EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP-2024-239
16 September 2024

Measurement of $f_1(1285)$ production in pp collisions at $\sqrt{s}$ = 13 TeV

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Abstract

This study presents the first measurement of the $f_1(1285)$ resonance using the ALICE detector in inelastic proton–proton collisions at a center-of-mass energy of 13 TeV. The resonance is reconstructed at midrapidity ($|y| < 0.5$) through the hadronic decay channel $f_1(1285) \rightarrow K^0_S K^{\pm}\pi^{\mp}$. Key measurements include the determination of its mass, transverse-momentum integrated yield, and average transverse momentum. Additionally, the ratio of the transverse-momentum integrated yield of $f_1(1285)$ to pion is compared with calculations from the canonical statistical hadronization model. The model calculation, assuming a zero total strangeness content for $f_1(1285)$, reproduces the data within 1σ deviation, shedding light on the quark composition of $f_1(1285)$.

*See Appendix A for the list of collaboration members

1 Introduction

Quantum chromodynamics (QCD), the theory that governs the strong force, describes how colored quarks and gluons interact, forming various types of hadronic states. This includes mesons, which consist of quark–antiquark pairs, and baryons, composed of three quarks or antiquarks. Beyond these conventional structures, there is a growing interest in exotic states like tetraquarks and pentaquarks, which feature unconventional quark combinations [1–9]. Investigations into exotic states can be traced back to the early development of the constituent quark model, which serves as a fundamental framework for understanding the composition of hadrons [10–13].

An exemplary candidate for an exotic particle under consideration is the $f_1(1285)$ meson [14]. Aligned within the quark model as a member of the $^3P_1$ axial-vector nonet, the $f_1(1285)$ was independently discovered in $p\overline{p}$ annihilation experiments at BNL [15] and CERN [16] in 1965. Both experiments observed a resonance decaying to $K\overline{K}\pi$ with quantum numbers $I^G(J^{PC}) = 0^+(1^{++})$. Furthermore, it has been observed in central exclusive production measurements in pp collisions by the WA102 [17] and WA76 [18] experiments at CERN, E690 at Fermilab [19], and by the L3 Collaboration with $\gamma\gamma$ collisions at CERN [20, 21]. Additionally, it has been observed in hadronic Z decays at LEP [22], in photoproduction from a proton target with CLAS data [23], and beauty-hadron decays at LHCb [24]. Despite the numerous experimental observations, the precise quark composition of the $f_1(1285)$ remains elusive. Theoretical predictions regarding the valence quark content of the $f_1(1285)$ meson are broadly classified into three categories: (i) as a bound state comprising of light up (u) and down (d) quarks, (ii) as a bound state formed by both light and strange (s) quarks, and (iii) as molecular configurations involving $K\overline{K}^*$ [25]. Quark composition of the $f_1(1285)$ meson involving only light quarks can be expressed as a linear combination of u and d quarks, $\frac{1}{\sqrt{2}}(\bar{u}u + \bar{d}d)$ [26], whereas the presence of strange quarks in the $f_1(1285)$ meson gives three different possibilities of quark compositions: tetraquark state $\frac{1}{\sqrt{2}}(su\bar{s}\bar{u} + sd\bar{s}\bar{d})$ [27], bound state of light quarks with a mixture of strange quarks ($\frac{\alpha}{\sqrt{2}}(\bar{u}u + \bar{d}d)$ + $\delta s\bar{s}$) [28], and the bound state of light quarks with a mixture of strange quarks and gluons ($\frac{\alpha}{\sqrt{2}}(\bar{u}u + \bar{d}d)$ + $\delta_1 s\bar{s}$ + $\delta_2 G$) [29], where G is the gluon state. Here α, δ, δ_1, and δ_2 are the Clebsch Gordan Coefficients of appropriate value. Recently, the LHCb collaboration disfavored the interpretation of the tetraquark structure of $f_1(1285)$, with a significance of 3.3σ [24]. The yield of the $f_1(1285)$ can largely vary with the diverse assumptions for compositions of quarks [30]. Notably, calculations using the canonical-ensemble-based Statistical Model (γ_SCSM) [31] reveal significant differences in hadron yields based on their strangeness content [32]. The study reported in this Letter explores the strangeness content of the $f_1(1285)$ meson by comparing its transverse-momentum (p_T) integrated yield obtained from ALICE data with γ_SCSM calculations.

In high-energy heavy-ion collisions, compelling evidences for the formation of a strongly-interacting quark–gluon plasma (QGP) have been observed [33–47]. This deconfined and strongly interacting state expands and cools down as a nearly perfect liquid [48] until the temperature reaches the pseudo-critical temperature of approximately 155 MeV [49]. After this phase, a transition to confined QCD matter occurs which creates a hot and dense gas of interacting hadrons. Within this environment resonances decay and particles interact (pseudo)elastically until they decouple [50]. At the LHC, the system produced in Pb–Pb collisions undergoes decoupling after approximately 10 fm/c [51]. The study of hadronic resonances with varying lifetimes is crucial for characterizing the late hadronic stage of the collision. Depending on the lifetime of resonances, rescattering and regeneration processes affect their yield [52–65]. Given that $f_1(1285)$ has a lifetime of approximately 8.7 fm/c [14], placing it between the lifetimes of K^{*0} meson and Λ^* baryon, it becomes an indispensable component for systematically studying rescattering effects and properties of the hadronic phase in heavy-ion collisions. Furthermore, theoretical studies suggested that the $f_1(1285)$ meson could be pivotal in exploring the partial restoration of chiral symmetry within the nuclear medium [66]. It has been found that the $f_1(1285)$, a chiral partner of the ω meson, could exhibit a significant mass shift from its vacuum expectation (1281.9 ± 0.5 MeV/c^2) in the presence of finite baryon density. Similar trends for chiral partners are predicted at the high temperatures reached in heavy-ion collisions at LHC energies [67]. Searches for (partial) chiral symmetry restoration effects are typically investigated through the electromagnetic decays of vector mesons, as they are not affected by rescattering, unlike hadronic decays. However, since the $f_1(1285)$ meson is not particularly broad, rescattering effects may be less dominant in this case. Additionally, by performing measurements in peripheral Pb–Pb collisions, such effects could be further minimized. Another important aspect of the measurement is the yield ratio of the $f_1(1285)$ meson to its chiral partner, the ω, which can provide valuable insights into chiral symmetry restoration. This yield ratio is expected to approach unity [68] as one moves towards more peripheral Pb–Pb collisions due to the mass degeneracy of the chiral partners. Therefore, measurements of the $f_1(1285)$ production in pp collisions are crucial to constitute a reference for studying the partial restoration of chiral symmetry and rescattering effects in heavy-ion collisions.

