Measurement of hadronic resonances with ALICE at the LHC

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(for the ALICE collaboration)
Resonances in ALICE

- A wide variety of resonances is studied with ALICE:
  - $\rho(770)$  $K^*(892)^0$  $K^*(892)^+$  $\phi(1020)$  $\Sigma(1385)\pm$  $\Lambda(1520)$  $\Xi(1530)$

- Resonances are excited hadronic states with lifetimes comparable to that of the fireball produced in heavy-ion collisions:
  - ✓ sensitive to the re-scattering and regeneration processes occurring between the chemical and the kinetic freeze-outs → can be used to study properties and lifetime of the late hadronic phase

- Resonances differ by mass and quark content:
  - ✓ insights on the multiplicity-dependent enhancement of strangeness production
ALICE experiment

- Resonances are measured in hadronic decays with invariant mass method → reconstruction and identification of daughter particles

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass (MeV/c²)</th>
<th>Width (MeV/c²)</th>
<th>Decay</th>
<th>BR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>π⁺π⁻</td>
<td>770</td>
<td>150</td>
<td>π⁺π⁻</td>
<td>100</td>
</tr>
<tr>
<td>π⁺K⁺</td>
<td>896</td>
<td>47.4</td>
<td>π⁺K⁺</td>
<td>66.7</td>
</tr>
<tr>
<td>K⁺K⁻</td>
<td>1019</td>
<td>4.27</td>
<td>K⁺K⁻</td>
<td>48.9</td>
</tr>
<tr>
<td>π⁺Λ</td>
<td>1383</td>
<td>36</td>
<td>π⁺Λ</td>
<td>87</td>
</tr>
<tr>
<td>Λ(1520)</td>
<td>1520</td>
<td>15.7</td>
<td>K⁺p</td>
<td>22.5</td>
</tr>
<tr>
<td>Ξ⁺</td>
<td>1532</td>
<td>9.1</td>
<td>π⁺Ξ⁻</td>
<td>66.7</td>
</tr>
</tbody>
</table>

$p_T$ ranges for 3σ separation

<table>
<thead>
<tr>
<th></th>
<th>TPC</th>
<th>TOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>π⁺</td>
<td>0.2 - 0.7</td>
<td>0.5 - 2.0</td>
</tr>
<tr>
<td>K⁺</td>
<td>0.3 - 0.6</td>
<td>0.5 - 2.0</td>
</tr>
<tr>
<td>p⁺</td>
<td>0.5 - 1.0</td>
<td>0.5 - 2.5</td>
</tr>
</tbody>
</table>

- Different collision systems:
  ✓ pp at $\sqrt{s} = 2.76, 5.02, 7, 13$ TeV
  ✓ p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV
  ✓ Pb-Pb at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV
Hadronic phase

- Reconstructed resonance yields in heavy ion collisions are defined by:
  - resonance yields at chemical freeze-out
  - hadronic processes between chemical and kinetic freeze-outs:
    - **rescattering**: daughter particles undergo elastic scattering or pseudo-elastic scattering through a different resonance $\rightarrow$ parent particle is not reconstructed $\rightarrow$ loss of signal
    - **regeneration**: pseudo-elastic scattering of decay products ($\pi K \rightarrow K^*0$, $KK \rightarrow \phi$ etc.) $\rightarrow$ increased yields

- Effect of hadronic processes depends on:
  - lifetime and density of hadronic phase
  - resonance lifetime and scattering cross sections

- Resonances with lifetimes comparable to that of the fireball are well suited to study properties of the hadronic phase

