sensitive to the initial geometry

• Higher flow harmonics are particularly sensitive to:
  ➤ **initial state fluctuations** (odd harmonics as $v_3$ should be 0 without fluctuations)
  ➤ the value of $\eta/s$ (shear viscosity / entropy density) in hydrodynamic calculations.

\[
\frac{dN}{d\varphi} = \frac{N_0}{2\pi} \left\{ 1 + 2 \sum_{n=1}^{\infty} v_n(p_T) \cos [n(\varphi - \Psi_{RP})] \right\}
\]

\[
v_n = \langle \cos [n(\varphi - \Psi_{RP})] \rangle
\]
Anisotropic transverse flow - light flavors

- Elliptic flow ($v_2$) at low $p_T$ governed by hydrodynamics: mass ordering originating from collective radial flow velocity
- At ~3 GeV/$c$: baryon-meson crossing → particle production via coalescence
- Connection between initial-state fluctuations and final-state particle $v_n$ sensitive to QGP properties such as shear and bulk viscosity
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- **Elliptic flow has been observed also for light nuclei as deuteron (and $^3$He)**
  - Hydrodynamical simulation (iEBE-VISHNU) + coalescence give a good description of the observed $v_2$ (and $v_3$)
Constrain initial state and QGP properties

Multiple experimental info are needed:
- \( v_2 \) and higher harmonics
- Data at different collision energies
- Correlations amongst \( v_n \)

Energy dependence is sensitive to \( \eta/s \) (viscosity / entropy density)
Constrain initial state and QGP properties

ALICE measurements help in constraining \( \eta/s \) vs \( T \)

\( \eta/s \) is close to its quantum limit

\( v_2 \) and higher harmonics

Data at different collision energies

Correlations amongst \( v_n \)

Energy dependence is sensitive to \( \eta/s \)

\( (*) \) KSS bound \( 1/4\pi \)


\( ALICE, JHEP07 (2018) 103 \)

\( J. Bernhard et al, Phys. Rev. C 94, 024907 \)
**D-meson anisotropic transverse flow**

- Charm produced isotropically in the early stage of the collision
  - azimuthal anisotropy \( v_2 \) acquired by interactions with the QGP
- For HF, specifically at high \( p_T \), parton energy loss is the driving factor of the observed anisotropy
- Positive \( D \)-meson \( v_2 \) in mid-central \( \text{Pb-Pb} \) collisions indicates participation of charm quark in the collective motion
  - \( v_2(D) \approx v_2(\pi^\pm) \) for \( p_T > 3 - 4 \) GeV/c
  - Hint of \( v_2(D) < v_2(\pi^\pm) \) for \( p_T < 3 - 4 \) GeV/c

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![Graph](ALICE Preliminary)

**ALICE Preliminary**

- 30–50% \( \text{Pb-Pb}, \sqrt{s_{NN}} = 5.02 \) TeV
- Prompt \( D^0, D^+, D^{**} \) average, \(|y|<0.8\)
- \( v_2 \) \{SP, \(|\Delta\eta|>0.9\}\)
- \( \pi^\pm, |y|<0.5\)
- \( v_2 \) \{SP, \(|\Delta\eta|>2\} \) JHEP 1809 (2018) 006
- Charged particles, \(|\eta|<0.8\)
- \( v_2 \) \{SP, \(|\Delta\eta|>2\} \) JHEP 07 (2018) 103

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Syst. from data

Syst. from B feed-down

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**ICNFP 2019 | M. Masera**
**D-meson anisotropic transverse flow**

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- Same $v_2$ for $D_s^+$ and non strange $D$ mesons within uncertainties down to 3 GeV/$c$
- $v_2(D) > v_2(J/\psi)$ for $p_T < 6$ GeV/$c$
  - charm-quark coalescence with flowing light-flavor quarks?
The significant $J/\psi$ flow observed confirms the contribution of $J/\psi$ production from recombination.

- Transport models including (re)generation component describe low $p_T$ well.

$v_2$ at $p_T > 6$ GeV/$c$ not described by transport models.