This Letter presents the first measurement of the inclusive production of the $f_1(1285)$ resonance at midrapidity ($|y| < 0.5$) in inelastic pp collisions at a center-of-mass energy $\sqrt{s}$ of 13 TeV. The article is structured as follows: Section 2 outlines the ALICE experimental setup, Section 3 details the event and track selection criteria, Section 4 presents the data analysis technique, and Section 5 describes the study of systematic uncertainties. Results are presented in Section 6, and the Letter concludes with a summary in Section 7.

2 Experimental apparatus

The yield of the $f_1(1285)$ meson is measured in pp collisions at $\sqrt{s} = 13$ TeV using data collected by the ALICE detector. A detailed description of the ALICE detector and its performance can be found in Refs. [69, 70]. Several key detectors, including the Inner Tracking System (ITS) [71], Time Projection Chamber (TPC) [72], Time-of-Flight (TOF) [73, 74], and V0 [75] detectors, have been used for the analysis presented in this Letter.

For event triggering and mitigating beam-induced background effects, the V0 detector is used. It consists of two scintillator arrays, V0A and V0C, which are positioned on either side of the interaction point along the beam line and cover the pseudorapidity intervals $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively. The minimum bias trigger used in this analysis is defined by coincident signals in the V0A and V0C detectors.

The ITS and TPC detectors, housed within a 0.5 T solenoidal magnet, play crucial roles in tracking and identifying charged particles and reconstructing primary and secondary vertices. The ITS and TPC cover a pseudorapidity range of $|\eta| < 0.9$ and full azimuthal angle.

The ITS comprises six cylindrical silicon layers surrounding the beam vacuum tube. The two innermost layers are formed by Silicon Pixel Detectors (SPD), followed by two layers of Silicon Drift Detectors and two layers of Silicon Strip Detectors. The ITS is crucial for determining primary and secondary vertices. Additionally, the ITS improves the momentum and angle resolution for charged particles reconstructed by the TPC.

The TPC serves as the core of the ALICE detector [70, 72]. It is a large cylindrical drift detector, spanning radial and longitudinal ranges of approximately $85 < r < 250$ cm and $-250 < z < 250$ cm, respectively. The endcaps of the TPC incorporate multiwire proportional chambers segmented radially into pad rows. The TPC provides three-dimensional spatial information for up to 159 tracking points. Charged tracks originating from the primary vertex can be reconstructed down to $p_{\mathrm{T}} \sim 150$ MeV/c. The particle identification is based on the specific energy loss ($\mathrm{d}E/\mathrm{d}x$) in the TPC, which is measured with a resolution of 5% in pp collisions [72]. The measured $\mathrm{d}E/\mathrm{d}x$ is compared with the expected value for a given particle species calculated with a Bethe–Bloch parameterization.

The TOF is placed outside the TPC and employs Multigap Resistive Plate Chambers, covering the pseudorapidity range of $|\eta| < 0.9$ and full azimuthal angle. The TOF detector identifies particle species at intermediate p_T via measurements of their time-of-flight from the interaction point to the TOF detector with a time resolution of 80 ps in pp collisions [73].

3 Data sample, event and track selections

The data utilized in the present analysis were collected by the ALICE detector in 2016, 2017, and 2018. The position of the primary vertex along the beam axis (z-axis of the ALICE reference frame) is required to be within 10 cm from the nominal center ($z = 0$) of the ALICE detector. As detailed in Refs. [70, 76], offline event selections are applied to reduce the beam-induced background and pileup events. After applying the event selection criteria, approximately 1.5 billion minimum-bias events (corresponding to an integrated luminosity of 32.08 ± 0.51 nb^{-1} [77]) have been analyzed for this $f_1(1285)$ measurement.

Given the short-lived nature of the $f_1(1285)$ meson, its reconstruction is performed through the hadronic decay channel, $f_1(1285) \rightarrow K^0_S K^{\pm}\pi^{\mp}$, with a branching ratio (BR) of (2.25±0.1)% [14]. The BR value is computed from the one of $K\overline{K}\pi$ reported in [14] accounting for all possible combinations of kaons and pions and 50% probability that K^0 is K^0_S. The analysis is performed in the transverse momentum range of $1 < p_T < 12$ GeV/c at midrapidity ($|y| < 0.5$). At lower p_T (< 1 GeV/c), the $f_1(1285)$ signal is not statistically significant because of the presence of large backgrounds.
Charged tracks are reconstructed using the ITS [78] and TPC [72] detectors. To ensure high track quality, the standard track selection criteria [79, 80] are employed in this work. Charged tracks originating from the primary vertex are required to satisfy $p_T > 0.15$ GeV/c and $|\eta| < 0.8$ for uniform acceptance. Selected tracks need to have two hits in the ITS, of which at least one hit in the SPD, and traverse radially a minimum of 70 out of the total 159 pad rows of the TPC. The maximum χ^2 per space point in the TPC and ITS, obtained from the track fit, is required to be 4 and 36, respectively. To mitigate the contamination of secondary charged particles, the distance of closest approach in the transverse plane of reconstructed tracks to the primary vertex (DCA$_{xy}$) is required to be smaller than $7\sigma_{\mathrm{DCA}_{xy}}$, where $\sigma_{\mathrm{DCA}_{xy}}$ denotes the DCA$_{xy}$ resolution. The p_T-dependent DCA$_{xy}$ resolution is parameterized as $\sigma_{\mathrm{DCA}_{xy}} = 0.0105 + 0.0350/(p_T/(\mathrm{GeV/c}))^{1.1}$ cm [80]. The DCA to primary vertex in the longitudinal direction is constrained to be within 2 cm. The detected charged particles are identified using information from the TPC and TOF detectors [73]. In the TPC, particle identification is based on their specific ionization energy loss (dE/dx), ensuring that pions and kaons have a specific energy loss within 2 standard deviations (σ_{TPC}) from the expected dE/dx values derived from the Bethe–Bloch parameterization. Here, σ_{TPC} represents the TPC's dE/dx resolution [72]. In the TOF, identification relies on the measured time of flight, which must be within $3\sigma_{\mathrm{TOF}}$ of the expected value for each particle species, provided the track has a hit in the TOF [74]. If a track lacks a hit in the TOF, identification is carried out using only the TPC.

