Enhanced production of (multi-)strange hadrons in high multiplicity pp collisions

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Strange hadron production: key tool for understanding hadronization in different environments

Strangeness enhancement:

- Enhanced production of strange hadrons was observed in heavy-ion collisions with respect to elementary collisions
- Originally proposed as a signature of QGP formation in nuclear collisions (Rafelsky, Muller[1])
  - Lower Q-value for $s\bar{s}$ relative to $H_sH_s$ formation
  - Faster equilibration in partonic medium

Detectors used for strangeness analysis:

**TPC** (|\(\eta\)| < 0.9)
- Gas-filled detector
- Tracking, vertexing, PID (dE/dx)

**ITS** (|\(\eta\)| < 0.9)
- 6 layers of silicon detectors
- Triggering, tracking, (secondary) vertexing

**V0A** (2.8 < \(\eta\) < 5.1) and **V0C** (-3.7 < \(\eta\) < -1.7)
- Forward-rapidity arrays of scintillators
- Triggering, beam gas rejection, multiplicity estimator

**TOF** (|\(\eta\)| < 0.9)
- Made by MRPCs
- PID
- Pile-up rejection
**Multiplicity** → Number of particles produced in a defined kinematic region

Multiplicity estimation:

- data sample divided in V0M amplitude classes
- **Average multiplicity** → measurement of the primary charged particles at central rapidity for each V0M amplitude class

![Graph showing V0M multiplicity classes](image)
Particle Identification techniques:
• Energy Loss → ITS TPC

• Time of Flight → TOF
### Analyses in pp collisions at LHC

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>vs multiplicity</th>
<th>Published results on strangeness</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.02</td>
<td>Yes</td>
<td>NEW for this conference!</td>
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</table>
Particle reconstruction via weak decay topology. Cuts are applied on kinematical, geometrical and topological variables.

**V0s:**
- \( \Lambda \rightarrow p + \pi^- / \bar{\Lambda} \rightarrow \bar{p} + \pi^+ \) (BR= 69.2%)
- \( K^0_S \rightarrow \pi^+ + \pi^- \) (BR= 63.9%)

Neutral particles decaying into two particles with opposite charge → charge conservation

**Cascades:**
- \( \Xi^- \rightarrow \Lambda + \pi^- / \Xi^0 \rightarrow \bar{\Lambda} + \pi^+ \) (BR=99.9%)
- \( \Omega^- \rightarrow \Lambda + K^- / \Omega^0 \rightarrow \bar{\Lambda} + K^+ \) (BR= 67.8%)

The reconstructed \( \Lambda \) candidate is associated to a “bachelor” track to obtain the cascade candidate

\[
\begin{align*}
K^0_S & \quad M=497.61 \text{ MeV/c}^2 \\
& \quad c\tau = 2.68 \text{ cm} \\
\Lambda & \quad M=1115.68 \text{ MeV/c}^2 \\
& \quad c\tau = 7.89 \text{ cm} \\
\Xi & \quad M=1321.71 \text{ MeV/c}^2 \\
& \quad c\tau = 4.91 \text{ cm} \\
\Omega & \quad M=1672.45 \text{ MeV/c}^2 \\
& \quad c\tau = 2.46 \text{ cm}
\end{align*}
\]
Invariant mass distributions for V0s and Cascades reconstructed for selected p_T and multiplicity bins→polynomial background and Gaussian peak
The $\phi$ meson is reconstructed via invariant mass analysis from $K^\pm$ identified with TPC and TOF

- Geometrical and kinematical cuts
- Primary tracks selection
- TPC PID selection $|N\sigma_{K,TPC}| < 2$ with TOF “veto” $|N\sigma_{K,TOF}| < 3$

Invariant mass spectra

- Combinatorial background subtraction
- Polynomial residual background and Voigtian peak fit

$\phi \rightarrow K^+ + K^- \ (BR = 48.9\%)$

$M = 1019.5 \ \text{MeV/c}^2$
$c\tau = 46.5 \ \text{fm}$
The $p_T$ spectra became harder as the multiplicity increases—evolution is similar to large systems where spectra hardening is connected to hydrodynamical radial expansion of the produced medium (radial flow).
Blast-Wave model:

- Thermalized medium (QGP) expands with a common $\langle \beta_T \rangle$ and undergoes to istanteneous kinematic freeze-out at $T_{kin}$

Simultaneous BW fit to $\pi$, $K$ and $p$ spectra to:

- Predict spectra of $K^0_S$, $\Lambda$, $\Omega$, $\Xi$, $K^{*0}$ and $\phi$
  - Strange hadrons spectra reasonably described by BW model→strange particles follow a common motion→radial flow
  - Not true for resonances!

- Evaluate $T_{kin}$ vs $\langle \beta_T \rangle$
  - At similar multiplicities:
    - Similar values for pp and $p$-$Pb$ collisions
    - Lower values for Pb-$Pb$ collisions
Avarage $p_T$ as a function of multiplicity is obtained from the corrected spectra and the extrapolation at $p_T=0$ GeV/c with Lévy-Tsallis fit function

The new results $\sqrt{s} = 5.02$ TeV are consistent with the previous analyses at $\sqrt{s} = 7$ and 13 TeV:

- Mean $p_T$ increases as a function of $<dN_{ch}/d\eta>_{|\eta|<0.5}$
- Average $p_T$ is not dependent on the energy of the system
Baryon to meson ratio

$\Lambda/K_S^0$ enhancement present in all collision systems at the LHC:

- The effect is larger in larger colliding systems
- Smooth evolution with multiplicity when selecting specific $p_T$ intervals
- Radial flow (QGP) in small systems?

