IL NUOVO CIMENTO **47 C** (2024) 221
DOI 10.1393/ncc/i2024-24221-x

Colloquia: HADRON2023

Light flavour resonance production with ALICE at the LHC

Neelima Agrawal(*) on behalf of the ALICE Collaboration

Dipartimento di Fisica e Astronomia, Università di Bologna & INFN, Sezione di Bologna Bologna, Italy

received 21 December 2023

Summary. — Hadronic resonances produced in high-energy collisions at the LHC are powerful tools to investigate the hadron formation and, at the same time, describe the state of strongly interacting matter formed in heavy-ion collisions. Due to their short lifetimes, resonances experience the competing effects of regeneration and rescattering of their decay products in the hadronic medium. The study of how these processes affect the experimentally measured yields can extend the current understanding of the properties of the hadronic phase and the mechanisms that determine the shape of particle transverse momentum spectra. The $f_0(980)$ resonance was observed several years ago in $\pi\pi$ scattering experiments. Despite a long history of experimental and theoretical studies, the nature of this short-lived resonance is far from being understood, and there is no agreement about its quark content. According to different models, it has been associated with a meson, considered as a tetraquark or as a KK molecule. The ALICE experiment's excellent tracking and particle identification capabilities are exploited to measure the p_T-differential spectrum and integrated yield of the $f_0(980)$ meson produced in pp collisions at the energy of $\sqrt{s} = 5\,\text{TeV}$. These results are discussed in comparison with models and the properties of other hadrons. The new preliminary results and overall status of light-flavour resonances production measured in pp, p-Pb, Pb-Pb and Xe-Xe collisions at different collision energies in ALICE are shown and discussed. The Blast-Wave model, several Monte Carlo models such as EPOS3 and MUSIC with UrQMD and SMASH afterburner and statistical hadronization model predictions are also shown and compared to the results.

1. – Introduction

The Large Hadron Collider (LHC) at CERN creates the extreme condition of very high density ($\epsilon > 1\,\text{GeV/fm}^3$) and temperature ($T > 154 \pm 9\,\text{MeV}$) in the laboratory by colliding the particles and ions at very high center-of-mass energy (∼few TeV). In the heavy-ion collisions, a very hot, dense, and strongly interacting Quark-Gluon Plasma (QGP) medium fireball is expected to be formed for a very short time (∼few fm/c) [1, 2]. In the QGP medium, quarks and gluons are no longer confined inside the hadrons. Due to large pressure and energy density, the fireball further expands and cools down to make a subsequent transition to confined hadronic matter. The partonic phase is followed by the chemical and kinetic freeze-out, which makes a subsequent

(*) E-mail: `neelima.agrawal@cern.ch`

TABLE I. – *Resonance particles measured by the ALICE experiment.*

Resonance	lifetime (fm/c)	decay	B. R. (%)	quark constituents
$\rho(770)^0$	1.3	$\pi\pi$	100	$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$
$\mathrm{K}^*(892)^{\pm}$	3.6	$K_s^0\pi$	33.3	$u\bar{s}, \bar{u}s$
$\mathrm{K}^*(892)^0$	4.2	$K^+\pi^-$ and cc.	66.6	$d\bar{s}, \bar{d}s$
$\mathrm{f}_0(980)$	large unc.	$\pi\pi$	46	unknown
$\Sigma(1385)^{\pm}$	5 - 5.5	$\Lambda\pi^+$ and cc.	87	uus, dds
$\Xi(1820)^{\pm}$	8.1	ΛK^+ and cc.	unknown	$dss, \bar{d}ss$
$\Lambda(1520)$	12.6	$p\mathrm{K}^-$ and cc.	22.5	uds
$\Xi(1530)^0$	21.7	$\Xi^-\pi^+$	66.7	uss
$\phi(1020)^0$	46.4	KK	48.9	$s\bar{s}$

transition to hadrons, and eventually the produced particles reach the detectors. Hydrodynamic and statistical models [3-5] are successful in describing the bulk properties of the QGP matter created in heavy-ion collisions in which the abundances of stable particles are consistent with the chemical equilibrium scenario. The particle abundances are determined by the baryochemical potential (μ_{B}) and chemical freeze-out temperature (T_{ch}) [3, 6]. The hadronic resonances are excellent tools to probe the various properties of QCD matter and its evolution stages due to their typical lifetime ranging from few fm/c to a few tens of fm/c, which is comparable to the lifetime of the fireball (∼10 fm/c) [7].