The K^0_S is reconstructed through its weak decay topology (V^0 topology) [81], via the $K^0_S \rightarrow \pi^-\pi^+$ decay channel with a BR of (69.2 ± 0.05)% [14]. The selection criteria for K^0_S reconstruction are detailed in Table 1. Two oppositely-charged pions produced from the K^0_S decay are identified with the $4\sigma_{\mathrm{TPC}}$ requirement in the acceptance window $|\eta| < 0.8$. The distance of closest approach between negatively and positively charged tracks ($\mathrm{DCA}_{\pi^-\pi^+}$) is required to be less than 1.0 cm. Additionally, the DCA of charged tracks and V^0 to the primary vertex must be greater than 0.06 cm and less than 0.3 cm, respectively. The cosine of the pointing angle, representing the angle between the V^0 momentum and the line connecting the secondary to the primary vertex, has to be greater than 0.97. Only K^0_S candidates whose secondary vertex radial position is larger than 0.5 cm are selected to reconstruct $f_1(1285)$. Furthermore, candidates with a proper lifetime $LM_{K^0_S}/p$ greater than 15 cm/c are excluded. Here, L represents the linear distance between the primary and secondary vertex, $M_{K^0_S}$ is the world-average mass [14] of K^0_S, and p indicates the total momentum of K^0_S. An additional selection, called "Competing V0 rejection" or veto on Λ invariant mass, is applied by recalculating the V0 mass, assuming that one of two pions is a proton. If the recalculated mass is compatible with the Λ mass within 4.3 MeV/c^2, which is about three times the width of the Λ invariant mass peak in ALICE [80–82], the selected particle is rejected. Finally, the invariant mass of $\pi^+\pi^-$ must be compatible within $6\sigma_M$ of the K^0_S nominal mass, where σ_M is the width of the K^0_S invariant mass peak and is about 5 MeV/c^2. The K^0_S candidates that satisfy the aforementioned topological selection criteria at midrapidity ($|y| < 0.5$) are used in the reconstruction of the $f_1(1285)$ resonance.

Table 1: Selection criteria for K^0_S.

Selection criteria	Value
TPC crossed rows	> 70
Acceptance window of pions ($\|\eta\|$)	< 0.8
$n\sigma_{TPC}$ for $\pi^\pm$	< 4
$DCA_{\pi^-\pi^+}$	< 1.0 cm
DCA of V^0 daughters to PV	> 0.06 cm
DCA of V^0 to PV	< 0.3 cm
V^0 cosine pointing angle	> 0.97
V^0 radius	> 0.5 cm
Proper lifetime	< 15 cm/c
Veto on Λ invariant mass	> 4.3 MeV/c^2
K^0_S mass window (in units of σ_M)	$\pm$ 6

4 Data analysis

The reconstructed K^0_S are paired with charged kaons forming a $K^0_S K^\pm$ pair. This $K^0_S K^\pm$ pairs are combined with oppositely charged pions to reconstruct the $f_1(1285)$ resonance. To enhance the significance of the $f_1(1285)$ signal, the invariant mass of the $K^0_S K^\pm$ pair is required to be below 1040 MeV/c^2. The invariant-mass distribution of $K^0_S K^\pm \pi^\mp$ triplets accommodates all resonances that decay into $K^0_S K^\pm \pi^\mp$ as well as substantial combinatorial background, as can be seen in the invariant mass distribution of unlike-sign combinations in the f_1-candidate p_T interval $3 < p_T < 4$ GeV/c, shown by the black markers in the left panel of Fig. 1. The combinatorial background is estimated using like-sign $K^0_S K^\pm \pi^\pm$ triplets [64, 79] (red markers in left panel of Fig. 1). The right panel of Fig. 1 presents the invariant mass distribution of the like-sign-subtracted $K^0_S K^\pm \pi^\mp$ triplets for $3 < p_T < 4$ GeV/c in pp collisions at $\sqrt{s}$ = 13 TeV. After the subtraction, three resonances, i.e, $f_1(1285)$, $f_1(1420)$, and $\eta(1475)$ can be identified in the considered invariant mass range along with a residual background of correlated pairs. It is worth noting that the $f_1(1420)$ resonance is situated just above the threshold (1385 MeV/c^2) of $K^*\overline{K}$ coupled channels, leading to the observation of cusp-like structures in the invariant-mass distribution of $K^0_S K^\pm \pi^\mp$ triplets. Theoretical models based on $K^*\overline{K}$ dynamics [25, 83] offer intriguing insights into the nature of $f_1(1420)$, which could be explored in future studies.

The correlated background mainly arises from jets and decays of resonances with misidentification and multiple decay chains [64]. The like-sign-subtracted invariant-mass distribution is fitted assuming a sum of three non-relativistic Breit–Wigner distributions [22, 64] for the $f_1(1285)$, $f_1(1420)$, and $\eta(1475)$ mesons and an additional residual background [22]. The fit function is given by

$$\frac{dN}{dM} = \sum_{i=1}^{3} \frac{Y_i}{2\pi} \frac{\Gamma_i}{(M-M_i)^2 + \Gamma_i^2/4} + f_{Res.Bkg}(M), \tag{1}$$

where the index i ranges over $f_1(1285)$, $f_1(1420)$, and $\eta(1475)$ resonances. The M_i, Γ_i, and Y_i parameters denote the masses, widths, and normalization constants of these three resonances, respectively. The M corresponds to the invariant mass of the $K^0_S K^\pm \pi^\mp$ ($M_{K^0_S K\pi}$) triplets. The mass resolution of the detector for the reconstruction of $f_1(1285)$ is negligible as compared to its vacuum width (22 $\pm$ 1) MeV/c^2 [14]

