Strangeness in ALICE at LHC

F. Bellini* on behalf of the ALICE Collaboration
*University of Bologna and INFN, Italy
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Three collision systems compared

Pb-Pb collisions
- Particle production mechanisms
- Strangeness enhancement
- In-medium energy loss
- Properties of the hadronic phase

p-Pb collisions
- Disentangle final from initial-state effects
- Collectivity in small systems?

pp collisions
- No deconfinement expected
- No collectivity expected
- Reference for “larger” system

A comprehensive set of measurements of identified particles production with ALICE in all collision systems, including

\[ \pi^\pm, K^\pm, K^0_S, p, \Lambda, \Xi, \Omega \]
\[ \rho, K^{*0}, \phi, \Sigma^{*\pm}, \Xi^{*0} \]
…plus light nuclei and exotica

(anti)d, (anti)\(^3\)H, (anti)\(^3\)He, (anti)\(^4\)He, (anti)\(^3\)\(_\Lambda\)H
Three collision systems compared

Pb-Pb $\sqrt{s_{NN}} = 2.76, 5.02$ TeV
p-Pb $\sqrt{s_{NN}} = 5.02$ TeV
pp $\sqrt{s} = 0.9, 2.76, 5.02, 8, 13$ TeV
$\sqrt{s} = 7$ TeV (multip. dep.)

A comprehensive set of measurements of identified particles production with ALICE in all collision systems, including

$\pi^\pm, K^\pm, K^0_S, p, \Lambda, \Xi, \Omega$,
$\rho, K^{*0}, \phi, \Sigma^{*\pm}, \Xi^{*0}$

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(anti)d, (anti)$^3$H,
(anti)$^3$He, (anti)$^4$He, (anti)$^3$\Lambda H
Forward detectors
Multiplicity, centrality, trigger and timing
A Large Ion Collider Experiment at the LHC

Inner Tracking System
Vertexing and tracking down to very low $p_T$

Detector Acceptance

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Event multiplicity/centrality classes are defined based on the amplitude measured in the V0 scintillators, placed at $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C).

$<dN_{ch}/d\eta>$ is measured in $|\eta|<0.5$ to avoid “auto-biases” in multiplicity determination.

In Pb-Pb the Glauber model is used to relate the V0A&V0C (“V0M”) amplitude* distribution to the geometry of the collision.

| Centrality | $<dN_{ch}/d\eta>_{|\eta|<0.5}$ | $<N_{part}>$ |
|------------|---------------------------------|-------------|
| 0-5%       | $1601 \pm 60$                   | $328.8 \pm 3.1$ |
| 70-80%     | $35 \pm 2$                      | $15.8 \pm 0.6$ |

(*alternatively, multiplicity of spectators in the Zero Degree Calorimeters or number of tracks in the Silicon Pixel Detector or the Time Projection Chamber)
Event classes in Pb-Pb, p-Pb and pp

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0-5%: $<dN_{ch}/d\eta>_{|\eta|<0.5} = 1601 \pm 60$  
$<N_{part}> = 328.8 \pm 3.1$

70-80%: $<dN_{ch}/d\eta>_{|\eta|<0.5} = 35 \pm 2$  
$<N_{part}> = 15.8 \pm 0.6$

(*alternatively, multiplicity of spectators in the Zero Degree Calorimeters or number of tracks in the Silicon Pixel Detector or the Time Projection Chamber)

In p-Pb collisions, V0A (Pb side) is used:

0-5%: $<dN_{ch}/d\eta>_{|\eta|<0.5} = 45 \pm 1$  
60-80%: $<dN_{ch}/d\eta>_{|\eta|<0.5} = 9.8 \pm 0.2$

In pp collisions, V0A&V0C (“V0M”) us used:

0-0.95%: $<dN_{ch}/d\eta>_{|\eta|<0.5} = 21.3 \pm 0.6$  
48-68%: $<dN_{ch}/d\eta>_{|\eta|<0.5} = 3.90 \pm 0.14$
ALICE Central Barrel
B = 0.5 T, |η|<0.9
2π tracking and PID
Identification of light flavour hadrons and light (anti-)nuclei via practically all known PID techniques in $0.1 \text{ GeV/c} < p_T < 20 \text{ GeV/c}$
π, K, p in Pb-Pb, pp at $\sqrt{s_{NN}} = 2.76$ TeV

Low $p_T$ ($p_T < 3$ GeV/c)
→ Study collective phenomena (radial flow)

Mid-$p_T$ ($3 < p_T < 8-10$ GeV/c)
→ Study fragmentation vs recombination

High $p_T$ ($p_T > 8-10$ GeV/c):
→ Study jet quenching and energy loss nuclear via nuclear modification factors

(High-$p_T$ π, K, p and $R_{AA}$)
Nuclear modification of spectra

At high-$p_T$ (>8-10 GeV/c):

- **strong** flavour-independent suppression in central Pb-Pb with respect to pp

- **no suppression** observed in p-Pb for $\pi,K,p$ above 6-8 GeV/c

$\rightarrow$ In Pb-Pb, due to **parton energy loss in the hot nuclear matter**

\[
R_{xA}(p_T) = \frac{d^2 N_{ch}^{xA} / d\eta dp_T}{\langle T_{xA}\rangle d^2 \sigma_{ch}^{pp} / d\eta dp_T}
\]

\textit{arXiv:1601.03658} \\
\textit{(High-$p_T$ $\pi,K,p$ and $R_{pPb}$)}
Nuclear modification of spectra

At intermediate-$p_T$ ($3 < p_T < 6$ GeV/$c$):

- **Baryon/meson** difference in central Pb-Pb
- **Cronin peak** in p-Pb collisions

→ presence of **other final state effects or dynamics** (flow, recombination, ...)?

\[
R_{xA}(p_T) = \frac{d^2 N_{ch}^{xA}}{\eta dp_T} / \langle T_{xA} \rangle \frac{d^2 \sigma_{pp}^{ch}}{\eta dp_T}
\]

arXiv:1601.03658

(\textit{High-$p_T$} \pi,K,p and $R_{pPb}$)
Baryon-to-meson ratio: Λ/K₀ˢ, p/π, p/ϕ

**B/M enhancement at intermediate pₜ**

- **Hydrodynamics** describes only the rise < 2 GeV/c
- **Recombination** reproduces effect but overestimates
- **EPOS** gives good description of the data (with flow)
Baryon-to-meson ratio: $\Lambda/K^0_s$, $p/\pi$, $p/\phi$

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$p/\phi$ have similar mass
$p/\phi$ ratio is flat in central Pb-Pb
→ **Mass determines the spectral shapes** (as in hydrodynamics)
In pp, p-Pb and Pb-Pb collisions the B/M ratio as a function of multiplicity is
- qualitatively similar: **depletion** at low $p_T$, **enhancement** at intermediate $p_T$
- quantitatively different in the three systems
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Simultaneous **Blast-Wave model** fit to the $\pi$, $K$, $p$ spectra

- In **Pb-Pb**: increase of radial flow with centrality

- In **pp** and **p-Pb**, similar evolution of the parameters towards high multiplicity
Simultaneous **Blast-Wave model** fit to the $\pi$, K, p spectra

- In **Pb-Pb**: increase of radial flow with centrality

- In **pp** and **p-Pb**, similar evolution of the parameters towards high multiplicity

- **Stronger $\langle \beta_T \rangle$ for smaller systems at similar multiplicity**

... but mind:

• Sensitivity to **fit range** and the set of **particles included in the fit**

• Mechanisms such as **color reconnection** in models of pp collisions can mimic the effects of radial flow
New measurement of **deuteron** $v_2$ in comparison to
- **Hydrodynamic (Blast-Wave) model** from a simultaneous fit of $\pi,K,p$ spectra and $v_2$
- **simple coalescence model**, from measured proton as $2v_{2,p}(2p_{T,p})$

Blast-wave model describes the d $v_2$
Deuteron follows mass-scaling, simple coalescence model doesn’t work
K*⁰ resonance not described by the Blast-Wave model (also in p-Pb, pp)

- On the right: Blast wave model from a fit to π,K,p in 0-20% Pb-Pb and normalization to thermal model prediction for Rsn/K scaled to the measured K yield

Better agreement for φ in Pb-Pb, p-Pb

**Suppression of K*⁰/K** in central Pb-Pb consistent with re-scattering of the decay products during the late hadronic phase
K*\(^0\) resonance not described by the Blast-Wave model (also in p-Pb, pp)

- On the right: Blast wave model from a fit to \(\pi, K, p\) in 0-20% Pb-Pb and normalization to thermal model prediction for \(R_{sn}/K\) scaled to the measured \(K\) yield

Better agreement for \(\phi\) in Pb-Pb, p-Pb

**Suppression of K*\(^0\)/K** in central Pb-Pb consistent with **re-scattering of the decay products during the late hadronic phase**

New results for \(\rho/\pi\) in Pb-Pb collisions show similar behaviour

\[
[\tau_\rho \sim 1.3 \text{ fm/c} < \tau_{K^*} \sim 4 \text{ fm/c} << \tau_\phi \sim 45 \text{ fm/c}]
\]

→ Suppression qualitatively described by EPOS3 (with UrQMD)
Strangeness enhancement in AA

One of the first proposed QGP signatures

In **pp collisions** the production of strangeness relative to $\pi$ at LHC is larger than at RHIC

From **pp to Pb-Pb** strangeness production increases

For $N_{\text{part}} > 150$ the ratios saturate and match predictions from the grand-canonical thermal models. For instance, models at equilibrium

- GSI-Heidelberg: $T_{\text{ch}} = 164$ MeV
- THERMUS: $T_{\text{ch}} = 170$ MeV
Strangeness production in p-Pb

In p-Pb collisions

- $\Xi/\pi$ reaches values seen in Pb-Pb

- $\Omega/\pi$ exhibits a strong rise (~2x) and reaches 60-80% Pb-Pb


($\Xi$ and $\Omega$ in p-Pb)
In p-Pb collisions

- $\Xi/\pi$ reaches values seen in Pb-Pb
- $\Omega/\pi$ exhibits a strong rise (~2x) and reaches 60-80% Pb-Pb

$\Xi(1530)^0$ resonance:
- Same strangeness content as $\Xi$
- Intermediate in mass between $\Xi$ and $\Omega$

$\Xi^*/\pi$ shows an increase compatible with that of $\Xi/\pi$

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New results in pp vs multiplicity

**Increase of (multi)strange production to non-strange with multiplicity in pp**
- $\Lambda/K^0_s$ and $p/\pi$ do not increase significantly
  → **Increase** is not mass related but **strangeness related**

- **MC models** as DIPSY (color ropes) and EPOS LHC exhibit a trend with multiplicity but may still need tuning…

![Graphs showing the increase of strangeness production](image)
New results in pp vs multiplicity

**Normalised values to INEL>0 show**

- No increase for p/\pi
- **Hierarchy** of the increase clearly associated with the strangeness content

**arXiv:1606.07424**
Outlook: pp at $\sqrt{s} = 13$ TeV

Recent measurements in pp at 13 TeV

$$\frac{dN_{\text{ch}}}{d\eta}|_{|\eta|<0.5}$$ increases by ~15% from 7 to 13 TeV

Identified hadron production:
- shift of the maximum of $p/\pi$ ratio towards higher $p_T$ with energy
- No significant evolution with energy for $K/\pi$ and integrated $K^*/K$, $\phi/K$
- hint for increase of hyperon-to-pion ratios in min. bias collisions

