Acta Physica Polonica B Proceedings Supplement **16**, 3-A21 (2023)

ATLAS RESULTS ON EXOTIC HADRONIC RESONANCES* **

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Received 28 September 2022, accepted 19 December 2022, published online 15 February 2023

Recent results from the LHC proton–proton collision data taken by the ATLAS experiment on exotic resonances are presented. A search for $J/\psi p$ resonances which are potential pentaquarks in the $\Lambda_b \to J/\psi pK$ decays with large pK-invariant masses is reported.

DOI:10.5506/APhysPolBSupp.16.3-A21

1. Introduction

The quark model of conventional hadrons successfully describes mesons and baryons as being composed of two or three valence quarks. At the same time, theorists also predicted the existence of exotic hadrons with more than three quarks, whose properties would not fit the standard picture of the quark model. The study of exotic hadrons can provide a unique insight into the nature of strong interaction. These proceedings overviews the study of $J/\psi p$ resonances in the $\Lambda_b^0 \to J/\psi pK^-$ decays with the LHC pp collision data collected in the ATLAS detector [1] at the centre-of-mass energies of $\sqrt{s} = 7$ and 8 TeV [2, 3].

2. Event selection and reconstruction

Due to lack of particle identification, the $\Lambda_b^0 \to J/\psi pK^-$ decays are reconstructed together with the $B^0 \to J/\psi K^+\pi^-$, $B^0 \to J/\psi\pi^+\pi^-$, $B_s^0 \to J/\psi K^+K^-$, and $B_s^0 \to J/\psi\pi^-\pi^+$ decays. The J/ψ candidate is reconstructed through the $J/\psi \to \mu^+\mu^-$ decays. Both muons are required to

* Presented at the XIV International Conference on *Beauty, Charm and Hyperon Hadrons*, Kraków, Poland, 5–10 June, 2022.

have $p_{\mathrm{T}} > 4$ GeV and $|\eta| < 2.3$. The invariant mass of the two muons is required to be $2807 < m_{\mu^+\mu^-} < 3387$ MeV. To form B-hadron (H_b) candidates, the J/ψ candidate and two additional tracks from hadrons are refitted to a common vertex with the J/ψ mass constraint.

To select H_b candidates, there are requirements on fit quality, transverse momentum, and angles between different reconstructed mesons and baryons in different rest frames. Since contributions from dominant backgrounds (B^0 and B_s^0) are concentrated at small values of the invariant mass of the two additional hadrons, the $M(K\pi) > 1.55$ GeV requirement is imposed.

3. Fit procedure

Multi-dimensional fits are performed in mass distributions with kinematic regions as input to estimate background contributions and extract pentaquark parameters. There are three kinematic regions:

— Λ_b signal region (SR):
$5.59\ \text{GeV} < m(J/\psi, h_1 = p, h_2 = K) < 5.65\ \text{GeV}$,

— B^0 control region (CR):
$5.25\ \text{GeV} < m(J/\psi, h_1 = K, h_2 = \pi)(m(J/\psi, h_1 = \pi, h_2 = K)) < 5.31\ \text{GeV}$,

— B_s^0 control region (CR):
$5.337\ \text{GeV} < m(J/\psi, h_1 = K, h_2 = K) < 5.397\ \text{GeV}$.

The fit procedure is complex; it is iterative with four steps in each iteration. Parameters obtained in the previous step are an input to the next step. The four steps are:

— Step 1: 2D and 1D fits of the $m(J/\psi hh)$, $m(J/\psi h)$, and $m(hh)$ spectra to obtain parameters of B^0 and B_s^0 backgrounds,

— Step 2: the χ^2 $m(J/\psi, h_1 = p, h_2 = K)$ fit to retrieve the total number of Λ_b decays, number of combined B^0 and B_s^0 decays,

— Step 3: 2D and 1D fits of the $m(J/\psi, h_1 = p)$, $m(J/\psi, h_2 = K)$, and $m(h_1 = p, h_2 = K)$ spectra in the SR to get decay constants of decays,

— Step 4: the χ^2 $m(J/\psi, h_1 = p)$ fit in the SR to obtain pentaquark masses, widths, amplitudes, and $\Delta\phi$.

4. Fit results

Two hypotheses are tested in the fit:

1. Hypothesis with two pentaquarks with spin parity of $3/2^-$ and $5/2^+$,
2. Hypothesis with four pentaquarks with masses, widths, and relative yields fixed to the results from the LHCb [4].

Figure 1 shows the χ^2 fit results of the $m(J/\psi p)$ distribution for the two hypotheses. The data description by hypotheses of two pentaquarks and four pentaquarks are both good ($\chi^2/N_{\mathrm{dof}} = 37.1/39$ and $\chi^2/N_{\mathrm{dof}} = 37.1/42$, where N_{dof} is the number of degrees of freedom).