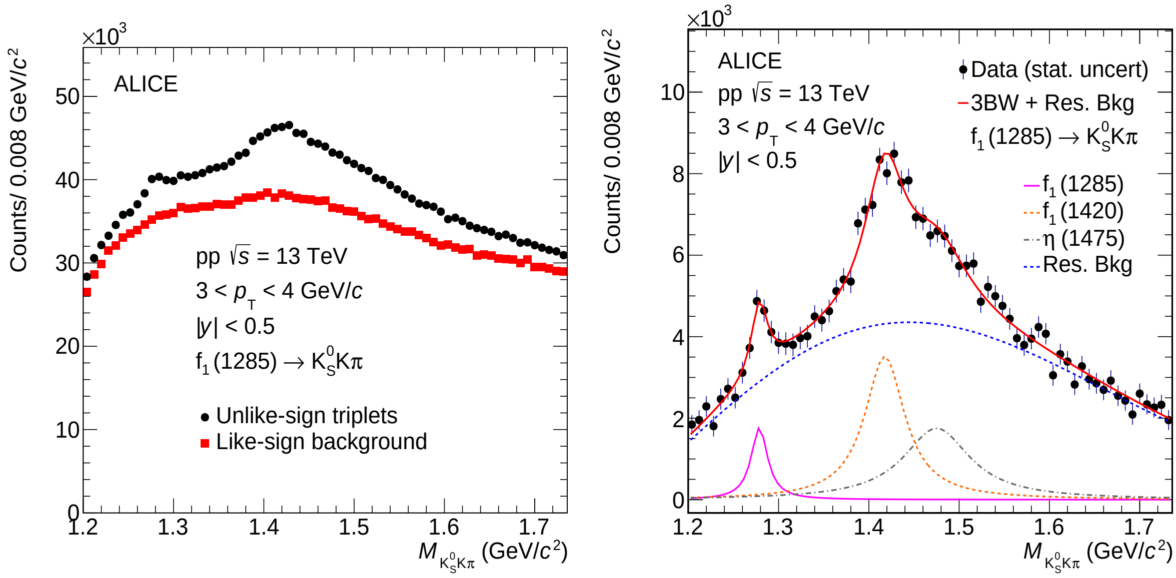

Figure 1: Like- and unlike-sign (left) and the like-sign-subtracted (right) invariant mass distribution of $K^0_S K\pi$ triplets in $|y| < 0.5$ in minimum-bias pp collisions at $\sqrt{s} = 13$ TeV. The subtracted distribution is fitted with the function defined by Eq. 1, and the dotted blue line describes the residual background distribution, which is given by Eq. 2.

and is not included in the fit function. The residual background function [22] is expressed as

$$f_{\mathrm{Res.Bkg}}(M) = [M - (m_\pi + M_{K^0_S K})]^n \exp(-AM - BM^2), \quad (2)$$

where m_π is the mass of π meson and $M_{K^0_S K}$ is the invariant mass of the $K^0_S K$ pair. Here, A, B, and n are the fit parameters. The width parameters of the Breit–Wigner functions are fixed to their world-average values [14] in the standard fit case, which are 22, 54, and 90 MeV/c^2, respectively. The masses and the normalization constants of the three resonances are left free. Finally, the raw yields of $f_1(1285)$ in each p_T interval are obtained from the integral of the Breit–Wigner distribution, as done in Refs. [79, 84].

The extracted raw yields (N^{raw}) are corrected for detector acceptance and reconstruction efficiency ($A \times \varepsilon_{\mathrm{rec}}$) as well as the BR of the analyzed decay channel. The product $A \times \varepsilon_{\mathrm{rec}}$ is estimated using simulated pp events produced with the PYTHIA8 Monte Carlo (MC) event generator [85], in which $f_1(1285)$ particles are injected with a flat p_T distribution. The particles are then propagated through the ALICE detector using the GEANT3 transport code [86]. The $A \times \varepsilon_{\mathrm{rec}}$, defined as the ratio of reconstructed to generated $f_1(1285)$, is calculated as a function of p_T within $|y| < 0.5$. The event and track selections used in the data analysis are also applied in the simulation. Notably, $A \times \varepsilon_{\mathrm{rec}}$ initially increases with p_T, starting at around 1% at $p_T = 1.5$ GeV/c and reaching a maximum value of approximately 6.5% at $p_T \approx 6$ GeV/c before decreasing again, as depicted in Fig. 2. The relative statistical uncertainties on $A \times \varepsilon_{\mathrm{rec}}$ are found to be in the range of 5–10% across the p_T intervals. Moreover, since the generated p_T spectra of $f_1(1285)$ have a different shape than the measured p_T spectra, a reweighting procedure [52, 80] is implemented iteratively until convergence is reached by correcting at first the measured raw yields with the reconstruction efficiency obtained with the generated p_T spectra. The resulting p_T spectrum is then fitted with a Levy–Tsallis function and the extracted parametrization is finally used to weight the Monte Carlo spectra at generated and reconstructed level. From these reweighted spectra, the $A \times \varepsilon_{\mathrm{rec}}$ as a function of p_T is determined.

The measurements need to be further corrected for trigger inefficiency ($\varepsilon_{\mathrm{trig}}$), vertex reconstruction inefficiency ($\varepsilon_{\mathrm{vert}}$), and signal loss ($f_{\mathrm{SL}}$) factors, which are determined through MC simulations. Signal loss factor accounts for the loss of $f_1(1285)$ mesons due to trigger selection (i.e. $f_1(1285)$ mesons produced

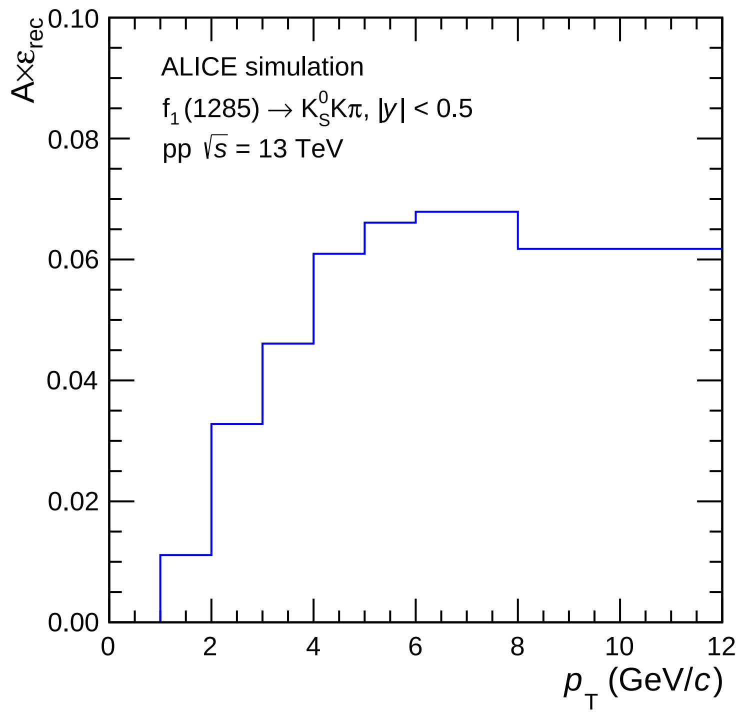

Figure 2: The product of the acceptance and the resonance reconstruction efficiency as a function of $p_{\rm T}$ for $f_1(1285)$ at midrapidity ($|y| < 0.5$) in simulated pp collisions at $\sqrt{s} = 13$ TeV.