Hadronic resonances are produced during hadronization and can decay inside the hadronic medium, between the chemical and kinetic freeze-out stage. Depending upon the time scale of the hadronic medium, the decay daughters of resonances might experience re-scattering via elastic scattering from nearby particles inside the medium which can modify their correlations. A lower reconstructed yield might be observed than the actual resonance yield. The possible effects of the re-generation of resonances due to the interactions of primary particles inside the hadronic medium can on the other hand increase the measured resonance yield. The re-scattering and re-generation effects are most sensitive to the relative interaction cross-section of the decay daughters inside the hadronic phase, resonance lifetime, density, and duration of the hadronic phase [8]. In the Statistical Hadronisation Models (SHMs) [3,9,10], hadronic resonances are expected to be produced at chemical equilibrium, however, due to the presence of the hadronic medium, the resonance yield in data might deviate from the model predictions. This article will discuss the recent measurements of light flavor resonances performed by the ALICE experiment at the LHC. A list of resonances [11] studied by the ALICE detector is reported in table I.

2. – Details on experimental setup: ALICE experiment

ALICE is a heavy ion dedicated experiment designed to explore the QGP and its features. The detailed description of the experimental setup of the ALICE detector can be found in [12] and the overall performance of the experiment and of its sub-detectors can be found in [13]. The main sub-detectors of ALICE used in the measurement are the V0 detector, the Inner Tracking System (ITS), the Time Projection Chamber (TPC) and the Time-Of-Flight (TOF). The V0 detector has been used for the collision centrality determination, triggering, and background suppression. The vertex reconstruction and charged particle tracking have been performed by using the ITS and TPC detectors.

Table II. – *Data collected by the ALICE detector for various collision systems and energy.*

Collision system	Collision energy, $\sqrt{s_{\mathrm{NN}}}$ (TeV)	Year(s) of collisions
pp	0.9, 2.76, 5.02, 7, 8, 13, 13.6	2009–13, 2015–18, 2021–22
p-Pb	5.02, 81.6	2013, 2016
Pb-Pb	2.76, 5.02	2010–11, 2015, 2018
Xe-Xe	5.44	2017

Charged hadrons have been identified by their specific ionization energy loss ($\mathrm{d}E/\mathrm{d}x$) in the TPC gas and by using the timing information from the TOF detector. The $\mathrm{d}E/\mathrm{d}x$ resolution of TPC is about 6.5% in most central (0–5%) Pb-Pb collisions and particle identification is possible up to about 1 GeV/c. The TOF has an excellent global time resolution of about 80 ps in Pb-Pb collisions which allows the identification of hadrons at higher momentum.

3. – Analysis description

The measurements of the resonance production are performed in several collision systems available at the LHC, *i.e.*, pp, p-Pb, Pb-Pb, and Xe-Xe collisions at various center-of-mass energies. A summary of recorded data sets and corresponding collision energy with the data collected year by the ALICE detector at the LHC is reported in table II.

The reconstruction of the resonance signal is generally performed by using the invariant mass method by combining the kinematics of the decay daughters of the specific resonance particle for each reconstructed event for various intervals of the pair p_{T}. This requires the reconstruction, selection, and identification of charged tracks in the inner barrel of the ALICE detector by using TPC and TOF detectors. The combinatorial background coming from the uncorrelated pairs within the same event is removed by the mixed event method, in which the decay daughters (unlike sign or like sign) from different events are combined. The resonance signal is obtained by subtracting the normalized mixed event invariant mass distribution from the single event distribution. The signal is fitted to extract the raw yield count by using the (non-)relativistic Breit-Wigner or Voigtean function with a residual background function (polynomial or Maxwell-Boltzmann) for each measured p_{T} interval for different centrality/multiplicity. To measure the resonance yield per unit of p_{T} and rapidity per event, several corrections such as vertex reconstruction efficiency, trigger efficiency, signal loss correction factor, branching ratio correction and detector acceptance times the resonance reconstruction efficiency calculated by detailed Monte Carlo study are applied. Afterward, a detailed systematic study related to the selection of events, tracks, particle identification, yield extraction method, and detector-related interactions is performed for each resonance analysis. The total systematic uncertainty is obtained by summing in the quadrature each of these contributions. Figure 1 shows examples of invariant mass for (left) $\Xi(1820)^{\pm}$ and (middle) $\mathrm{f}_0(980)$ reconstructed via their decay daughters and (right) transverse momentum distribution for $\mathrm{f}_0(980)$ in pp collisions for 5.02 TeV. Finally, the p_{T}-integrated yields and particle ratios are measured.

