Multiplicity and centre-of-mass energy dependence of light-flavor hadron production in pp, p-Pb, and Pb-Pb collisions with ALICE

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Introduction and motivations

• In high-energy nuclear collisions the $p_T$ distributions of identified hadrons carry information about the system evolution

Why study identified particle $p_T$-spectra in pp, p-A and A-A collisions at different energies?

✓ Comparison between collision systems:
  ↔ Radial flow (small systems?)
  ↔ In-medium energy loss

✓ Comparison between collision energies:
  ↔ Energy scaling?

✓ Comparison to hydro models
  ↔ Models describe the measured scenario?
  ↔ Kinetic freeze-out temperature?
  ↔ Transverse velocity distribution?
Overview

1. ALICE experimental apparatus
2. Transverse-momentum spectra
3. Integrated yields and $\langle p_T \rangle$
4. Comparison to models
ALICE experimental apparatus

> Focus on Particle Identification (PID)
ALICE experimental apparatus

> Focus on Particle Identification (PID)

**Inner Tracking System (ITS)**

Primary and secondary vertex determination, tracking, PID through dE/dx ($\sigma_{dE/dx} \sim 11\%$)
ALICE experimental apparatus

> Focus on Particle Identification (PID)

V0

- Trigger + centrality determination.
ALICE experimental apparatus

> Focus on Particle Identification (PID)

**Time Projection Chamber (TPC)**

- Tracking, PID through \( dE/dx \) (\( \sigma_{dE/dx} \sim 5\% \))
ALICE experimental apparatus

> Focus on Particle Identification (PID)

**Time Projection Chamber (TPC)**
- Tracking, PID through $dE/dx$ ($\sigma_{dE/dx} \sim 5\%$)

**Time Of Flight (TOF)**
- PID through time-of-flight measurement ($\rightarrow \beta$): $\sigma_{TOF} \sim 60-80$ ps
ALICE experimental apparatus

Focus on Particle Identification (PID)

**Time Projection Chamber (TPC)**
- Tracking, PID through $dE/dx$ ($\sigma_{dE/dx} \sim 5\%$)

**Time Of Flight (TOF)**
- PID through time-of-flight measurement ($\rightarrow \beta$): $\sigma_{TOF} \sim 60\text{–}80 \text{ ps}$

**High Momentum Particle IDentification (HMPID)**
- PID through Cherenkov angle: $\sigma \sim 3 \text{ mrad}$
Event centrality & multiplicity in ALICE

**pp, p-Pb, Pb-Pb**
- Centrality/multiplicity defined as the **percentile** of the hadronic cross section corresponding to a particle multiplicity above a given threshold.
- Event multiplicity classes defined from the amplitude of the signal in the V0 (VZERO) detectors.

**Pb-Pb**
- The centrality of the collision is directly related to the **impact parameter** ($b$).

\[ \overrightarrow{b} = \text{impact parameter} \]
• Spectra in Pb-Pb: **spectra become harder** as the multiplicity increases (flattening visible at low $p_T$)
  - The change is most pronounced for heavier particles → **Radial flow**
New: spectra in p-Pb at 8.16 TeV

- Spectra become harder as the multiplicity increases (flattening visible at low $p_T$)
- The change is most pronounced for heavier particles → Radial flow
- Spectra fit with a Lévy-Tsallis function
[pp] Particle spectra

- Spectra in pp:
  - Spectra become harder as the multiplicity increases
  - Hints of radial flow in a limited $p_T$ range in high multiplicity pp collisions
• Evidence of an increasing trend of the K/π ratio → **Strangeness enhancement?**
• Hints of a decreasing trend of the p/π ratio at high multiplicity → **Baryon-antibaryon annihilation?**
• Saturation at high multiplicities for K/π
• No significant evolution with the collision energy

The chemical composition is **independent of collision system at same \( \langle dN_{\text{ch}}/d\eta \rangle \)**
**$p_T$-integrated yield ratios vs multiplicity**

- **Steep increase** with multiplicity in pp and p-Pb
- **Saturation** at higher multiplicities
- **No significant evolution** with the collision energy and collision system

### Graphical Representation

![Graph showing yield ratios vs multiplicity](image)

- Plot of yield ratios to $p^+ + p^-$ vs multiplicity for various particles (e.g., $p$, $\Lambda$, $2\phi$, $\Xi^-$, $\Omega^+$) with different collision systems (e.g., pp, p-Pb, Pb-Pb).