in pp collisions that did not fire the trigger). Given the potential limitations of simulations involving injected $f_1(1285)$ signals in realistically assessing correction factors [32], these factors are taken to be the same as for the K^{*0} meson at the same collision energy [80]. The values of the correction factors for pp collisions at $\sqrt{s}$ = 13 TeV are $\varepsilon_{\rm trig}$ = 0.74, $\varepsilon_{\rm vert}$ = 0.93. The signal loss correction factor ($f_{\rm SL}$) is smaller than 2% for $p_{\rm T} > 1$ GeV/c [80]. Finally, the yields are normalized by the number of accepted events ($N^{\rm acc}_{\rm event}$) to obtain the $f_1(1285)$ $p_{\rm T}$-differential yield in inelastic pp collision, which can be formally expressed as

$$\frac{1}{N_{\rm evt}}\frac{{\rm d}^2N}{{\rm d}y{\rm d}p_{\rm T}} = \frac{1}{N^{\rm acc}_{\rm evt}}\frac{N^{\rm raw}}{\Delta y\Delta p_{\rm T}}\frac{\varepsilon_{\rm trig}\,\varepsilon_{\rm vert}\,f_{\rm SL}}{({\rm A}\times\varepsilon_{\rm rec}){\rm BR}}, \tag{3}$$

where $\frac{{\rm d}^2N}{{\rm d}y{\rm d}p_{\rm T}}$ is the number of $f_1(1285)$ produced in a given rapidity (dy) and transverse momentum (d$p_{\rm T}$) interval.

5 Systematic uncertainties

For the measurement of the $f_1(1285)$ mass and yields, various sources of systematic uncertainties have been taken into account: the signal extraction method, the primary track selections, the K^0_S reconstruction and selection, the particle identification criteria, the method adopted in matching track segments in the ITS with tracks in the TPC, as well as uncertainties in the material budget and hadronic interactions of the produced particles in the ALICE detectors. The resulting changes in the $f_1(1285)$ mass and yields for each $p_{\rm T}$ interval, obtained from repeating the entire analysis chain by varying one source at a time (as described below) while keeping others at default, are incorporated as systematic uncertainties.

Several factors are varied to evaluate the uncertainty in the signal extraction from the invariant mass fits, including fitting ranges, residual background fit function, and variations in the width of the three resonances ($f_1(1285)$, $f_1(1420)$, and $\eta(1475)$). When adjusting fitting range boundaries, a shift of $\pm$ 20

MeV/c^2 with respect to the default case is applied to both sides. The widths of all resonances are treated as free parameters in the fit, unlike the default case where they are fixed to their world-average values, and the differences in $f_1(1285)$ mass and yields contribute to the systematic uncertainties. Additionally, the residual background is modeled using second and third-order polynomials to investigate systematic effects on the mass and yield of $f_1(1285)$. Moreover, the mass of $f_1(1420)$ is held constant, unlike in the standard case where it is allowed to vary, to understand its impact on the $f_1(1285)$ observed mass and yield. The resulting uncertainty for signal extraction on the observed $f_1(1285)$ mass and yield varies from 0.13% to 0.19% and 10.5% to 14.5%, respectively, across the measured p_T ranges. For the primary-track selection, the criteria are varied following the procedure outlined in Ref. [80]. This results in an uncertainty on the $f_1(1285)$ mass ranging from 0.03% to 0.08% and an uncertainty on its yield ranging from 3.9% to 5.8% across the various p_T intervals. The uncertainty due to the K^0_S reconstruction is estimated by varying the selections in Table 1, resulting in a p_T-dependent systematic uncertainty ranging from 0.04% to 0.08% for the $f_1(1285)$ mass and from 6.4% to 9.2% for the $f_1(1285)$ yield. The uncertainties associated with the identification of the pions and kaons produced in the $f_1(1285)$ decay are assessed by varying the selection criteria in the TOF from $|n\sigma_{TOF}| < 3$ to $|n\sigma_{TOF}| < 4$. This variation results in $f_1(1285)$ mass uncertainties ranging from 0.003% to 0.027% and yield uncertainties ranging from 1% to 6%, depending on p_T. Furthermore, uncertainties related to the material budget, the cross section for hadronic interactions in the detector material, and the ITS–TPC matching efficiency, obtained from Ref. [80], contribute to the uncertainty on the yield of $f_1(1285)$. The total uncertainty is obtained by summing the uncertainties from all sources in quadrature. The uncertainty on the $f_1(1285)$ mass ranges from approximately 0.16% to 0.20%, while for the yield, it spans from 16% to 17% across the measured p_T intervals.

6 Results

The mass of $f_1(1285)$ resonance, i.e., the fit parameter M_0 obtained from Eq. 1, is shown in Fig. 3 for the different p_T intervals considered in this analysis. The systematic uncertainties on the measured mass, shown as boxes around the data points, are evaluated following the description in Sec. 5. The measured mass is consistent with its world-average value [14] within uncertainties.

Figure 4 illustrates the $f_1(1285)$ p_T-differential yield in pp collisions at $\sqrt{s} = 13$ TeV, incorporating all the corrections detailed in Sec. 5. The p_T spectrum is fitted with a Levy–Tsallis function, a combination of an exponential and power law function [87], to extrapolate the yield down to zero p_T. An exponential function describes the low-p_T section of the spectrum, while a power law characterizes the high-p_T region. Since there are only two p_T bins above 6 GeV/c with large bin width, the Levy–Tsallis fit in the default case is performed in the $0 < p_T < 6$ GeV/c range.

