Prospects for Studying Hidden-Charm Pentaquark States with the ATLAS Detector
Перспективы изучения пентакварковых состояний со скрытым очарованием на установке ATLAS

A. Vasyukov[a,1], *I. Yeletskikh*[a], *L. Gladilin*[a]

А.О. Васюков[a,1], *И.В. Елецких*[a], *Л.К. Гладилин*[a]

[a] Joint Institute for Nuclear Research, Dubna, Moscow Region, Russia, 141980

[a] Объединенный институт ядерных исследований, г. Дубна, Московская обл., Россия, 141980

Пентакварковые состояния со скрытым очарованием были обнаружены коллаборацией LHCb в результате амплитудного анализа распадов $\Lambda_b^0 \to J/\psi p K^-$ в данных pp столкновений с энергией в системе центра масс $\sqrt{s} = 7,8$ ТэВ. Изучение спектра данных состояний впоследствии было проведено как и экспериментом LHCb на данных pp столкновений с $\sqrt{s} = 13$ ТэВ, так и экспериментом ATLAS при использовании данных pp столкновений с $\sqrt{s} = 7,8$ ТэВ. Текущие и будущие исследования распадов $\Lambda_b^0 \to J/\psi p K^-$ направлены на дальнейшее изучение свойств узких резонансов $P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$. В то же время, существование широкого резонанса $P_{c\bar{c}}(4380)^+$ остается под вопросом, равно как и потенциальный вклад в распады $\Lambda_b^0 \to J/\psi p K^-$ тетракварковых состояний со странностью: $T_{c\bar{c}s1}(4000)$ и $T_{c\bar{c}s1}(4220)$. В данной работе представлены обзор современных экспериментальных результатов, общая методология анализа распадов $\Lambda_b^0 \to J/\psi p K^-$ на установке ATLAS, а также обсуждаются перспективы дальнейших экспериментальных исследований пентакварков со скрытым очарованием.

Pentaquark states with hidden charm were discovered by the LHCb collaboration as a result of the analysis of $\Lambda_b^0 \to J/\psi p K^-$ decays in pp collision data with a center-of-mass energy of $\sqrt{s} = 7,8$ TeV. The study of the spectrum of these states was subsequently conducted both by the LHCb experiment using pp collision data with $\sqrt{s} = 13$ TeV and by the ATLAS experiment using pp collision data with $\sqrt{s} = 7,8$ TeV. Current and future studies of $\Lambda_b^0 \to J/\psi p K^-$ decays are aimed at further investigation of the properties of the narrow resonances $P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$. At the same time, the existence of the broad resonance $P_{c\bar{c}}(4380)^+$ remains in question, as does the potential contribution to $\Lambda_b^0 \to J/\psi p K^-$ decays from the strange tetraquark states $T_{c\bar{c}s1}(4000)$ and $T_{c\bar{c}s1}(4220)$. This paper presents a review of modern experimental results, the general methodology for analyzing $\Lambda_b^0 \to J/\psi p K^-$ decays at the ATLAS setup, and discusses the prospects for further experimental studies of pentaquark states in pp collision data with a center-of-mass energy of $\sqrt{s} = 13$ TeV.

[1]E-mail: avasyukov@jinr.ru

Introduction

Observations of charged hadron states with hidden charm are of particular interest. Internal structure of such states can not be described via conventional meson and baryon models. The existence of tetraquark and pentaquark states was predicted at the origin of the quark model of hadrons [1]. From that moment active searches for these states began. In 2003 the first candidate for light pentaquark state $\Theta^+(1540)$ was observed [2]. Later, the existence of that state was questioned. In 2015 the LHCb collaboration was the first to discover generally accepted candidates in hidden-charm pentaquarks $P_{c\bar{c}}(4380)^+$ and $P_{c\bar{c}}(4450)^+$ as intermediate states of $\Lambda_b^0 \to J/\psi p K^-$ decays [3]. The significance of the contributions of each of the states exceeded 9 σ. That result was complemented with model-independent analysis of $\Lambda_b^0 \to J/\psi p K^-$ decays [4]. It was shown at 9.8 σ that $m(J/\psi p)$ spectrum can not be described by reflections of pK resonances. The study of $\Lambda_b^0 \to J/\psi p K^-$ decays was continued using the data of pp collisions at the center of mass energy of $\sqrt{s} = 13$ TeV with integral luminosity $\mathcal{L} = 6\ fb^{-1}$ [5]. The narrow width of the pentaquark states allowed for one dimensional analysis of $m(J/\psi p)$ spectrum. LHCb collaboration discovered a new P_c state near $m(J/\psi p) \approx 4312$ MeV with a significance of 7.2σ. With a significance of 5.4σ they have demonstrated that the structure near $m(J/\psi p) \approx 4450$ MeV consists of two peaks those were associated with $P_{c\bar{c}}(4440)^+$ and $P_{c\bar{c}}(4457)^+$. One dimensional approach turned out to be insensitive to the pentaquark state $P_{c\bar{c}}(4380)^+$ with a large width $\Gamma = 210 \pm 90$ MeV, as well as other wide structures.