- $v_2$ of similar magnitude in this $p_T$ range observed in p-Pb collisions.
- Same (unknown) origin?
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- Πάντα ρεῖ? Does everything flow?
  - First measurement of $\Upsilon$ (1S) elliptic flow: $v_2$ is compatible with 0
  - A small $v_2$ was predicted by transport model simulations:
    - The dissociation of the $\Upsilon$ in the medium occurs at higher temperature w.r.t. $J/\psi$
    - Early dissociation when path length differences are less influential
    - Negligible contribution from $b\bar{b}$ recombination
The significant flow observed confirms the contribution of production from recombination \( J/\psi \to \psi \). Transport models including (re)generation component describe low \( p_T \) at \( GeV/c \) not described by transport models.

\[ v_2 \text{ at } p_T > 6 \text{ GeV} \]

\[ v_2 \text{ of similar magnitude in this range observed in } p-Pb \text{ collisions} \]

\[ \text{Same (unknown) origin?} \]

\[ \text{Πάντα ρεῖ?} \]

First measurement of elliptic flow: \( v_2 \) is compatible with 0 \( \Upsilon(1S) \). A small \( v_2 \) was predicted by transport model simulations. The dissociation of the in the medium occurs at higher temperature w.r.t. \( \Upsilon J/\psi \). Early dissociation when path length differences are less influential. Negligible contribution from recombination.

**Bottomonium particles don’t go with the flow**

The first measurement, by the ALICE collaboration, of an elliptic-shaped flow for bottomonium particles could help shed light on the early universe.

16 JULY, 2019 | By Ana Lopes
Measurement of $\Upsilon(1S)$ elliptic flow at forward rapidity in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

ALICE Collaboration

Abstract

The first measurement of the $\Upsilon(1S)$ elliptic flow coefficient ($v_2$) is performed at forward rapidity ($2.5 < y < 4$) in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV with the ALICE detector at the LHC. The results are obtained with the scalar product method and are reported as a function of transverse momentum ($p_T$) up to 15 GeV/c in the 5–60% centrality interval. The measured $\Upsilon(1S) v_2$ is consistent with zero and with the small positive values predicted by transport models within uncertainties. The $v_2$ coefficient in $2 < p_T < 15$ GeV/c is lower than that of inclusive $J/\psi$ mesons in the same $p_T$ interval by 2.6 standard deviations. These results, combined with earlier suppression measurements, are in agreement with a scenario in which the $\Upsilon(1S)$ production in Pb–Pb collisions at LHC energies is dominated by dissociation limited to the early stage of the collision whereas in the $J/\psi$ case there is substantial experimental evidence of an additional regeneration component.
Final state interactions: rescattering

- In the **hadronic phase**:
  - **Regeneration**: resonances formed in hadron scattering
  - **Re-scattering** of decay daughters: signal loss
- $\rho$, $K^*$, $\Lambda^*$ **reduced yield**: final state scattering of decay particles
- $\phi$, $\Xi^*$: longer lifetime $\rightarrow$ **constant yield**

### Results are consistent with the existence of a hadronic phase

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<tr>
<td>$\Sigma^*$</td>
<td>5.5</td>
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<tr>
<td>$\Lambda^*$</td>
<td>12.6</td>
</tr>
<tr>
<td>$\Xi^*$</td>
<td>21.7</td>
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<tr>
<td>$\phi$</td>
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### Particle Yield Ratios

- $K^0/K$ ($\times 1.2$)
- $\Sigma^0/\Lambda$ ($\times 0.5$)
- $\Lambda(1520)/\Lambda$
- $\Sigma^0/\Xi$ ($\times 0.08$)
- $\eta/K$ ($\times 0.08$)

**ALICE Preliminary**
- $pp$ $\sqrt{s} = 7$ TeV
- $p$-$p$ $\sqrt{s}_{NN} = 5.02$ TeV
- $Pb$-$Pb$ $\sqrt{s}_{NN} = 5.02$ TeV
- $Xe$-$Xe$ $\sqrt{s}_{NN} = 5.44$ TeV