This fitting procedure enables the extraction of the p_T-integrated yield (dN/dy) and the average transverse momentum ($\langle p_T \rangle$) of $f_1(1285)$, utilizing both the measured and extrapolated distributions. The extrapolation to the low-p_T (< 1 GeV/c) region encompasses approximately 41% of the total $f_1(1285)$ yield. The high-p_T extrapolation is found to be negligible. The $\langle p_T \rangle$ is determined by evaluating the mean value of the fit function within each p_T bin, weighted by the measured yield in that bin. The systematic uncertainties in the p_T spectrum, arising from the various sources described in Sec. 5, contribute to the systematic uncertainties in dN/dy and $\langle p_T \rangle$. The systematic uncertainties due to the extrapolation are evaluated by varying the fit functions: the Boltzmann–Gibbs blast wave function [88], Bose–Einstein distribution, and m_T exponential [80] are considered in place of the Levy–Tsallis. The uncertainties of dN/dy and $\langle p_T \rangle$ are approximately 31% and 17%, respectively. Table 2 shows dN/dy and $\langle p_T \rangle$ and their uncertainties in inelastic pp collisions at $\sqrt{s} = 13$ TeV. Figure 5 compares the average transverse momentum of $f_1(1285)$ with that of all other light-flavor hadrons [80, 89] measured at midrapidity ($|y| < 0.5$) in pp collisions at $\sqrt{s} = 13$ TeV. Two distinct linear trends are observed, one for mesons and the other for baryons. For particles with similar masses (K^{*0}, p, ϕ, Λ, f_1, Ξ^-), mesons exhibit a higher average transverse momen-

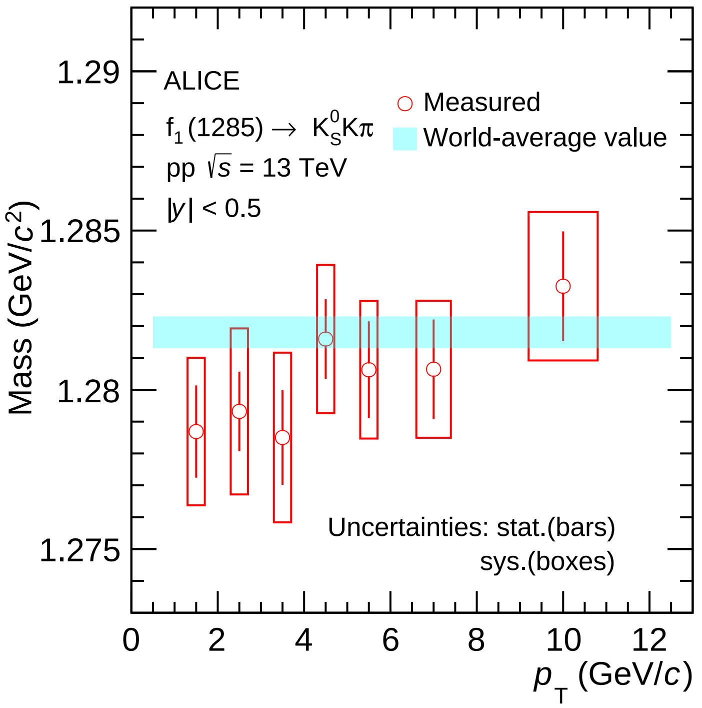

Figure 3: Measured $f_1(1285)$ mass as a function of p_T at midrapidity ($|y| < 0.5$) in minimum-bias pp collisions at $\sqrt{s} = 13$ TeV. The statistical and systematic uncertainties are shown as bars and boxes, respectively. The blue band represents the world-average value for the mass of $f_1(1285)$ [14] having an uncertainty of 0.5 MeV/c^2.

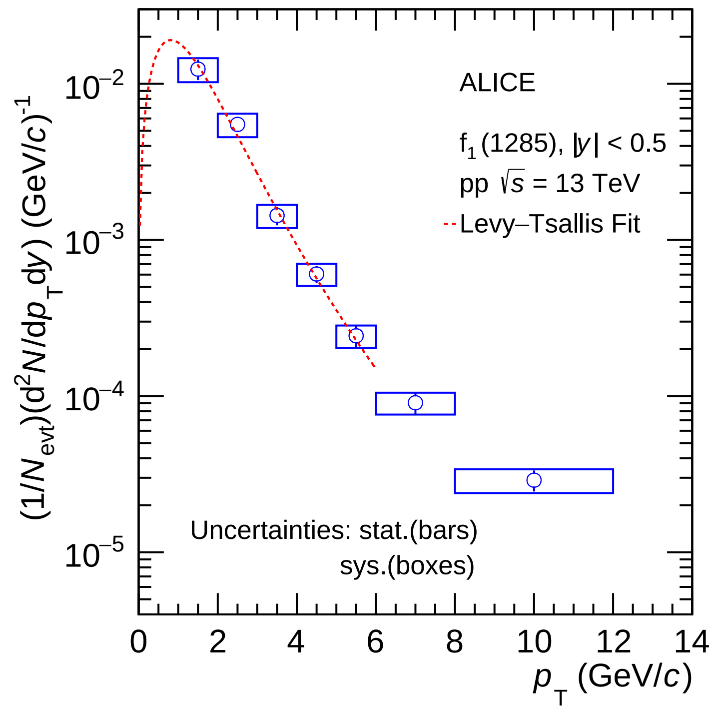

Figure 4: p_T-differential yield of $f_1(1285)$ measured at midrapidity ($|y| < 0.5$) in inelastic pp collisions at $\sqrt{s} =$ 13 TeV. The statistical and systematic uncertainties are shown as bars and boxes, respectively. The data points are fitted using a Levy–Tsallis function [87] and shown by the red dashed line. The BR uncertainty for $f_1(1285) \rightarrow K^0_S K^{\pm}\pi^{\mp}$ is 0.1%.

tum than baryons. Notably, $f_1(1285)$ aligns with the linear trend of other mesons, though within the large systematic uncertainties it is also compatible (within 1σ) with the $\langle p_T \rangle$ of baryons having similar mass (e.g. Ξ^-). This observation suggests that $f_1(1285)$ may have an ordinary meson structure.