Since 2015, an active search has been conducted for pentaquark states in other B-hadron decays. In 2016 LHCb collaboration performed amplitude analysis of $B_s^0 \to J/\psi p \bar{p}$ decays [6]. Decay model includes baryonic excitations ($N^* \to p\pi^-$), pentaquark states $P_{c\bar{c}}^+ \to J/\psi p$ and $T_{c\bar{c}1}(4200) \to J/\psi \pi^-$. The total significance of exotic resonances is 3.1σ. In 2016 LHCb collaboration performed amplitude analysis of $B_s^0 \to J/\psi p \bar{p}$ decays [7]. A new structure in $J/\psi p$ and $J/\psi \bar{p}$ incompatible with hypotheses of $P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$ was observed with significance in range $3.1 \div 3.7\sigma$ depending on its spin-parity.

That review will be incomplete without mentioning observations of hidden-charm pentaquark states with strangeness. In 2021 LHCb collaboration performed amplitude analysis of $\Xi \to J/\psi \Lambda K^-$ decays [8]. With 3.1σ significance they observed structure in $J/\psi\Lambda$ invariant mass spectrum consistent with pentaquark with strangeness $P_{c\bar{c}s}(4459)^0$. In 2023, the collaboration announced the discovery of a narrow resonance $P_{c\bar{c}s}(4338)^0 \to J/\psi\Lambda$ as a result of amplitude analysis of $B^- \to J/\psi \Lambda \bar{p}$ decays [9].

Despite recent progress, there are still open questions in pentaquarks with hidden-charm spectroscopy. First, the experimental evidence for the $P_{c\bar{c}}(4380)^+$ state is not yet definitive. Its existence demands validation via amplitude analysis methods using higher-statistics data. Potential contribution from $T^{\pm}_{c\bar{c}\bar{s}1}(4000)$, $T^{\pm}_{c\bar{c}\bar{s}1}(4220) \to J/\psi K^{\pm}$ states [10] to $\Lambda_b^0 \to J/\psi p K^-$

decays might affect its significance. Second, the quantum numbers of the narrow pentaquark states need to be measured. Answers to these questions can be found by performing an amplitude analysis of $\Lambda_b^0 \to J/\psi p K^-$ decays using pp collision data at the center of mass energy $\sqrt{s} = 13$ TeV recorded by the ATLAS detector.

Study of pentaquark states in ATLAS

The first attempt of amplitude analysis of $\Lambda_b^0 \to J/\psi p K^-$ decays by ATLAS Collaboration was made in 2019 using data of pp collisions $\sqrt{s} = 7, 8$ TeV with integrated luminosity $\mathcal{L} = 4.9, 20.6$ fb^{-1}, respectively [11]. The estimated decay yield of Λ_b^0 decays was 2270 ± 300. The pentaquark parameters were derived from fits. Although the data prefer model with two or more $P_{c\bar{c}}^+$ states, the model without pentaquarks was not excluded: p-value $= 0.009$.