<table>
<thead>
<tr>
<th>$c\tau$ (fm/c)</th>
<th>$\rho(770)$</th>
<th>$K^*(892)$</th>
<th>$\Sigma(1385)$</th>
<th>$\Lambda(1520)$</th>
<th>$\Xi(1530)$</th>
<th>$\phi(1020)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{rescatt}}$</td>
<td>$\sigma_\pi\sigma_\pi$</td>
<td>$\sigma_\pi\sigma_K$</td>
<td>$\sigma_\pi\sigma_\Lambda$</td>
<td>$\sigma_K\sigma_p$</td>
<td>$\sigma_\pi\sigma_\Xi$</td>
<td>$\sigma_K\sigma_K$</td>
</tr>
</tbody>
</table>
Particle ratios: $\rho/\pi$

- $\rho/\pi$:
  - suppression from pp to central Pb-Pb
  - central Pb-Pb is inconsistent with thermal models
  - reproduced by EPOS3 with UrQMD
  - domination of rescattering over regeneration

- Ratio in elementary collisions does not depend on collision energy, $\sqrt{s} > 10$ GeV, within uncertainties

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<th>$K^*(892)$</th>
<th>$\Sigma(1385)$</th>
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<th>$\Xi(1530)$</th>
<th>$\phi(1020)$</th>
</tr>
</thead>
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<tr>
<td>$\sigma_{\text{rescatt}}$</td>
<td>$\sigma_{\pi\pi}$</td>
<td>$\sigma_{\pi K}$</td>
<td>$\sigma_{\pi \Lambda}$</td>
<td>$\sigma_{K\rho}$</td>
<td>$\sigma_{K\Xi}$</td>
<td>$\sigma_{K\phi}$</td>
</tr>
</tbody>
</table>


Particle ratios: $K^*/K$ and $\phi/K$

- $\phi/K$:
  - No significant multiplicity dependence
  - consistent for pp, p-Pb and Pb-Pb
  - consistent with thermal models
  - no rescattering/regeneration due to long lifetime

- $K^*/K$:
  - suppression from pp to central Pb-Pb
  - central Pb-Pb is lower than thermal models
  - reproduced by EPOS3 with UrQMD
  - domination of rescattering over regeneration
  - smooth evolution with multiplicity in pp/p-Pb towards Pb-Pb→ rescattering in small systems?

- Ratios in pp, p-A and A-A do not show strong dependence on collision energy, $\sqrt{s} = 0.2–13$ TeV
Particle ratios: $\Lambda^*/\Lambda$

- $\Lambda^*/\Lambda$:
  - suppression from pp to central Pb-Pb
  - central Pb-Pb is inconsistent with thermal models
  - qualitatively reproduced by EPOS3 with UrQMD
  - domination of rescattering over regeneration
  - smooth evolution with multiplicity in pp/p-Pb towards Pb-Pb, no suppression in small systems

- Ratios in pp, p-A and A-A do not show strong dependence on collision energy, $\sqrt{s} = 0.2-5.02$ TeV
Particle ratios: $\Xi^*/\Xi$

<table>
<thead>
<tr>
<th>$\varphi$ (770)</th>
<th>$K^*$ (892)</th>
<th>$\Sigma$ (1385)</th>
<th>$\Lambda$ (1520)</th>
<th>$\Xi$ (1530)</th>
<th>$\phi$ (1020)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c\tau$ (fm/c)</td>
<td>1.3</td>
<td>4.2</td>
<td>5.5</td>
<td>12.7</td>
<td>21.7</td>
</tr>
<tr>
<td>$\sigma_{\text{rescatt}}$</td>
<td>$\sigma_{n}\sigma_{n}$</td>
<td>$\sigma_{n}\sigma_{K}$</td>
<td>$\sigma_{n}\sigma_{\Lambda}$</td>
<td>$\sigma_{K}\sigma_{p}$</td>
<td>$\sigma_{n}\sigma_{\Xi}$</td>
</tr>
</tbody>
</table>

- $\Xi^*/\Xi$:
  - no multiplicity dependence in pp, p-Pb
  - hint of suppression in central Pb-Pb, systematic uncertainties are to be reduced
  - models do not predict significant multiplicity dependence of the ratio
  - thermal models overestimate the ratio in Pb-Pb
  - Pythia8 and DPMJET underestimate the ratio in pp and p-Pb