→ disentangle multiplicity and energy dependence of spectral shapes and hard-scattering contribution
Outlook: PID in Pb-Pb at 5.02 TeV

Very promising PID performance in Run II

Analysis shown corresponding to ~3M Pb-Pb events at $\sqrt{s_{NN}} = 5.02$ TeV, about 3% of the recorded statistics
Outlook: (multi)strange particles in Pb-Pb at 5.02 TeV

- $K^*(892)^0$
  - $2.0 < p_T < 3.0$ GeV/c
  - Data (stat. uncert.)
  - Breit-Wigner Fit
  - Residual BG

- $K_S^0$
  - $1.5 < p_T < 1.6$ GeV/c
  - $-0.5 < y < 0.5$

- $\Lambda$
  - $1.7 < p_T < 1.8$ GeV/c
  - $-0.5 < y < 0.5$

- $\phi(1020)$
  - $2.5 < p_T < 2.8$ GeV/c
  - Data (stat. uncert.)
  - Voigtian Peak Fit
  - Residual BG

- $\Xi^-$
  - $1.2 < p_T < 1.4$ GeV/c
  - $-0.5 < y < 0.5$

- $\Omega^-$
  - $1.8 < p_T < 2.0$ GeV/c
  - $-0.5 < y < 0.5$
ALICE measurements of identified particle production in pp, p-Pb, Pb-Pb collisions have revealed interesting and **similar features across different systems**

- Collectivity in small systems? What origin (radial flow, color reconnection, …)?

**Enhancement of strangeness** production observed towards **high-multiplicity pp** events at $\sqrt{s} = 7$ TeV

- not described by the currently available QCD inspired MC generators
- What will happen at higher multiplicities

More details in the parallel talks...

...and yet more to come from the Run II data!

**D. Colella**, Today 28/6, 14:40

**A. Knospe**, Today 28/6, 16:00

**R. Derradi**, Today 28/6, 16:40

**B. Doenigus**, Thu. 30/6, 09:20
Additional slides
Charged particles spectra in Pb-Pb, pp at 5.02 TeV

ALICE Preliminary
Pb-Pb | $s_{NN} = 5.02$ TeV
charged particles, $|\eta| < 0.8$

\[ \frac{1}{N_{ev}} \frac{d^2N}{dp_T^2} d\eta \] (GeV$^{-2}$)

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- Data
- EPOS LHC
- PYTHIA 8 (Monash-2013)

MC / Data

Data syst. uncert.
Data syst.+stat. uncert.

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New measurement of nuclear modification factor of inclusive charged particles as a function of centrality

- Improved systematics wrt previous 2.76 TeV measurement
- $R_{AA}$ compatible with 2.76 TeV
- hotter/denser medium?
Strange and multi-strange vs multiplicity

ALICE V0Multiplicity Classes
- pp, $\sqrt{s} = 7$ TeV
- p-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
- Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
- PLB 728 (2014) 25-38
- PRC 88, 044910 (2013)

Graph showing $\langle dN_{ch}/d\eta \rangle$ vs multiplicity for different collision types.

MC predictions - pp $\sqrt{s} = 7$ TeV
- PYTHIA8 Monash No CR
- PYTHIA8 Monash With CR
- DIPSY Color Ropes
- EPOS LHC

ALICE
- p-Pb $\sqrt{s_{NN}} = 5.02$ TeV
- Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
- pp $\sqrt{s} = 7$ TeV
- V0M Mult. Evt. Classes

Graphs showing $\langle dN_{ch}/d\eta \rangle$ for different models and collision types.
Strangeness enhancement in Pb-Pb: $\phi/\pi$

\[ E(S=1) < E(S=0) \sim E(S=2) < E(S=3) \]
Charged particle multiplicity in Pb-Pb, p-Pb

Definition of the event classes as fractions of the analyzed event sample and their corresponding \( \langle dN_{ch}/d\eta \rangle \) within \( |\eta_{lab}| < 0.5 \) (systematic uncertainties only, statistical uncertainties are negligible).