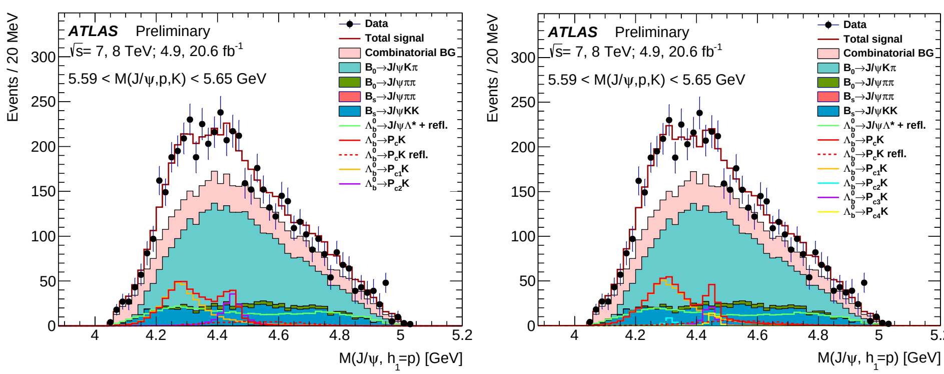

Fig. 1. The χ^2 fit results of the $m(J/\psi p)$ distribution in the SR with the hypothesis of two pentaquarks (left) and with the hypothesis of four pentaquarks (right) [5].

Table 1 summarizes the obtained pentaquark masses and widths for the hypothesis of two pentaquarks and compares them to the LHCb values [6]. The extracted pentaquark masses and widths are consistent with the LHCb values within uncertainties.

Table 1. Extracted pentaquarks masses and widths of the $\Lambda_b \to P_c^+ K^-$ decays for the hypothesis of two pentaquarks.

Parameter	Value [5]	LHCb value [6]
$m(P_{c1})$	$4282^{+33}_{-26}(\mathrm{stat.})^{+28}_{-7}(\mathrm{syst.})$ MeV	$4380 \pm 8 \pm 29$ MeV
$\Gamma(P_{c1})$	$140^{+77}_{-50}(\mathrm{stat.})^{+41}_{-33}(\mathrm{syst.})$ MeV	$205 \pm 18 \pm 86$ MeV
$m(P_{c2})$	$4449^{+20}_{-29}(\mathrm{stat.})^{+18}_{-10}(\mathrm{syst.})$ MeV	$4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma(P_{c1})$	$51^{+59}_{-48}(\mathrm{stat.})^{+14}_{-46}(\mathrm{syst.})$ MeV	$39 \pm 5 \pm 19$ MeV

The hypothesis without pentaquarks is also checked by repeating the fit procedure using decays without pentaquarks. The χ^2 fit result of the $m(J/\psi p)$ distribution for this hypothesis is shown in figure 2. The fit yields $\chi^2/N_{\text{dof}} = 69.2/37$ which means that data prefer hypotheses with two or more pentaquarks.

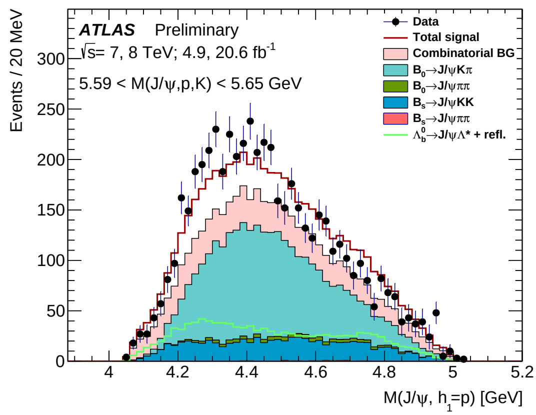

Fig. 2. The χ^2 fit result of the $m(J/\psi p)$ distribution in the SR with the hypothesis of no pentaquarks [5].

5. Systematic uncertainties

Systematic uncertainties on the pentaquark masses and natural widths are summarized in Table 2 [5]. The systematic uncertainties of B-meson decays modelling and non-pentaquark $\Lambda_b^0 \to J/\psi p K^-$ modelling have the largest impact on both masses and widths.

Table 2. Systematic uncertainties on the pentaquark masses and natural widths [5].

Source	$m(P_{c1})$	$\Gamma(P_{c1})$	$m(P_{c2})$	$\Gamma(P_{c2})$
Number of $\Lambda_b^0 \to J/\psi p K^-$ decays	$^{+0.06}_{-0.03}\%$	$^{+3.5}_{-2.5}\%$	$^{+0.07}_{-0.04}\%$	$^{+7}_{-13}\%$
Pentaquark modelling	$^{+0.6}_{-0.0}\%$	$^{+18}_{-0}\%$	$^{+0.2}_{-0.0}\%$	$^{+0}_{-33}\%$
Non-pentaquark $\Lambda_b^0 \to J/\psi p K^-$ modelling	$^{+0.23}_{-0.05}\%$	$^{+9.2}_{-1.2}\%$	$^{+0.24}_{-0.02}\%$	$^{+2}_{-62}\%$
Combinatorial background	$^{+0.03}_{-0.15}\%$	$^{+0}_{-11}\%$	$^{+0.01}_{-0.17}\%$	$^{+22}_{-4}\%$
B-meson decays modelling	$^{+0.24}_{-0.00}\%$	$^{+21}_{-21}\%$	$^{+0.27}_{-0.14}\%$	$^{+17}_{-57}\%$
Total systematic uncertainty	$^{+0.7}_{-0.2}\%$	$^{+30}_{-24}\%$	$^{+0.4}_{-0.2}\%$	$^{+28}_{-91}\%$

6. Conclusion

A search for $J/\psi p$ resonances in the $\Lambda_b \to J/\psi pK$ decays is highlighted in these proceedings. The result is obtained with the LHC pp collision data collected in the ATLAS detector at $\sqrt{s} = 7$ and 8 TeV, with an integrated luminosity of 4.9 fb^{-1} and 20.6 fb^{-1}, respectively. More results of exotic hadrons at ATLAS are expected in the near future with Run 2 and Run 3 data.

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