The p_T-integrated yield is further compared with calculations from the canonical-ensemble-based statistical hadronization model (γ_SCSM) [31], also shown in Table 2. The conventional statistical framework employs an ideal hadron–resonance gas (HRG) in thermal and chemical equilibrium at the chemical freeze-out stage. In the canonical ensemble, the values of three Abelian charges — baryon number (B), electric charge (Q), and strangeness (S) — are fixed and conserved exactly across the designated correlation volume V_C. In this model, the multiplicity dependence of hadron production is influenced by the canonical suppression of these three Abelian charges. It incorporates the incomplete equilibrium of strangeness via the strangeness saturation parameter γ_S and effectively reproduces various multiplicity-dependent hadron-to-pion ratios [31]. Thermal fits to the yields of various particles, including π, K, p, K^{*0}, Λ, Ω, K^0_S, Ξ, and ϕ, as measured by the ALICE Collaboration in pp collisions at $\sqrt{s} = 13$ TeV [80], have been conducted. The fit parameters include the freeze-out temperature, radius of the produced fireball, V_C, and γ_S. It is assumed that the baryon chemical potential is zero [90]. The thermal model calculations for the p_T-integrated yield of $f_1(1285)$ are carried out for two different scenarios: one with $|S| = 0$ (indicating the presence of no strange or anti-strange quarks within $f_1(1285)$) and another with $|S| = 2$ (representing a total strangeness content of 2 within $f_1(1285)$). The calculated yield with $|S| = 0$ scenario is consistent with the experimental measurement.

Table 2: The p_T-integrated yield and average transverse momentum of the $f_1(1285)$ meson in proton–proton collisions at center-of-mass energy of 13 TeV. The comparison of the p_T-integrated yield of $f_1(1285)$ from ALICE data with thermal model (γ_SCSM) calculations [31] is shown.

	ALICE data	Thermal model	
		$\|S\|$=0	$\|S\|$=2
dN/dy	0.034 ± 0.004 (stat) ± 0.010 (sys)	0.025	0.014
$\langle p_T \rangle$ (GeV/c)	1.52 ± 0.10 (stat) ± 0.24 (sys)	-	-

To gain insights into the valence quark composition of the $f_1(1285)$ meson, the p_T-integrated yield ratio of f_1/π in pp collisions at $\sqrt{s} = 13$ TeV is compared with calculations from the γ_SCSM, as depicted in Fig. 6. At first, as a baseline check for this methodology, the ϕ/π ratio is calculated by γ_SCSM with two scenarios and compared with experimental data [80]. The ϕ meson is a neutral particle comprising a strange quark–antiquark pair. It has a net strangeness of zero, thus remaining unaffected by the precise conservation of strangeness in the canonical suppression picture. However, in the strangeness nonequilibrium picture, the ϕ meson is considered a double-strange particle [31]. Thus, the experimental data is compared in Fig. 6 with γ_SCSM calculations for $|S| = 0$ (indicating a total strangeness content of ϕ to be zero, depicted by the solid line) and $|S| = 2$ (indicating a total strangeness content of ϕ to be two, represented by the dotted line). As expected in the strangeness nonequilibrium picture, the γ_SCSM calculation for ϕ/π ratio with the ϕ meson having $|S| = 0$ shows a large deviation of 9.15σ from the experimental measurements, whereas $|S| = 2$ is in good agreement with the experimental measurements within 0.5σ.

The calculation of the f_1/π ratio from γ_SCSM is carried out for the two different scenarios of $|S| = 0$ (represented by the solid line) and $|S| = 2$ (represented by the dotted line). The measured f_1/π ratio deviates by 0.96σ from $|S| = 0$ and by 1.97σ from $|S| = 2$, indicating that the γ_SCSM calculation with $|S| = 0$ is favored over $|S| = 2$ by the ALICE data.

Therefore, this study suggests that $f_1(1285)$ is more likely to have no strange quark content than a combination of a strange and an anti-strange quark. This finding contradicts the hypothesis that $f_1(1285)$ is a tetraquark state (according to the γ_SCSM model) and is consistent with the results of the LHCb Collaboration [24].

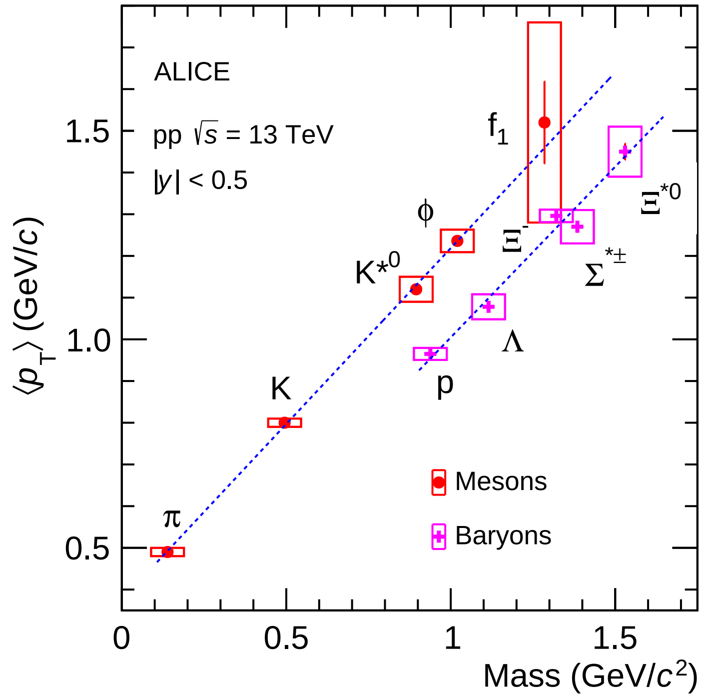

Figure 5: Average transverse momentum of light-flavor hadrons as a function of hadron mass at midrapidity ($|y| < 0.5$) in inelastic pp collisions at $\sqrt{s} = 13$ TeV. The statistical and systematic uncertainties are shown as bars and boxes, respectively. The blue dotted lines are linear fits to the data points.

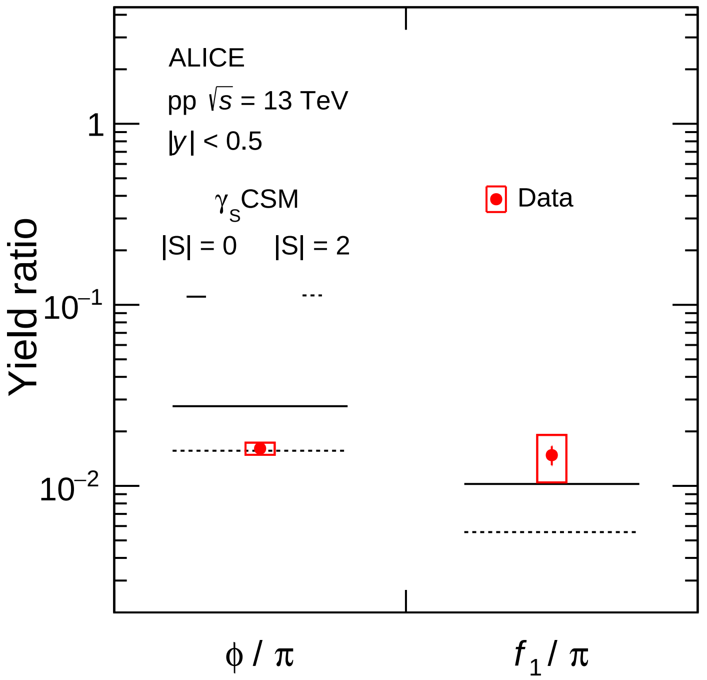

Figure 6: The transverse-momentum-integrated yield ratio of ϕ/π (left) [80] and f_1/π (right) measured in inelastic pp collisions at $\sqrt{s} = 13$ TeV. The statistical and systematic uncertainties on the data points are shown as bars and boxes, respectively. The black solid and dotted lines represent the calculations from the γ_SCSM with different strangeness content of ϕ and f_1 mesons.