**ALICE**
- $pp$ $\sqrt{s} = 2.76$ TeV
- $p$-$p$ $\sqrt{s} = 7$ TeV
- $p$-$Pb$ $\sqrt{s}_{NN} = 5.02$ TeV
- $Pb$-$Pb$ $\sqrt{s}_{NN} = 2.76$ TeV

**STAR**
- $pp$ $\sqrt{s} = 200$ GeV
- $Au$-$Au$ $\sqrt{s}_{NN} = 200$ GeV

- EPOS3
- EPOS3 (UrQMD OFF)
**Final state interactions: rescattering**

- **In the hadronic phase:**
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- **$\rho$, $K^*$, $\Lambda^*$ reduced yield:** final state scattering of decay particles
- **$\phi$, $\Xi^*$** : longer lifetime $\rightarrow$ constant yield

**Results are consistent with the existence of a hadronic phase**

**ALICE Preliminary**

- $p^0/\pi$ ($\times 7.0$)
- $K^{0s}/K$ ($\times 1.2$)
- $\Sigma^+/\Lambda$ ($>0.5$)
- $\Lambda(1520)/\Lambda$
- $\Sigma^0/\Sigma$ ($>0.08$)
- $\phi/K$ ($>0.08$)

**Hadron** | **Lifetime (fm/c)**
---|---
$\rho$ | 1.3
$K^*$ | 4.2
$\Sigma^*$ | 5.5
$\Lambda^*$ | 12.6
$\Xi^*$ | 21.7
$\phi$ | 46.2
Final state interactions: correlations

- Femtoscopy: final-state momentum correlations.
- Sensitive to:
  - Space-time distribution of production points
  - Interaction and quantum statistics
- Traditionally femtoscopy is used to study the space-time characteristics of the emitting source ($S(\vec{r})$)
- Here we assume a common source, measure correlation $C(k^*)$ to study Hyperon-Nucleon and Hyperon-Hyperon interactions
- Relevant for nuclear EOS at $T=0$

ALICE: first observation of an attractive interaction between a proton and a multi-strange baryon (arXiv:1904.12198). Data set: p-Pb at 5.02 TeV
Final state interactions: correlations

- Data set: pp collisions at 13 TeV
- Source size identical for pp and p-Λ
- One common source distribution for all particle pairs
- Data agree with **HAL QCD potential**
Final state interactions: correlations

- Data set: pp collisions at 13 TeV
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- Data agree with HAL QCD potential
- HAL QCD: the nucleon-Ω system was studied in the $^5S_2$ channel

(T. Iritani et al. arXiv:1810.03416)
Hadrochemistry

- At the chemical freeze-out
  - Inelastic collisions cease
  - Abundances of different species of hadrons are fixed
- Hadron yields described by statistical / thermal models

Yields depend on
- masses/spin
- Chemical potentials
- Temperature

Hadron yields: statistical model

- Good experimental precision
- Overall good description of the data
  - Tensions with baryons and resonances
- Temperature and chemical potential:
  - $T = 152 \pm 3$ MeV
  - $\mu_B \approx 0$
- Agreement with Lattice QCD:
  - $T_{PC} = 156.5 \pm 1.5$ MeV

A.Bazavov et al. (Hot QCD)
arXiv:1812.08235

(*) QCD pseudo-critical temperature for chiral crossover at $\mu_B = \mu_S = \mu_Q = 0$
**Strangeness production**

- **Charged particle multiplicity** is the driving variable governing strangeness production.
- Charged particle multiplicity is a proxy for the system size.
- A smooth increase of strange hadrons w.r.t. pions with multiplicity is observed until saturation is reached.
- Consistent results for different collision systems and energies measured in ALICE: pp, p-Pb, Xe-Xe and Pb-Pb.
  - Common microscopic description?
- Strangeness enhancement with growing system size is consistent with its canonical suppression in small systems.
  - No longer seen as a smoking gun for QGP formation.
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- Charged particle multiplicity is a proxy for the system size.
- A smooth increase of strange hadrons w.r.t. pions with multiplicity is observed until saturation is reached.
- Consistent results for different collision systems and energies measured in ALICE: pp, p-Pb, Xe-Xe and Pb-Pb
  - Common microscopic description?
- Strangeness enhancement with growing system size is consistent with its canonical suppression in small systems
  - No longer seen as a smoking gun for QGP formation.