### Data Points

- ALICE Preliminary
  - $pp$, $\sqrt{s} = 13$ TeV
  - $pp$, $\sqrt{s} = 7$ TeV
  - Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
  - Pb-Pb, $\sqrt{s_{NN}} = 8.16$ TeV

### Mathematical Formulas

- $\phi(S=0)/\pi$ increase in small systems is inconsistent with simple canonical suppression ($\phi$ behaves like a particle with $S=1$ or $S=2$).

- Slope of the increase depends on strangeness content.
$\rho_T$-integrated yield ratios vs multiplicity

- Steep increase with multiplicity in pp and p-Pb
- Saturation at higher multiplicities
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$\phi$(S=0)/$\pi$ increase in small systems is inconsistent with simple canonical suppression ($\phi$ behaves like a particle with $S$ between 1 and 2)

- Slope of the increase depends on strangeness content

Hierarchy determined by the hadron strangeness content.
Mean transverse momenta ($\langle p_T \rangle$)

$\Omega(1672)$
$\Xi(1322)$
$\phi(1020)$
$\Lambda(1116)$
$p(938)$
$K(494)$
$\pi(140)$
Similar hierarchy is observed in pp, p-Pb and peripheral A-A

- In Central A-A collisions particles with similar masses have similar $\langle p_T \rangle$ (as expected from hydrodynamics)
Mean transverse momenta ($\langle p_T \rangle$)

- Similar hierarchy is observed in pp, p-Pb and peripheral A-A
  - In Central A-A collisions particles with similar masses have similar $\langle p_T \rangle$ (as expected from hydrodynamics)
  - $\phi$ above $\Lambda$ and $p$, and close to $\Xi$: mass ordering violated in pp, p-Pb and peripheral Pb-Pb
**Mean transverse momenta ($\langle p_T \rangle$)**

- **Similar hierarchy** is observed in pp, p-Pb and peripheral A-A
  - In Central A-A collisions particles with similar masses have similar $\langle p_T \rangle$ (as expected from hydrodynamics)
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- The p-Pb data exhibit mass-hierarchy features of both pp and Pb-Pb
- The moderate increase is usually attributed to increasing **collective radial flow**

**Approximate masses**
- $\Omega(1672)$
- $\Xi(1322)$
- $\phi(1020)$
- $\Lambda(1116)$
- $p(938)$
- $K(494)$
- $\pi(140)$

**Graphs**

- ALICE, pp
- ALICE, p-Pb
- ALICE, A-A

**Equations**

- $\pi(140)$
- $p(938)$
- $\Omega(1672)$
- $K(494)$
- $\Lambda(1116)$
- $\Xi(1322)$
- $\phi(1020)$

**References**

- PRC 99, 024906 (2019)
- EPJC 76, 245 (2018)
- PRL 758, 389-401 (2016)
- Xe-Xe, $\sqrt{s_{NN}} = 5.44$ TeV (Preliminary)
- Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV (Preliminary)
- Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
- PRC 91, 024909 (2015)
Blast-wave analysis

**Boltzmann-Gibbs blastwave model:** a three-parameter simplified hydrodynamical model*

\[
E \frac{d^3N}{dp^3} \propto \int_0^R m_T I_0 \left( \frac{p_T \sinh(\rho)}{T_{\text{kin}}} \right) K_1 \left( \frac{m_T \cosh(\rho)}{\beta_T} \right) r \, dr
\]

\[m_T = \sqrt{m^2 + p_T^2}\]

\[\rho = \tanh^{-1}(\beta_T)\]

\[\beta_T(r) = \beta_s \left( \frac{r}{R} \right)^n\]

The resulting spectrum is a superposition of individual thermal sources, each boosted with the boost angle \(\rho\)

- Simultaneous Boltzmann-Gibbs fit to \(\pi, K\) and \(p\) using Pb-Pb 2.76 TeV fit ranges

\(\Rightarrow\) Good description of data in the fit range


\(n\): exp. of velocity profile \(\leftrightarrow\) profile

\(T_{\text{kin}}\): kinetic freeze-out temperature

\(\beta_T(r)\): transverse velocity distribution

\(\beta_s\): surface velocity

\(\rho\): boost angle
Blast-wave analysis (predictions)

**Boltzmann-Gibbs blastwave model:** a three-parameter simplified hydrodynamical model*

\[ E \frac{d^3N}{dp^3} \propto \int_0^R m_T I_0 \left( \frac{p_T \sinh(\rho)}{T_{\text{kin}}} \right) K_1 \left( \frac{m_T \cosh(\rho)}{\beta_T} \right) r \, dr \]

\[ m_T = \sqrt{m^2 + p_T^2} \quad \rho = \tanh^{-1}(\beta_T) \quad \beta_T(r) = \beta_s \left( \frac{r}{R} \right)^n \]

The resulting spectrum is a superposition of individual thermal sources, each boosted with the boost angle \( \rho \).