4. – Results and discussion

The upper panel of fig. 2 (top left) shows the $\mathrm{f}_0(980)/\pi$ [14] ratio in pp collisions at $\sqrt{s} = 5.02$ TeV. The particle yield ratio is compared by the low energy experiments and

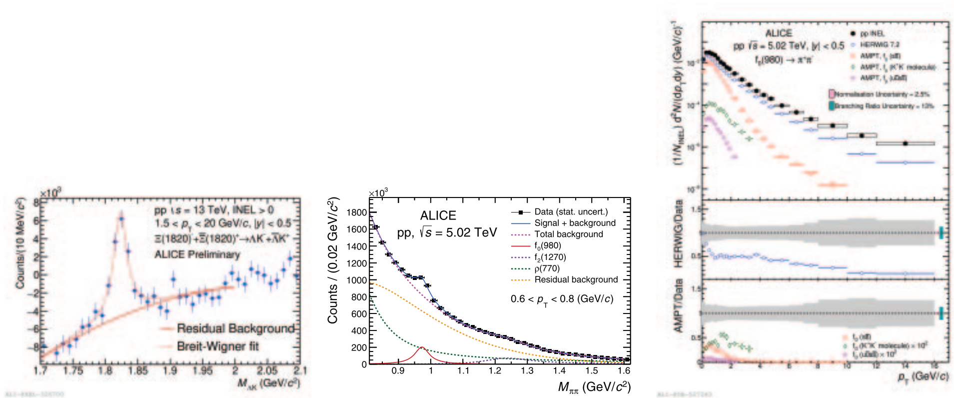

Fig. 1. – The invariant mass distribution of ΛK (left) and $\pi^+\pi^-$ (middle) for $\Xi(1820)$ and $f_0(980)$, respectively. (Right) The p_T-differential yield of $f_0(980)$ for pp, INEL collisions at $\sqrt{s} = 5.02$ TeV.

several SHMs model predictions as shown in fig. 2 (top right). The lower panel (bottom left) shows the $\langle p_T \rangle$ of resonances ($K^*(892)^0$, $K^*(892)^{\pm}$, $\phi(1020)^0$) together with charged particles at Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The measured resonance yield to charge particle yield ratio is used for the estimate of the hadronic medium lifetime by considering a negligible regeneration of the resonance yield inside the hadronic medium. This lifetime is shown in the lower panel (bottom-middle) from the measurements of $\rho(770)^0$ [15], $K^*(892)^0$, $K^*(892)^{\pm}$ [16] and $\Lambda(1520)$ [17] resonances in Pb-Pb collisions at 2.76 and 5.02 TeV. The lack of knowledge of regeneration fraction of resonance yield inside the hadronic medium is a driving factor that different resonance yield ratio estimates different hadronic lifetimes between the chemical to kinetic freezeout stage. Figure 2 (bottom right) shows the overall summary of the measured resonance yield ratios to stable particles with similar quark content in pp, p-Pb, and Pb-Pb collisions for various sets of collision energies by using the ALICE detector.

These results show the suppression of the short-lived resonances, *i.e.*, $\rho(770)^0$,

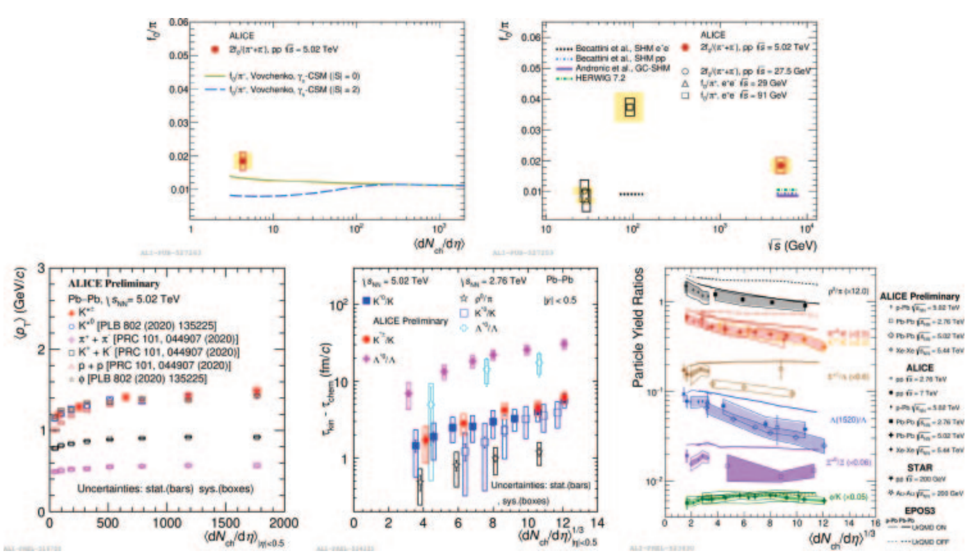

Fig. 2. – Selected recent results from the light-flavored resonance measurements by the ALICE detector.