This analysis was continued using data of pp collisions at the center of mass energy $\sqrt{s} = 13$ TeV, $\mathcal{L} = 139\ fb^{-1}$. The features of the ATLAS detector significantly complicate the task of conducting amplitude analysis of $\Lambda_b^0 \to J/\psi(\to \mu^+\mu^-)pK^-$ + c.c. decays compared to the LHCb setup. First, due to absence of light hadron identification, events of $H_b \to J/\psi h^+ h^-$ type were selected for analysis, where H_b can be B_s^0, B^0, Λ_b^0, and for light hadron $h^\pm$ mass hypotheses of π, K, p are considered. As a result, very accurate background modeling is needed. All candidate events are required to have large invariant masses of two hadrons $m(K\pi) > 1.55$ GeV. That working point was optimized to maximize signal significance for $B^0 \to J/\psi K^+\pi^-$ decays. This allows suppressing large backgrounds from light K^*, Λ^*, etc. states, as well as combinatorial background. Modelling of signal and main background components is accomplished with initial generation of the so-called "phase space" MC using a simplified model for $H_b \to J/\psi hh$ decays. For $B^0 \to J/\psi K^+\pi^-$, $B_s^0 \to J/\psi K^+K^-$ and $\Lambda_b^0 \to J/\psi p K^-$ decays each generated phase space MC event is weighted by the analytically derived decay matrix element [12]. The parameters of these matrix elements (m, Γ and decay constants of P_c states, decay constants of Λ^* states) are obtained from the fit to the real data. Second, $m(J/\psi p)$ resolution is extremely important to separate narrow $P_{c\bar{c}}(4440)$ and $P_{c\bar{c}}(4457)$ states. To improve it the refit of four final state to Λ_b vertex was performed. The $m(J/\psi p)$ resolution was measured using the signal MC. The difference in invariant mass of $J/\psi p$ system values before and after reconstruction was fitted with sum of three gaussian functions (see figure 1). Resolution is averaged sum of their standard deviations $\sigma_{m(J/\psi p)} \approx 10$ MeV. It is significantly larger compared with LHCb value $\sigma_{LHCb} = 2 \div 3$ MeV [5] and does not allow us to separate narrow $P_{c\bar{c}}(4440)^+$ and $P_{c\bar{c}}(4457)^+$, but it is good enough to be sensitive to the $P_{c\bar{c}}(4312)^+$ and $P_{c\bar{c}}(4380)^+$ parameters.

Preliminary study of $\Lambda_b^0 \to J/\psi p K^-$ decays was done as a part of amplitude analysis of $B^0 \to J/\psi K^+\pi^-$ decays. After applying the selection

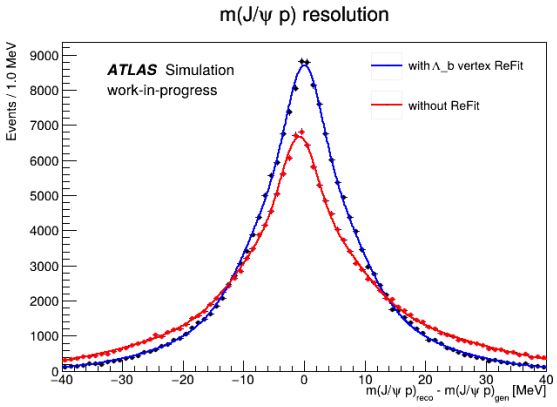
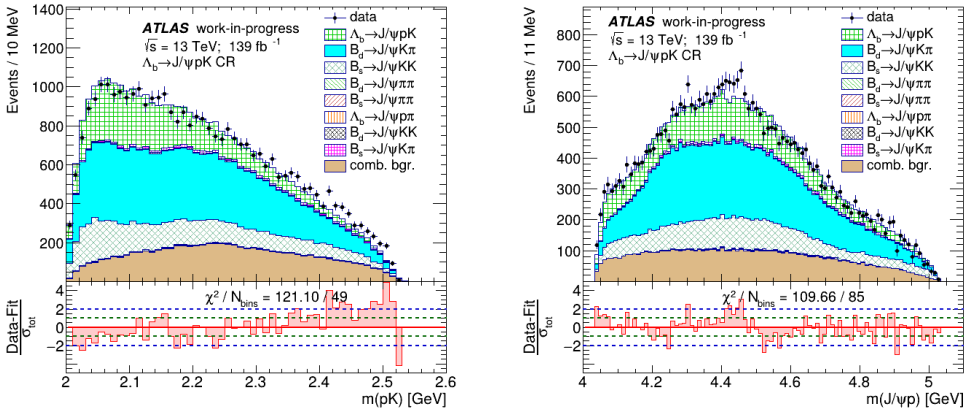


Fig. 1: Deviation of the value of the invariant mass of $J/\psi p$ system from the generated value after reconstruction.