- Simultaneous Boltzmann-Gibbs fit to \( \pi, K \) and \( p \) used to predict \( \Lambda, \Xi, \Omega, \phi \)

\[ \rightarrow \text{Good description of data for } p_T \lesssim 2-3 \text{ GeV/c depending on the mass} \]


\[ n: \text{exp. of velocity profile } \leftrightarrow \text{profile} \]

\[ T_{\text{kin}}: \text{kinetic freeze-out temperature} \]

\[ \beta_T(r): \text{transverse velocity distribution} \]

\[ \beta_s: \text{surface velocity} \]

\[ \rho: \text{boost angle} \]
Blast-wave fit results

Large systems
- Largest $\langle \beta_T \rangle$ and lowest $T_{\text{kin}}$ for central Pb-Pb collisions
- Comparable $T_{\text{kin}}$ and $\langle \beta_T \rangle$ in Pb-Pb collisions at a similar $\langle dN_{\text{ch}}/d\eta \rangle$
Blast-wave fit results

Large systems
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Small systems
- p-Pb & pp vs A-A
  - p-Pb and Pb-Pb show a similar increase of $\langle \beta_T \rangle$ consistent with the presence of radial flow in p-Pb collisions.
  - At similar $\langle dN_{\text{ch}}/d\eta \rangle$,
    - comparable $T_{\text{kin}}$ for p-Pb and Pb-Pb, whereas $\langle \beta_T \rangle$ is significantly higher in p-Pb
    - pp and p-Pb show a similar trend and values are comparable
    - Higher $T_{\text{kin}}$ in p-Pb 8.16 TeV wrt 5.02 TeV

**p-Pb $\rightarrow$ Stronger radial gradients**

- Viscous hydrodynamics (QGP expansion) + Hadron cascade model (UrQMD) to simulate the evolution of the hadron resonance gas

\textbf{Trento initial conditions}: effective model where entropy is deposited proportional to the generalized mean of nuclear overlap density

\textbf{AMPT initial conditions}: initial state includes fluctuations at the nucleonic and subnucleonic levels and considers pre-equilibrium dynamics of partonic matter.

\textbf{Good agreement at low-intermediate }p_T\textbf{.}
A Large Ion Collider Experiment


- Non uniform fireball divided into the **core** (high density) and **corona** (lower density).

→ **Describes particle ratios better** in central Pb-Pb collisions

**McGill** (Phys. Rev. C 95, 064913 (2017))

- IP-Glasma initial condition matched to hydrodynamic variables and evolved using viscous hydrodynamic model (MUSIC).

→ **Good agreement at low-intermediate** $p_T$.
Summary

• Charged-hadron production results in several collision systems have been shown in this talk

• Messages to take home
  – **Radial flow effects** are measurable on the hadron distributions (*hardening*)
  – Hints of radial **flow in small systems** (high multiplicity pp)
  – **Hadron chemistry driven by multiplicity** and not by collision energy
  – **Yields and \( \langle p_T \rangle \) show a hierarchy** based on particle strangeness content
  – **Strong radial gradients in p-Pb** collisions (higher \( T_{kin} \) at 8.16 TeV)
  – Importance of **hydrodynamical models** which go beyond an incoherent superposition of parton-parton scatterings in the description of the measured data
Backup slides
Strange/non-strange ratio compared to models

- DIPSY, is a model where interaction between partonic strings is allowed to form “color ropes” which are expected to produce more strange particles and baryons.
**Blast-wave analysis**

The resulting spectrum is a superposition of individual thermal sources, each boosted with the boost angle $\rho$.

