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# Exploring the internal structure of exotic resonances with ALICE

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**Abstract.**
The investigation of the quark content of hadrons has been a major goal of non-perturbative strong interaction physics. In the last decade, several resonances in the mass range 1000-2000 MeV/$c^2$ have emerged that cannot be explained by the quark model. The internal structure of exotic resonances such as $f_0$, $f_1$, and $f_2$ is currently unknown. Different scenarios are possible ranging from two-quark, four-quark, molecule, a hybrid state, to glueballs. A modification of the measured yields of these exotic hadrons in A–A and p–A collisions as compared to pp collisions has been proposed as a tool to investigate their internal structure. In this proceeding, the first-ever measurement of $f_1$ production in pp collisions and measurements of $f_0$ and $f_2$ production both in pp and p–Pb collisions will be discussed. The measurements of their mass, width, yields and their sensitivity to the internal structure of these exotic resonances will be shown. These results will pave the way for future experimental investigations on the internal structure of other exotic hadrons.

## 1 Introduction

In non-perturbative quantum chromodynamics, one of the major goals has long been to comprehend the quark composition of hadrons. The conventional classification of standard hadrons follows the quark model, categorizing baryons as trios of quarks ($qqq$) and mesons as pairings of a quark and an antiquark ($q\bar{q}$) [1]. Although many established hadrons are well described by this model, certain particles, including observed resonances, suggest an unconventional and exotic structure. The investigation of the nature of light scalar mesons remains interesting as their internal composition sparks several theoretical discussions on whether their internal structure is a multi-quark state or exhibits a more complex, molecular-like configuration.

Hadronic resonances are particles characterized by relatively short lifetimes, comparable to or shorter than the lifetime of the medium formed in heavy-ion collisions. This phenomenon is not only observed in these collisions but also potentially in high-multiplicity p-A and pp collisions at collider energies. Exotic resonances, which typically have masses falling within the 1 to 2 GeV/$c^2$ range, contribute to the intriguing landscape of subatomic particle physics. A particular focus of ongoing research lies in unravelling the quark composition of scalar mesons, such as $f_0(980)$ and $f_1(1285)$.

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Furthermore, Lattice QCD postulates the presence of glueballs, which comprise gluons. It is the fundamental carrier of the strong force. This theoretical framework sparks a compelling search of these unique entities, with proposed candidates including $f_0(1370)$, $f_0(1500)$, and $f_0(1710)$. Glueballs hold significance in particle physics as their existence and properties offer valuable insights into the strong force dynamics and the behaviour of gluons in the quantum chromodynamics framework. Investigating glueballs contributes to a deeper understanding of fundamental particles and their interactions, enriching our comprehension of the universe's building blocks within the realm of quantum chromodynamics [2, 3].

The ALICE detector, installed in one of the interaction points of the Large Hadron Collider is designed to study heavy-ion collisions and investigate the properties of quark-gluon plasma. Essential sub-detectors, including the Inner Tracking System (ITS) and the Time Projection Chamber (TPC), contribute significantly to tasks such as primary vertex determination, particle tracking, and Particle Identification (PID) through precise energy loss measurements. The Time-Of-Flight (TOF) detector provides the PID information through accurate particle time-of-flight measurements. Additionally, the V0A ($2.8 < \eta < 5.1$) and V0C ($-3.7 < \eta < -1.7$) detectors play crucial roles in event triggering and selection, focusing on charged-particle multiplicity at forward rapidities [4].

## 2 Potential structures of exotic resonances

The internal structure of $f_0(980)$ has been a subject of theoretical debate, encompassing proposed interpretations like a conventional mesonic state [5], a molecular composition involving mesons and other particles [6], and, more recently, a tetraquark hypothesis suggesting a structure with two quarks and two anti-quarks [7]. Similarly, the nature of $f_1(1285)$ is also a topic of discussion, with considerations for both a conventional mesonic state [8], a molecular structure [9] and a tetra quark structure [10]. Recent theoretical interpretations even predict a potential hybrid structure[11] involving additional quark-antiquark pairs.

ALICE's recent findings on $f_0(980)$ and pion yield ratios in pp collisions at $\sqrt{s} = 5.02$ TeV has been compared to $\gamma$-CSM model predictions in two scenarios [12]. In the scenarios where $f_0(980)$ has no net strangeness content ($|S| = 0$), the model predicts higher yield ratios at low multiplicities ($\langle dN_{ch}/d\eta \rangle$) compared to the assumption of $|S| = 2$. Remarkably, these predictions converge and closely match when the multiplicity surpasses 100 [13].

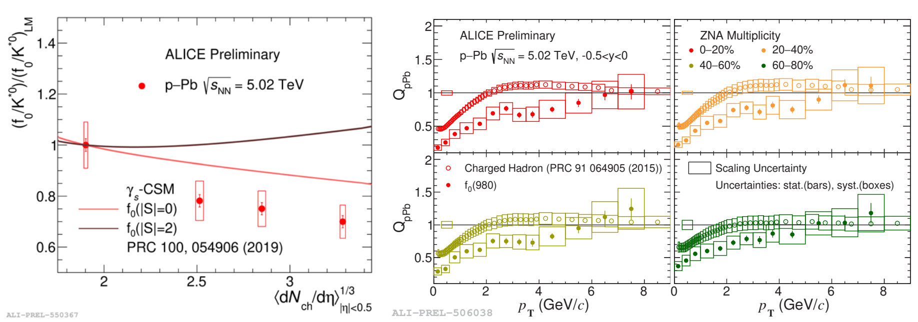


**Figure 1.** (Left side) Double ratio of $(f_0(980)/K^{*0})/(f_0(980)/K^{*0})_{LM}$ compared with $\gamma$-CSM model predictions for ($|S| = 0$) and ($|S| = 2$) in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. (Right side) Nuclear modification factor for $f_0(980)$ yield for different ZNA multiplicity class.

