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Inclusive production of the P_c resonances in $p\overline{p}$ collisions

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We present a study of the inclusive production in $p\overline{p}$ collisions of the pentaquark states $P_c(4440)$ and $P_c(4457)$ with the decay to the $J/\psi p$ final state previously observed by the LHCb experiment. Using a sample of candidates originating from decays of b-flavored hadrons, we find an enhancement in the $J/\psi p$ invariant mass distribution consistent with the sum of $P_c(4440)$ and $P_c(4457)$. The significance, with the mass and width parameters set to the LHCb measured values and including the D0 systematic uncertainties and uncertainties in the LHCb input parameters for the $P_c(4440)$ and $P_c(4457)$, is 3.2σ. The study of the semi-exclusive process $\Lambda_b \to J/\psi pX$ indicates the possibility that decays $\Lambda_b \to P_c X$ other than those with $X = K^-$ exist. This is the first confirmatory evidence for these pentaquark states. We measure the ratio $N_{\text{prompt}}/N_{\text{nonprompt}} = 0.1 \pm 0.4$ and set an upper limit of 0.9 at the 95% credibility level. The ratio of the yield of the $P_c(4312)$ to the sum of $P_c(4440)$ and $P_c(4457)$, measured to be 0.18±0.22, is consistent with the LHCb result. The study is based on 10.4 fb^{-1} of data collected by the D0 experiment at the Fermilab Tevatron collider.

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Since the discovery [1] of the charmonium-like state $\chi_{c1}(3872)$ (known also as $X(3872)$) in 2003, evidence has accumulated for mesons with a quark content beyond the color-singlet quark-antiquark combination. Currently, a dozen mesons require presence of a hidden charm $c\overline{c}$ pair in addition to a light-quark $q\bar{q}$ pair. Several models have been proposed to describe the internal structure of a multi-quark state: a compact heavy quark-antiquark core surrounded by a light-quark cloud; a bound state of hypothetical compact diquarks; a deuteron-like hadronic molecule composed of two color-singlet heavy hadrons. For recent reviews see Refs. [2–5].

Until recently, there have been no undisputed "pentaquark" baryons. That changed in 2015 with a discovery [6] by the LHCb Collaboration of two particles decaying to $J/\psi p$. The minimum quark content of such a state is $c\overline{c}uud$ (charge conjugation is implied throughout this paper). Recently, using an increased dataset, the LHCb Collaboration reported the discovery of three narrow resonances [7] in the $J/\psi p$ invariant mass spectrum, $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$ with the following mass and width parameters:

$$M = 4311.9 \pm 0.7^{+6.8}_{-0.6}\ \text{MeV},\ \Gamma = 9.8 \pm 2.7^{+3.7}_{-4.5}\ \text{MeV}$$
$$M = 4440.3 \pm 1.3^{+4.1}_{-4.7}\ \text{MeV},\ \Gamma = 20.6 \pm 4.9^{+8.7}_{-10.1}\ \text{MeV}$$
$$M = 4457.3 \pm 0.6^{+4.1}_{-1.7}\ \text{MeV},\ \Gamma = 6.4 \pm 2.0^{+5.7}_{-1.9}\ \text{MeV}.$$

These new results supersede those previously presented in Ref. [6].

The P_c states were found as resonances in the decay products of the Λ_b^0 baryon, $\Lambda_b^0 \to J/\psi pK^-$, and also in $\Lambda_b^0 \to J/\psi p\pi^-$ [8]. They might also be produced in other Λ_b^0 decay channels, such as $\Lambda_b^0 \to J/\psi pK^{*-}$ or any channel containing one or two pions in addition to $J/\psi pK^{-(0)}$, in decays of other b hadrons (H_b) or promptly in gluon-gluon or quark-antiquark fusion. In

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this Article we present results of a search for the inclusive production of the P_c states in $p\bar{p}$ collisions. Due to limited mass resolution and high background, this study is focused on a search for a signal consisting of a sum of the $P_c(4440)$ and $P_c(4457)$ resonances with the mass and width parameters taken from Ref. [7].

Although the observation of the P_c states in Refs. [6, 7] was in the decay channel $\Lambda_b^0 \to P_c^+ K^-$ with $P_c \to J/\psi p$, our analysis was initially based on the inclusive $J/\psi p$ sample so as to allow the contributions from other Λ_b decays and from b-quark meson states. We also discuss the study of the exclusive $\Lambda_b^0 \to J/\psi p K^-$ channel and confirm that it yields lower significance than the inclusive channel.

The data sample, corresponding to an integrated luminosity of 10.4 fb^{-1}, was collected with the D0 detector in $p\bar{p}$ collisions at 1.96 TeV at the Fermilab Tevatron collider.