- Simultaneous Boltzmann-Gibbs fit to $\pi$, $K$ and $\rho$ using Pb-Pb 2.76 TeV fit ranges

→ Good description of data in the fit range

**Boltzmann-Gibbs blastwave model**: a three-parameter simplified hydrodynamical model*

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\]

\[
m_T = \sqrt{m^2 + p_T^2} \quad \rho = \tanh^{-1}(\beta_T) \quad \beta_T(r) = \beta_s \left( \frac{r}{R} \right)^n
\]

$n$: exp. of velocity profile $\leftrightarrow$ profile  
$T_{kin}$: kinetic freeze-out temperature  
$\beta_T(r)$: transverse velocity distribution  
$\beta_s$: surface velocity  
$\rho$: boost angle

Blast-wave parameters vs multiplicity
Proton-to-pion ratios

**Pb-Pb 5.02 TeV vs Xe-Xe 5.44 TeV**
- Typical flow bump at around $p_T = 3 \text{ GeV/c}$, **more evident in central collisions**
- **Compatible** structure in the two colliding systems

**pp 13 TeV**
- Similar flow-like feature, the peak is more suppressed compared to A-A
- **Multiplicity dependence** is observed as in A-A
Particle ratios

- Pb-Pb at 2.76 vs 5.02 TeV
  - Indication of a slightly higher radial flow in central collisions compared to lower energies.
- pp, p-Pb and Pb-Pb
  - $p/\pi$: similar flow-like features for pp, p-Pb and Pb-Pb systems
• The $\phi$ meson behaves like a particle with strangeness between 1 and 2
Nuclear modification factor

\[ R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2N_{AA}/dydp_T}{d^2N_{pp}/dydp_T} \]

- (enhancement) \( > 1 \)
- (no medium effects) \( = 1 \)
- (suppression) \( < 1 \)

Test if AA or pA can be described by incoherent superposition of \( N_{coll} \) binary collisions

- \( \pi, K, p \) equally suppressed for all centralities at high \( p_T > 8 \text{ GeV/c} \)

- \( R_{pPb} \) compatible with 1 at high \( p_T \) for all particle species

- Mass ordering at intermediate \( p_T \) (Cronin region)
  - Strong enhancement for \( p, \Xi \) and \( \Omega \)
  - Similar enhancement observed in Pb-Pb and at RHIC.
Comparison with models


- **Krakow¹**: event-by-event (3+1)-D perfect fluid hydrodynamic
  - Reproduces particle spectra reasonably well
- **DPMJET²**: QCD-inspired model based on Glauber-Gribov formalism
  - Fails to reproduce particle spectra
- **EPOS-LHC**: pi, K and p reasonably well reproduced especially at low $p_T$

**pp collisions**

- Pythia 8³ generator overestimates $p/\pi$ and underestimates $K/\pi$

¹ Bozek, PRC 85, 014911 (2012)
² Roesler et al., arXiv:hep-ph/0012252
³ arXiv:1404.5630v1
Comparison with models

\[ \pi^+ + \pi^- (\times 10^4) \]

\[ K^+ + K^- (\times 10^2) \]

\[ p + \bar{p} (\times 10^6) \]

\[
\frac{1}{N_{\text{ev}}} \frac{dN}{d\Sigma (dE/dx)} \text{ (GeV/c)} \]

\( \text{ALICE Preliminary} \)

\( \text{Pb-Pb} \)

\( \text{70-80}\% \)

\( \text{iEBE-VISHNU with TRENTo and AMPT initial conditions} \)

\[ \text{Good agreement at low } p_T \]

\[ \text{EPOS-LHC (Phys. Rev. C 92, 034906 (2015))} \]

- Non uniform fireball divided in the core (high density) and corona (lower density).
  - Describes better \( \pi, K, K/\pi \) in peripheral Pb-Pb collisions

\[ \text{Data / Model} \]

\( \text{Data} / \text{Model} \)

\( (K^+ + K^-) / (\pi^+ + \pi^-) \)

\[ (p + \bar{p}) / (\pi^+ + \pi^-) \]

\( \text{Pb-Pb} \)

\( 60-80\% \)
[p-Pb 5-10 % and pp] Comparison to models

- Kraków¹: event-by-event (3+1)-D perfect fluid hydrodynamic
  - Reproduces particle spectra **reasonably well**
- DPMJET²: QCD-inspired model based on Glauber-Gribov formalism
  - **Fails** to reproduce particle spectra
- EPOS-LHC: π, K and p reasonably well reproduced especially at low $p_T$
  - **EPOS-LHC** agrees better in low $p_T$ ranges
- DIPSY⁴ with color ropes correctly reproduces the $p/\pi$ shape at low $p_T$, → better agreement at higher $p_T$ and low $\langle dN_{ch}/d\eta \rangle$
- HERWIG⁵ is an event generator that performs simulations at next-to-leading order in QCD → **Fails** to describe data