In p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, the $f_0(980)/K^{*0}$ ratio is calculated using the same two scenarios for the $\gamma$-CSM model predictions. In the double ratio

$(f_0(980)/K^{*0})/(f_0(980)/K^{*0})_{LM}$, if strangeness content exists ($|S| = 2$), an increasing trend is expected due to $K^{*0}$ characterized by ($S = 1$), and the model suggesting a mild increasing trend. The data qualitatively aligns with the scenario when ($|S| = 2$) as shown in Figure 1. The ALICE experiment recently conducted an analysis of the nuclear modification factor for $f_0(980)$ in p–Pb collisions, The findings unveil a notable suppression of $f_0(980)$ yield at low $p_T$, surpassing those observed for charged hadrons and displaying a more pronounced effect in more central collisions. This suppression is indicative of potential rescattering effects. Intriguingly, the absence of a Cronin peak in the intermediate $p_T$ range suggests that the $f_0(980)$ meson may possess a conventional meson structure.

ALICE has recently identified the $f_1(1285)$ in pp collisions at $\sqrt{s} = 13$ TeV, marking the first-ever measurement of this particle at ALICE. The reconstruction utilized the invariant mass technique, focusing on the $K^0_S K\pi$ decay channel. The left panel in Figure 2 illustrates the invariant mass distribution of $f_1(1285)$ after background subtraction. On the right panel of Figure 2, the integrated particle yield ratio is compared with thermal model predictions in pp collisions at $\sqrt{s} = 13$ TeV [14]. Notably, the thermal model predictions for particle ratios, considering $f_1(1285)$ with strange quark content ($|S| = 0$), closely align with experimental measurements compared to predictions assuming ($|S| = 2$).

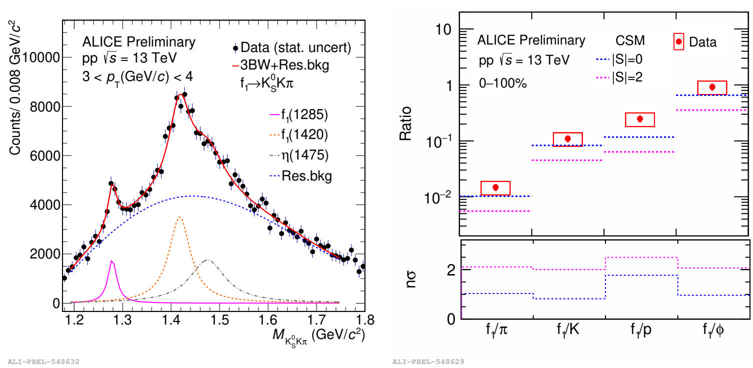


**Figure 2.** (Left side) Invariant mass distribution of $f_1(1285)$ after background subtraction from $K^0_S K\pi$ decay channel. (Right side) Comparison of integrated particle yield ratio with thermal model predictions in pp collisions at $\sqrt{s} = 13$ TeV.

## 3 Glueball search

The exploration of glueballs, distinct particles composed solely of gluons, has been a focal point of experimental investigations by WA102 [15]. This research delves into understanding the unique characteristics and behaviour of these entities, offering valuable insights into the fundamental nature of gluons and the strong force within the framework of quantum chromodynamics.

Scalar mesons, particularly $f_0(980)$, emerge as promising candidates in detecting glueballs. Measurements performed through the $K^0_S - K^0_S$ decay channel in both pp and p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV have successfully allowed for signal extraction. Resonances such as $f_0(1370)$, $f_2(1525)$, and $f_0(1710)$ have been identified. In the initial attempt to extract residual background and $f_0(980)$, the subtraction of these components revealed the initial signal distribution. Multiple Breit-Wigner functions were then applied for fitting, as depicted in Figure 3.

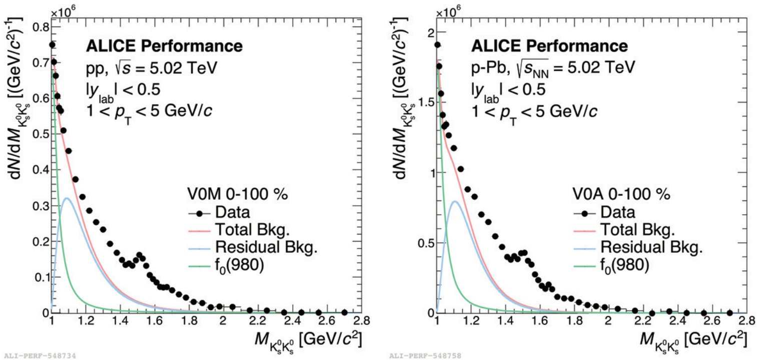


**Figure 3.** The $f_0(980)$ signal is the contribution from multiple Breit-Wigner functions in pp (right ) and p–Pb (left) collisions at 5.02 TeV.

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