V. Riabov for the ALICE Collaboration, ICPPA, Oct 2-5, 2017
Summary of ratios

- Results support the existence of a hadronic phase long enough to cause a significant reduction of the reconstructed yields of short lived resonances.
- Lower limit for the lifetime of the hadronic phase, $\tau > 2 \text{ fm/c}$

Enhanced strangeness production

- Clear increase of strangeness production from pp to Pb-Pb
- First observation of enhanced production of strange particles in high-multiplicity pp collisions
- Strange resonances show increasing patterns depending on the strangeness content → consistent with observations for ground-state hadrons
- Thermal model predictions for Pb-Pb are consistent with the highest multiplicity results in p-Pb while PYTHIA and DPMJET underestimate data
Enhanced strangeness production

- Ratios of resonances to stable particles with the same strangeness do not depend on multiplicity in pp and p-Pb collisions, confirming that strangeness enhancement depends predominantly on the strangeness content, rather than on the particle mass.
- Ratios do not show strong dependence on collision energy, \( \sqrt{s} = 0.2 - 5.02 \) TeV.
- No model reproduces all measurements simultaneously.
Summary

- Results support the existence of a hadronic phase in central heavy-ion collisions that lasts long enough to cause a significant reduction of the reconstructed yields of short lived resonances. Similar effects are observed in high-multiplicity collisions of small systems.
- In small systems strangeness enhancement as a function of multiplicity is found to be driven by particle strangeness content and not by mass.
- Shapes of particle spectra are mostly defined by particle masses, which is consistent with hydrodynamical models.
Backup
FIG. 13: Ratio of integrated yields $\Sigma(1385)^{\pm}/\Lambda$ and $\rho(770)^0/\pi^\pm$ (left) $\Xi(1530)^0/\Xi^-$, $\Sigma(1385)^{\pm}/\Lambda$ and $\Delta(1232)^{++}/p$ (right) for multiple centrality intervals calculated using EPOS3 with UrQMD ON (numerators and denominators are sums of particles and antiparticles). The shaded bands around the EPOS3 curves represent their statistical uncertainties. The theoretical data are plotted as functions of the values of $\langle dN_{ch}/d\eta \rangle^{1/3}$ measured by the ALICE experiment [28] at mid rapidity ($|\eta| < 0.5$).
Baryon-to-meson ratios

- Baryon anomaly manifested in increased baryon-to-meson (p/π, Λ/K_s^0) ratios at intermediate momentum
- Driving force of enhancement is not yet fully understood:
  - particle mass (hydro)?
  - quark count (recombination)?
- φ and K* are ideally suited for tests as mesons with masses very close to that of a proton:
  - Δm_φ ~ 80 MeV/c^2, Δm_K* ~ -45 MeV/c^2
Particle ratios: $p/\phi(p_T)$, $p/K^*(p_T)$

- Ratios evolve from pp to central Pb–Pb collisions → change of the spectral shapes
- In central Pb–Pb the ratios show weak $p_T$ dependence at $p_T < 4$ GeV/c
- Similarity of $K^{*0}$, $p$, $\phi$ spectral shapes at $p_T < 4$ GeV/c suggests that the shapes are mostly defined by hadron masses as expected from hydrodynamic models
- Some models which combine recombination and flow can also describe the data, PRC 92 054904 (2015)
Some of the resonances are measured in a wide $p_T$ range, up to ~ 10-20 GeV/c.

Pythia and Phojet reasonably reproduce measurements at high $p_T$, worse situation at low $p_T$.

Used as a reference for Pb-Pb.
In central Pb-Pb collisions light hadrons are similarly suppressed at high $p_T$ → no flavor/mass dependence

Similar behavior of light hadrons is also observed in p-Pb collisions at high $p_T$

$R_{AA}$ measurements at top LHC energy of 5.02 TeV are fully consistent with the measurements shown in this slide