Much more on strangeness in M. Vasileiou’s talk This morning Room 2
Production of (anti-)deuterons

- Production of (anti-)(hyper-)nuclei is described by
  - Thermal models: they are emitted in statistical equilibrium at the chemical freeze-out
  - Coalescence models: they are formed at the kinetic freeze-out by coalescence of baryons close in phase space

- Both models describe particular aspects of the available data. As an example:
  - The d/p ratio has a smooth dependence on the multiplicity, independently on the collision system
    ✓ This may indicate a common production mechanism driven by the system size
    ✓ The ratio increases smoothly at low multiplicity → consistent with simple coalescence (d ∝ p²)
    ✓ It flattens at higher multiplicities → consistent with the thermal model
    ✓ The hint of suppression at the highest multiplicities is not significant with the present uncertainties
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Hard Probes of the QGP medium

- Produced at the **very early stage** of the collision in partonic scattering processes with large momentum transfer

- Traverse the hot and dense medium interacting with its constituents
  - The hard-scattered parton interacts with the medium constituents -> energy loss through:
    - Elastic collisions
    - Gluon radiation
  - Gluon radiation Energy loss depends on:
    - Medium density
    - Path-length in the medium
    - Parton species (gluon vs. quark) and mass

- Unique probes of the properties of the QGP
  - Tomography of the medium
A Large Ion Collider Experiment

**Nuclear Modification Factor**

- In nuclear collisions hard processes expected to scale with the number of binary collisions ($N_{\text{coll}}$)

- The nuclear modification factor is defined as

$$R_{AA}(p_T) = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

- If no nuclear effects $R_{AA} = 1$

- In-medium energy loss $\rightarrow R_{AA} < 1$ at high $p_T$ (jet quenching).

- $R_{pp} \sim 1$ at high $p_T$: no jet quenching in p-Pb collisions

- $R_{AA} < 1$ in Pb-Pb collisions

  - Jet quenching increases with centrality

- Open question: collectivity in p-A without energy loss

  - When does energy loss turns on?
**$R_{AA}$ and jet production**

- Jets are reconstructed to lower momentum thanks to ML-based analysis tools
- Good agreement with standard analysis method at high $p_T$
- Substantial suppression of jets on the whole $p_T$ range
- The suppression is large even when opening the jet cone
  - Interactions with the medium transport momentum to large angles

$p_T$ spectra

$R_{AA}$ - Jet radius R=0.2

$R_{AA}$ - Jet radii R=0.4 and 0.6

- **ALICE** Pb-Pb 5.02 TeV, 0-10%
  - Charged jets, anti-$k_T$, $|\eta_{jet}| < 0.9 - R$
  - ML estimator trained on PYTHIA

- **ALICE** Pb-Pb 5.02 TeV, 0-10%
  - Charged jets, anti-$k_T$, $R = 0.2$, $|\eta_{jet}| < 0.7$
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- **ALICE** Preliminary
  - $T_{AA}$ normalization uncertainty

- **ALICE** Preliminary
  - Hybrid model, $L_{res} = 0$
    - $R = 0.4$
    - $R = 0.6$
$R_{AA}$ and jet production

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More on HF jets in A. Isakov’s talk on August, 22nd

**$p_T$ spectra**

ALICE Pb-Pb 5.02 TeV, 0-10%
Charged jets, anti-$k_T$, $|\eta_{jet}| < 0.9 - R$
ML estimator trained on PYTHIA

- $R = 0.2$
- $R = 0.4$
- $R = 0.6$

**$R_{AA}$ - Jet radius $R=0.2$**

ALICE Pb-Pb 5.02 TeV, 0-10%
Charged jets, anti-$k_T$, $R = 0.2$, $|\eta_{jet}| < 0.7$
ML estimator trained on PYTHIA
- ML-based
- Area-based ($p_{T,lead} > 5 \text{ GeV/c, POWHEG ref.}$)