7 Summary

The ALICE Collaboration presents the first measurement of the $f_1(1285)$ meson production in inelastic proton–proton collisions at $\sqrt{s}$ = 13 TeV. This measurement spans a wide transverse momentum range from 1 to 12 GeV/c at midrapidity ($|y| < 0.5$). The mass of $f_1(1285)$ reconstructed from the $K^0_S K^\pm \pi^\mp$ decays is in good agreement with the world-average value within the uncertainties. Notably, the average transverse momentum of $f_1(1285)$ aligns with the linear trend with mass observed for other mesons and it is higher, although compatible within 1σ of the systematic uncertainty, with the $\langle p_T \rangle$ of baryons of similar masses. Moreover, the γ_SCSM of the f_1/π p_T-integrated yield ratio, considering no strange quarks inside $f_1(1285)$, agrees with the ALICE data within 1σ. However, it deviates by $\sim 2\sigma$ when assuming the presence of one strange and one anti-strange quark. These observations suggest that the state of $f_1(1285)$ is a conventional meson, which disfavors the tetraquark hypothesis and aligns with the findings of the LHCb Collaboration. With larger data samples available in Run 3 and Run 4, combined with the improved tracking efficiency of the upgraded ITS detector, it may become feasible to reconstruct the $f_1(1285)$ meson at low transverse momentum (< 1 GeV/c), thereby improving the significance of future analyses. Additionally, future studies of the elliptic flow of $f_1(1285)$ and femtoscopy measurements in the $K^*\overline{K}$ coupled channel, using the large data samples from Run 3 and the upcoming Run 4, may help to distinguish the di-quark or molecular nature of $f_1(1285)$.

Acknowledgements

The ALICE Collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex. The ALICE Collaboration gratefully acknowledges the resources and support provided by all Grid centres and the Worldwide LHC Computing Grid (WLCG) collaboration. The ALICE Collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector: A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation (ANSL), State Committee of Science and World Federation of Scientists (WFS), Armenia; Austrian Academy of Sciences, Austrian Science Fund (FWF): [M 2467-N36] and Nationalstiftung für Forschung, Technologie und Entwicklung, Austria; Ministry of Communications and High Technologies, National Nuclear Research Center, Azerbaijan; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (Finep), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Universidade Federal do Rio Grande do Sul (UFRGS), Brazil; Bulgarian Ministry of Education and Science, within the National Roadmap for Research Infrastructures 2020-2027 (object CERN), Bulgaria; Ministry of Education of China (MOEC) , Ministry of Science & Technology of China (MSTC) and National Natural Science Foundation of China (NSFC), China; Ministry of Science and Education and Croatian Science Foundation, Croatia; Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Cubaenergía, Cuba; Ministry of Education, Youth and Sports of the Czech Republic, Czech Republic; The Danish Council for Independent Research | Natural Sciences, the VILLUM FONDEN and Danish National Research Foundation (DNRF), Denmark; Helsinki Institute of Physics (HIP), Finland; Commissariat à l'Energie Atomique (CEA) and Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) and Centre National de la Recherche Scientifique (CNRS), France; Bundesministerium für Bildung und Forschung (BMBF) and GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany; General Secretariat for Research and Technology, Ministry of Education, Research and Religions, Greece; National Research, Development and Innovation Office, Hungary; Department of Atomic Energy Government of India (DAE), Department of Science and Technology, Government of India (DST), University Grants Commission, Government of India (UGC) and Council of Scientific and Industrial Research (CSIR), India; National Research and Innovation Agency - BRIN, Indonesia; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Japan Society for the Promotion of Science (JSPS) KAKENHI, Japan; Consejo Nacional de Ciencia (CONACYT) y Tecnología, through Fondo de Cooperación Internacional en Ciencia y Tecnología (FONCICYT) and Dirección General de Asuntos del Personal Academico (DGAPA), Mexico; Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; The Research Council of Norway, Norway; Pontificia Universidad Católica del Perú, Peru; Ministry of Science and Higher Education, National Science Centre and WUT ID-UB, Poland; Korea Institute of Science and Technology Information and National Research Foundation of Korea (NRF), Republic of Korea; Ministry of Education and Scientific Research, Institute of Atomic Physics, Ministry of Research and Innovation and Institute of Atomic Physics and Universitatea Nationala de Stiinta si Tehnologie Politehnica Bucuresti, Romania; Ministry of Education, Science, Research and Sport of the Slovak Republic, Slovakia; National Research Foundation of South Africa, South Africa; Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW), Sweden; European Organization for Nuclear Research, Switzerland; Suranaree University of Technology (SUT), National Science and Technology Development Agency (NSTDA) and National Science, Research and Innovation Fund (NSRF via PMU-B B05F650021), Thailand; Turkish Energy, Nuclear and Mineral Research Agency (TENMAK), Turkey; National Academy of Sciences of Ukraine, Ukraine; Science and Technology Facilities Council (STFC), United Kingdom; National Science Foundation of the United States of America (NSF) and United States Department of Energy, Office of Nuclear Physics (DOE NP), United States of America. In addition, individual groups or members have received support from: Czech Science Foundation (grant no. 23-07499S), Czech Republic; FORTE project, reg. no. CZ.02.01.01/00/22_008/0004632, Czech Republic, co-funded by the European Union, Czech Republic; European Research Council (grant no. 950692), European Union; ICSC - Centro Nazionale di Ricerca in High Performance Computing, Big Data and Quantum Computing, European Union - NextGenerationEU; Academy of Finland (Center of Excellence in Quark Matter) (grant nos. 346327, 346328), Finland.

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