criteria optimized for maximizing B^0 significance the Λ_b^0 decay yield is 9000 $\pm$ 1200. The parameters of matrix elements of $\Lambda_b^0 \to J/\psi p K^-$ decays were measured using the combine χ^2 fit of $m(J/\psi p)$, $m(J/\psi K)$, $m(pK)$ distributions of events from Λ_b^0 control region (5590 MeV $< m(J/\psi pK) <$ 5650 MeV). The default decay model contains $\Lambda^*(1800)$, $\Lambda^*(1810)$, $\Lambda^*(1890)$, $\Lambda^*(2100)$, $\Lambda^*(2090)$. Figure 2 shows $m(J/\psi p)$, $m(pK)$ distributions together with Λ_b^0 control region fit result for the model without contribution from exotic states. The default model does not provide a satisfactory description of the data, the preliminary p-value is 1.7×10^{-9}.



(a) (b)

Fig. 2: Distributions of $M(pK)$ (a) and $M(J/\psi p)$ (b) resulting from the preliminary Λ_b^0 control region fit for the model without contribution from exotic states

At the moment, the existence of $P_{c\bar{c}}(4380)$ state requires confirmation, and it is also necessary to measure quantum numbers of $P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4450)^+$ states. Amplitude analysis of $\Lambda_b^0 \to J/\psi p K^-$ decays can answer the questions raised. Preliminary analysis of pp collisions $\sqrt{s} = 13$ TeV ATLAS data shows that decay model that excludes exotic hadrons does not yield a satisfactory fit to the data. Our analysis procedure is sensitive to contributions from both the broad $P_{c\bar{c}}(4380)^+$ state and $T_{c\bar{c}\bar{s}1}$ states in Λ_b^0 decays. Further conclusions require detailed statistical studies.

REFERENCES

1. *M. Gell-Mann,* A Schematic Model of Baryons and Mesons — Phys. Lett. 8 (1964), 214-215

2. *Nakano, T. et al.* [LEPS Collaboration], Observation for Narrow S=+1 Baryon Resonance in Photo-production from Neutron — Phys. Rev. Lett. 91 (2003), 012002.

3. *Aaij, R. et al.* [LHCb Collaboration], Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays — Phys. Rev. Lett. 115 (2015), 072001.

4. *Aaij, R. et al.* [LHCb Collaboration], Model-Independent Evidence for $J/\psi p$ Contributions to $\Lambda_b^0 \to J/\psi p K^-$ Decays — Phys. Rev. Lett. 117 (2016), 082002.

5. *Aaij, R. et al.* [LHCb Collaboration], Observation of a Narrow Pentaquark State, $P_c(4312)^+$, and of the Two-Peak Structure of the $P_c(4450)^+$ — Phys. Rev. Lett. 122 (2019), 222001.

6. *Aaij, R. et al.* [LHCb Collaboration], Evidence for exotic hadron contributions to $\Lambda_b^0 \to J/\psi p \pi^-$ decays — Phys. Rev. Lett. 117 (2016), 082003.

7. *Aaij, R. et al.* [LHCb Collaboration], Evidence for a New Structure in the $J/\psi p$ and $J/\psi \overline{p}$ Systems in $B_s^0 \to J/\psi p \overline{p}$ Decays — Phys. Rev. Lett. 128 (2022), 062001.

8. *Aaij, R. et al.* [LHCb Collaboration], Evidence of a $J/\psi\Lambda$ structure and observation of excited Ξ^- states in the $\Xi_b^- \to J/\psi \Lambda K^-$ decay — Science Bulletin 66 (2021), 1278-1287 p.

9. *Aaij, R. et al.* [LHCb Collaboration], Observation of a J/$\psi\Lambda$ Resonance Consistent with a Strange Pentaquark Candidate in B-$\to$J/$\psi\Lambda$p$^-$ Decays — Phys. Rev. Lett. 131 (2023), 031901.

10. *Aaij, R. et al.* [LHCb Collaboration], Observation of New Resonances Decaying to $J/\psi K^+$ and $J/\psi\phi$ — Phys. Rev. Lett. 127 (2021), 082001.

11. *Yeletskikh, I., Gladilin L. et al.* [ATLAS Collaboration], Study of $J/\psi p$ resonances in the $L_b \to J/\psi p K^-$ decays in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector — ATLAS-CONF-2019-048

12. *Richman J. D.* An Experimenter's Guide to the Helicity Formalism — CALT-68-1148.