**$R_{AA}$ - Jet radii $R=0.4$ and 0.6**

ALICE Pb-Pb 5.02 TeV, 0-10%
Charged jets, anti-$k_T$, $|\eta_{jet}| < 0.9 - R$
ML estimator trained on PYTHIA
- $R = 0.4$
- $R = 0.6$

$N_{coll}$ uncertainty not shown
ALICE Preliminary
D mesons $R_{AA}$

- D-meson $R_{AA}$ larger than pion $R_{AA}$ for $p_T < 8$ GeV/c
- Described by models including
  - Energy loss hierarchy: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c$
  - Different $p_T$ shapes of produced partons
  - Different fragmentation functions of gluons, light and charm quarks

![Graph showing $R_{AA}$ as a function of $p_T$]
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Much more on D mesons in F. Catalano’s talk on August, 24th
D mesons $R_{AA}$ and elliptic flow

- Simultaneous comparison of $R_{AA}$ and $v_2$ to models can constrain QGP properties and the description of charm-quark interaction and diffusion in the medium
- Interplay of Cold Nuclear Matter effects, collisional and radiative energy loss, hadronization via coalescence and fragmentation and realistic underlying medium evolution required to describe data

![Graph 1](ALICE Preliminary)

$R_{AA}$ for 0–10% Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
Prompt $D^0$, $D^+$, $D^{**}$ average, $|y| < 0.5$

![Graph 2](ALICE Preliminary)

$v_2$ for $30–50\%$ Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
- Prompt $D^0$, $D^+$, $D^{**}$ average
- Open markers: $p_T$-extrapolated reference
- Filled markers: pp measured reference

![Graph 3](ALICE Preliminary)

$v_2$ for $|y| < 0.8$
- $p_T$ (GeV/c) range from 5 to 35
**$\Lambda_c$ production**

- $\Lambda_c/D^0$ ratio in pp:
  - Significantly larger than from $e^+ + e^-$ expectations
- $\Lambda_c/D^0$ ratio in Pb-Pb:
  - Enhanced at low $p_T$ (<6 GeV/c) with respect to pp
  - Compatible with pp results for $p_T > 10$ GeV/c
  - Consistent with a scenario of baryon enhancement due to charm quark hadronization via recombination
ALICE @ LHC Runs 3 and 4

- ALICE will exploit its specific potentials:
  - Tracking & PID
  - Low $p_T$ reach
- ALICE aims to carry out high precision measurements of
  - heavy flavor and quarkonia
  - jets
  - low-mass dileptons
  - light (hyper-)nuclei
- The Pb-Pb data sample in Runs 3 and 4 is expected to increase by an order of magnitude w.r.t. Run 2

Run 2: $\mathcal{L}_{\text{Pb-Pb}} = 1.0$ nb$^{-1}$
Run 3: $\mathcal{L}_{\text{Pb-Pb}} = 6.0$ nb$^{-1}$
Run 4: $\mathcal{L}_{\text{Pb-Pb}} = 7.0$ nb$^{-1}$
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A Large Ion Collider Experiment

Ongoing upgrades

Inner Tracking System

Time Projection Chamber

Fast Interaction Trigger

Requirements

- operation at high interaction rates (50 kHz of Pb–Pb collisions)
- continuous (i.e. untriggered) read-out for core detectors
Timeline

- TPC remove MWPC ROC
- TPC survey
- ITS construction and assembly complete
- ITS IB construction complete commissioning beginning on ground
- MFT disk production complete
- TPC QEM ROC installation
- TPC irradiation tests
- ITS on ground commissioning ends
- ITS, MFT, FIT installation begins
- LHC commissioning begins

- May 19
- Aug’ 19
- Oct’ - Dec’ 19
- Feb’ 20
- May 20
- Feb’ 21
Conclusions

- LHC Run2 is yielding a rich harvest of physics results.
- ALICE has a broad physics program comprising \textit{pp, p-Pb and Pb-Pb} collision systems to study QCD in its non perturbative regime.
- Small collision systems turned out to be \textit{a lot more than a mere comparison} for Pb-Pb studies, providing interesting results (e.g. collectivity, strangeness production) and posing new questions.
- The analysis of the data collected in Run 2 is advancing at full blast and several new results have been presented this summer.
- \textbf{Run 2 results constrain}
  - Initial stage from azimuthal anisotropies and UPC
  - QGP transport parameters, such as shear viscosity, quark diffusion and energy loss
- \textbf{Impressive progress in understanding QCD} at high temperature and energy density: LHC Runs 3 & 4 will provide unprecedented \textit{precision} to move further
  - The construction and commissioning activities for the LHC Run 3 are proceeding on schedule.
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Σας ευχαριστώ για την προσοχή σας
Additional material
Blast-wave fits - details