$p_T$-integrated yield as a function of multiplicity obtained integrating the corrected spectra and the Lévy-Tsallis function down to 0 GeV/c

The $\langle dN/dy \rangle$ at $\sqrt{s} = 5.02$ TeV is in good agreement with the previous analyses results at $\sqrt{s} = 7$ and 13 TeV so, it is not dependent on the energy of the system.
The ratio shows an enhanced trend from low multiplicity pp to central Pb-Pb collisions for strange hadrons.

Smooth evolution among pp, p-Pb and Pb-Pb collisions.

Saturation is observed in (semi-) central Pb-Pb collisions.
$p_T$-integrated yield ratio to $(\pi^+ + \pi^-)$ over the $p_T$-integrated yield ratio to $(\pi^+ + \pi^-)$ in INEL>0

Enhancement proportional to the strangeness content of the hadron
The $\phi$ meson has hidden strangeness ($s\bar{s}$ total $S=0$)

The $\phi$ meson enhanced as a $1 < S < 2$ particle
PHYTHIA Lund string model:

- Confined color fields $\rightarrow$ “string” with tension $\sim 1$ GeV/fm
- String breaking $\rightarrow$ hadron formation
- MPI + Color Reconnection mechanisms at play in high energy hadronic interactions

DIPSY: partonic model

- implements color ropes in high density environment:
  - densely packed strings $\rightarrow$ increase in string tension
  - Higher string tension $\rightarrow$ more baryons and more flavours $\neq (u,d)$

![Diagram of quarks and gluons]
**Model comparison: PYTHIA & DIPSY**

**PYTHIA** underestimates strangeness production in pp and no progression with multiplicity is foreseen

**DIPSY** in qualitative agreement with measured ratios
**Model comparison: EPOS LHC**

**EPOS LHC** model implementing a double regime scenario

- **CORONA**: strings can hadronize as in the Lund approach
- **CORE**: hydrodynamic system, hadronization happens statistically at a common $T_H$

Hadron evolution explained by core-to-corona ratio changing in events with different final state multiplicity

**EPOS LHC qualitatively describes enhancement pattern**

**NOTE**: Does this imply QGP in small systems?
**Model comparison: EPOS LHC**

**EPOS LHC** model implementing a double regime scenario

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Statistical hadronization thermal model $\rightarrow$ particles spilling from an ideal hadron resonances gas in thermal and chemical equilibrium at chemical freeze-out stage.

Canonical Statistical Model (CSM):
- as multiplicity decreases, quantum numbers (Q,B,S) are forced to be conserved in smaller and smaller volumes
- It qualitatively describes $\Omega, \Xi$ ratio but there are issues for p and K
- It fails to describe $\phi$

Statistical hadronization thermal model → particles spilling from an ideal hadron resonances gas in thermal and chemical equilibrium at chemical freeze-out stage

Canonical Statistical Model + $\gamma_s$ ($\gamma_s$CSM):

- Introducing undersaturation parameter $\gamma_s$ (incomplete equilibration of S) and fitting also $T_{ch}$ and $dV/dy$ in all systems
- Better agreement, but still problems with $p$, $K$ and $\phi$

Analysis of data collected during the LHC Run1 and Run 2 shows **strangeness enhancement**, which saturates at high-multiplicity.

Typical features traditionally observed in A-A collisions also present in pp and p-A collisions.

The steepness of the enhancement pattern is proportional to the **valence strange quark content** in the hadron.

**Microscopic models**

- **PYTHIA** shows strong disagreement with data.
- **DIPSY** and **EPOS** qualitatively describe the observed trend, but the quantitative description needs further refinements.

**Macroscopic model**

- **$\gamma_s$CSM** is capable of describing the hadron yields with roughly 15% relative accuracy.
- $\phi$ is still a weak point (and $p$ and $K$).
Other new results:

**ALICE Preliminary**

$\phi \to \mu^+\mu^-$

$2.5 < y < 4, 2.5 < p_T < 3 \text{ GeV/c}$

- **PP, $\sqrt{s} = 13 \text{ TeV}$**
- **PYTHIA 8 (Monash 2013)**
  - HadronScattering
  - ColorRope

**ALICE Preliminary**

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- **PP, $\sqrt{s} = 13 \text{ TeV}$**
- **PYTHIA 8 (Monash 2013)**
  - $y = x$

**Particle Yield Ratios**

<table>
<thead>
<tr>
<th>Particle</th>
<th>Yield Ratio</th>
</tr>
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<tbody>
<tr>
<td>$\pi^0/\pi^0$</td>
<td>$12.6$</td>
</tr>
<tr>
<td>$K^0/S$</td>
<td>$2.0$</td>
</tr>
<tr>
<td>$\Sigma^+/\Lambda$</td>
<td>$0.6$</td>
</tr>
<tr>
<td>$\Lambda(1520)/\Lambda$</td>
<td>$0.06$</td>
</tr>
<tr>
<td>$\phi/K$</td>
<td>$0.05$</td>
</tr>
</tbody>
</table>

**ALICE, mult. dependent (V0M):**

- Preliminary pp $\sqrt{s} = 5.02 \text{ TeV}$
- P-Pb $\sqrt{s} = 5.02 \text{ TeV}$

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Thank you.