$K^*(892)^0$, $K^*(892)^{\pm}$, Ξ, $\Sigma(1385)^{\pm}$ and $\Lambda(1520)$, which is expected due to rescattering of their decay daughters inside the hadronic medium produced in central/high multiplicity heavy-ion collisions as compared to peripheral Pb-Pb, p-Pb and pp collisions. The EPOS3 [18] Monte Carlo model predictions with/without an UrQMD afterburner to include/exclude the hadronic medium interaction are also shown for each resonance. It is noted that the longer-lived $\phi(1020)^0$ is not suppressed in central collisions as it decays outside the hadronic medium and the decay daughters do not experience the interactions of the hadronic medium.

5. – Conclusions

In conclusion, this article represents a short and overall summary of the recently measured light-flavored hadronic resonances such as $\rho(770)^0$, $K^*(892)^0$, $K^*(892)^{\pm}$, $\Lambda(1520)$, $\phi(1020)^0$, $\Xi(1530)^0$, $\Xi(1820)^{\pm}$, $\phi(1020)^0$, $f_0(980)$ and $\Sigma(1385)^{\pm}$) by the ALICE detector for pp, p-Pb, Pb-Pb, and Xe-Xe collisions data set for different collision energies. The short-lived resonance particles such as $\rho(770)^0$, $K^*(892)^0$, $K^*(892)^{\pm}$, $\Sigma(1385)^{\pm}$, $\Xi(1820)^{\pm}$ and $\Lambda(1520)$ show suppression in high multiplicity central collisions as compared to low multiplicity peripheral Pb-Pb, p-Pb, and pp collisions. These observations provide evidence of the existence of the dense and prolonged highly interacting hadronic medium created in the heavy-ion central collisions to be able to decrease the resonance yield via the rescattering phenomenon of the decay daughters. The results on the production of $f_0(980)$ relative to pions are closer to the γ_s-CSM model [19] prediction assuming net strangeness equal to zero. A future measurement in differential multiplicity and theoretical development will be able to give more insight into the structure of this particle.

REFERENCES

[1] Laermann E. and Philipsen O., *Annu. Rev. Nucl. Part. Sci.*, **53** (2003) 163.
[2] Muller B. and Nagle J. L., *Annu. Rev. Nucl. Part. Sci.*, **56** (2006) 93.
[3] Andronic A., Braun-Munzinger P. and Stachel J., *Nucl. Phys. A*, **772** (2006) 167.
[4] Becattini F. and Fries R., *Landolt-Börnstein*, **23** (2010) 208.
[5] Cleymans J. and Redlich K., *Phys. Rev. Lett.*, **81** (1998) 5284.
[6] Andronic A., Braun-Munzinger P., Redlich K. and Stachel J., *J. Phys. G*, **38** (2011) 124081.
[7] Markert C., Bellwied R. and Vitev I., *Phys. Lett. B*, **669** (2008) 92.
[8] Bleicher M. and Aichelin J., *Phys. Lett. B*, **530** (2002) 81.
[9] Wheaton S. and Cleymans J., *J. Phys. G*, **31** (2005) S1069.
[10] Petran M., Letessier J., Rafelski J. and Torrieri G., *Comput. Phys. Commun.*, **185** (2014) 2056.
[11] Particle Data Group (Workman R. L. *et al.*), *PTEP*, **2022** (2022) 083C01.
[12] Alice Collaboration (Aamodt K. *et al.*), *JINST*, **3** (2008) S08002.
[13] Alice Collaboration (Abelev B. B. *et al.*), *Int. J. Mod. Phys. A*, **29** (2014) 1430044.
[14] Alice Collaboration (Acharya S. *et al.*), *Phys. Lett. B*, **846** (2023) 137644.
[15] Alice Collaboration (Acharya S. *et al.*), *Phys. Rev. C*, **99** (2019) 064901.
[16] Alice Collaboration (Acharya S. *et al.*), arXiv:2308.16119 [nucl-ex].
[17] Alice Collaboration (Acharya S. *et al.*), *Phys. Rev. C*, **99** (2019) 024905.
[18] Knospe A. G., Markert C., Werner K., Steinheimer J. and Bleicher M., *Phys. Rev. C*, **93** (2016) 014911.
[19] Vovchenko V., Dönigus B. and Stoecker H., *Phys. Rev. C*, **100** (2019) 054906.