<table>
<thead>
<tr>
<th>Event class</th>
<th>V0A range (arb. unit)</th>
<th>( \langle dN_{ch}/d\eta \rangle )</th>
<th>( \langle dN_{ch}/d\eta \rangle )</th>
<th>( \langle dN_{ch}/d\eta \rangle )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–5%</td>
<td>&gt;227</td>
<td>45 ± 1</td>
<td>45 ± 1</td>
<td>45 ± 1</td>
</tr>
<tr>
<td>5–10%</td>
<td>187–227</td>
<td>36.2 ± 0.8</td>
<td>36.2 ± 0.8</td>
<td>36.2 ± 0.8</td>
</tr>
<tr>
<td>10–20%</td>
<td>142–187</td>
<td>30.5 ± 0.7</td>
<td>30.5 ± 0.7</td>
<td>30.5 ± 0.7</td>
</tr>
<tr>
<td>20–40%</td>
<td>89–142</td>
<td>23.2 ± 0.5</td>
<td>23.2 ± 0.5</td>
<td>23.2 ± 0.5</td>
</tr>
<tr>
<td>40–60%</td>
<td>52–89</td>
<td>16.1 ± 0.4</td>
<td>16.1 ± 0.4</td>
<td>16.1 ± 0.4</td>
</tr>
<tr>
<td>60–80%</td>
<td>22–52</td>
<td>9.8 ± 0.2</td>
<td>9.8 ± 0.2</td>
<td>9.8 ± 0.2</td>
</tr>
<tr>
<td>80–100%</td>
<td>&lt;22</td>
<td>4.4 ± 0.1</td>
<td>4.4 ± 0.1</td>
<td>4.4 ± 0.1</td>
</tr>
</tbody>
</table>

**TABLE I.** \( dN_{ch}/d\eta \) and \( \langle dN_{ch}/d\eta \rangle/\langle \langle N_{part} \rangle/2 \rangle \) values measured in \( |\eta| < 0.5 \) for nine centrality classes. The \( \langle N_{part} \rangle \) obtained with the Glauber model are given.

| Centrality | \( dN_{ch}/d\eta \) \( \langle N_{part} \rangle \) \( \langle dN_{ch}/d\eta \rangle/\langle \langle N_{pan} \rangle/2 \rangle \) |
|------------|---------|-----------------|-----------------|
| 0%–5%      | 1601 ± 60 | 382.8 ± 3.1     | 8.4 ± 0.3       |
| 5%–10%     | 1294 ± 49 | 329.7 ± 4.6     | 7.9 ± 0.3       |
| 10%–20%    | 966 ± 37  | 260.5 ± 4.4     | 7.4 ± 0.3       |
| 20%–30%    | 649 ± 23  | 186.4 ± 3.9     | 7.0 ± 0.3       |
| 30%–40%    | 426 ± 15  | 128.9 ± 3.3     | 6.6 ± 0.3       |
| 40%–50%    | 261 ± 9   | 85.0 ± 2.6      | 6.1 ± 0.3       |
| 50%–60%    | 149 ± 6   | 52.8 ± 2.0      | 5.7 ± 0.3       |
| 60%–70%    | 76 ± 4    | 30.0 ± 1.3      | 5.1 ± 0.3       |
| 70%–80%    | 35 ± 2    | 15.8 ± 0.6      | 4.4 ± 0.4       |

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Baryon-to-meson ratio: \( \Lambda/K^0_s \)

- **Hydrodynamics** describes only the rise < 2 GeV/c
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B/M in jets significantly lower than inclusive ratio → **baryon anomaly is not a jet effect**, but arises from the bulk