- A simultaneous fit to transverse momentum spectra of $\pi^\pm$, $K^\pm$ and $p + \bar{p}$ is carried out.

- The Blast-Wave functional form is given by:

$$\frac{1}{p_T} \frac{dN}{dp_T} \propto \int_0^R rdr m_T I_0 \left( \frac{p_T \sinh \rho}{T_{kin}} \right) K_1 \left( \frac{m_T \cosh \rho}{T_{kin}} \right)$$

Where $\rho$ is the velocity profile and it is described as

$$\rho = \tanh^{-1} \beta_T \quad \text{with} \quad \beta_T(r) = \left( \frac{r}{R} \right)^n \beta_s$$

- The free parameters of the fit (in red color above) are:
  - The kinetic freeze-out temperature $T_{kin}$
  - The expansion transverse velocity $\beta_s$ at the surface of the fireball
  - The exponent $n$ of the velocity profile

$I_0$ and $K_0$ are modified Bessel functions
$R$ is the radius of the fireball
$m_T = \sqrt{p_T^2 + m^2}$ is the transverse mass
Blast-wave fits - details

- The Blast-Wave parameterization assumes a locally thermalized medium, expanding collectively with a common velocity field and undergoing an instantaneous common freeze-out.

- A simultaneous fit to transverse momentum spectra of $\pi$, $K$, $p$, and $\bar{p}$ is carried out.

- The Blast-Wave functional form is given by:

$$ \frac{1}{N_{\text{ev}}} \frac{d^2 N}{d^2 p_T} (\text{GeV}/c)^2 $$

$$ \rho(r) = \frac{1}{p_T} W(r) $$

$$ \frac{\rho}{T} : $$

$$ T_0 $$

$$ \frac{1}{p_T} $$

$$ W $$

- The kinetic freeze-out temperature $T_{\text{kin}}$
- The expansion transverse velocity $v_s$
- The exponent $n$ of the velocity profile $\pi^+ + \pi^-(\times 100)$ $K^+ + K^-(\times 10)$ $p + \bar{p}(\times 1)$

- The free parameters of the fit (in red color above) are:
  - $T_{\text{kin}}$
  - $v_s$
  - $n$

- ALICE, arXiv:1807.11321
$v_n$ and models

iEBE-VISHNU **hydrodynamical calculations** describe the measured $v_n$ of $\pi^\pm$, $K^\pm$ and $p + \bar{p}$ fairly well for $p_T < 2.5$ GeV/$c$, while MUSIC reproduces the measurements for $p_T < 1$ GeV/$c$. 

![Graph](image-url)

And references therein for the models.
$v_n$ and models

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$K^\pm$
\( v_n \) and models

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\[ p + \bar{p} \]
\( v_n \) scaling properties

- To test the hypothesis of particle production by coalescence both \( v_n \) and \( p_T \) are divided by the number of constituent quarks \( n_q \).
- For \( p_T/n_q > 1 \text{ Gev/c} \) the scaling is approximate.
- Deviations from perfect scaling in the range of
  - \( \pm 15\% - \pm 20\% \) for \( v_2 \)
  - \( \pm 20\% \) for \( v_3 \) and \( v_4 \)

![Graph showing \( v_2 \) scaling properties](image-url)
• Mid-rapidity and forward rapidity results exhibit comparable suppression at high $p_T$

• Stronger $R_{AA}$ increase towards lower $p_T$ for mid-rapidity
  → (re)generated $J/\psi$ concentrated at low $p_T$ at mid-rapidity

• Trend described by transport and statistical hadronization model within the current experimental and theoretical uncertainties