The D0 detector has a central tracking system consisting of a silicon microstrip tracker and a central fiber tracker, both located within a 1.9 T superconducting solenoidal magnet and a liquid argon calorimeter [9–11]. A muon system, covering $|\eta| < 2$ [12], consists of a layer of tracking detectors and scintillation trigger counters in front of a central and two forward 1.8 T iron toroidal magnets, followed by two similar layers after the toroids [13]. Events used in this analysis are collected with both single-muon and dimuon triggers. Single-muon triggers require a coincidence of signals in trigger elements inside and outside the toroidal magnets. All dimuon triggers require at least one muon to have track segments after the toroid; muons in the forward region are always required to penetrate the toroid. The minimum muon transverse momentum is 1.5 GeV. No minimum p_T requirement is applied to the muon pair, but the effective threshold is approximately 4 GeV due to the requirement for muons to penetrate the toroids, and the average value for accepted events is 10 GeV.

The event selection, detailed below, follows that of Refs. [14, 15] that reported evidence for the presence of the decay process $Z_c(3900) \to J/\psi\pi$ in the final states of b-hadron decays. Candidate events are selected by requiring a pair of oppositely charged muons and a charged particle at a common vertex with $\chi^2 < 10$ for 3 degrees of freedom. Muons must have transverse momentum $p_T > 1.5$ GeV. At least one muon must traverse both inner and outer layers of the muon detector. Both muons must match tracks in the central tracking system. The reconstructed invariant mass $M(\mu^+\mu^-)$ must be between 2.92 and 3.25 GeV, consistent with the world average mass of the J/ψ [16].

There are several differences appropriate for this analysis. The charged particle accompanying the J/ψ candidate is required to have transverse momentum $p_T > 2$ GeV and is assigned the proton mass. The increased limit on the particle p_T is based upon the kinematic fact that in particle decays, a heavy particle (e.g. a proton) carries more momentum than a light particle (e.g. a pion) According to simulations, the lower limit of 2 GeV enhances the decays of Λ_b^0 over decays of other b hadrons by a factor of about two. It also suppresses background from pairing a J/ψ produced in a b-hadron decay with a random low-p_T hadron from hadronization.

We set an upper limit on the $J/\psi p$ transverse momentum based upon the observation that the p_T distribution of Λ_b^0's is softer than that for B mesons [17], and on our expectation that a P_c signal has a dominant contribution from Λ_b^0 decays. Our unpublished study of the decay $\Lambda_b^0 \to J/\psi\Lambda$ shows that the fraction of accepted Λ_b^0 s with $p_T > 13$ GeV is less than 10%. On average we expect the other particle from Λ_b^0 decay (K, K^* etc.) to contribute a p_T of about 1 GeV, leading to our choice of 12 GeV for the $J/\psi p$ transverse momentum thus retaining an estimated 90% of Λ_b^0's.

The invariant mass of the $J/\psi p$ candidate is limited to the range 4.2–4.6 GeV.

Similarly to Refs. [14, 15], to select events where the $J/\psi p$ pair originates from a b-hadron decay, the $J/\psi p$ vertex is required to be displaced in the transverse plane from the $p\bar{p}$ interaction vertex by at least 5σ. The combination of the above requirements suppresses promptly produced J/ψ proton candidates. Figure 1 indicates that a further cut on proton impact parameter [18], as employed in Refs. [14, 15] is not necessary. Our analysis assumes no leakage from prompt $J/\psi p$ events. The resulting "displaced vertex" sample contains 137,357 events.

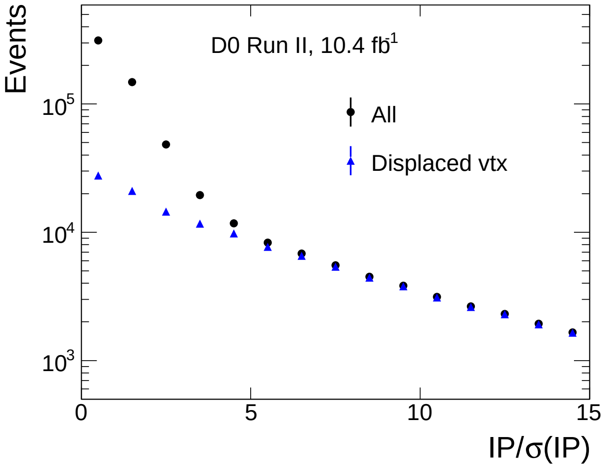

FIG. 1: Impact parameter significance of the proton candidate before (black circles) and after (blue triangles) the requirement of the $J/\psi p$ vertex separation from the primary vertex.

In a search for P_c states coming from b-hadron decays, we study the $M(J/\psi p)$ distribution of the "displaced vertex" events. We perform binned maximum likelihood fits assuming a signal described below, convolved with a Gaussian resolution, and a baseline background choice of a second-order Chebyshev polynomial. The choice of a smooth background shape is justifed by the absence of narrow peaking background. Contributions from

$P_c(4312)$ or any peaking background are neglected. However, including those states would not diminish the fitted signal. Reflections from $J/\psi\pi$ resonances make contributions that are wider than the parent state and can be incorporated in the polynomial background. At around 4.45 GeV, the mass resolution is 12±2 MeV. As a test of the smooth background parametrization we have conducted a likelihood scan using data in the mass range 4.2–4.4 GeV, assuming several values of the resonance mass. The largest deviation from zero among 13 points is $S = 1.7\sigma$, consistent with a background-only behavior. The fit quality for null signal is $\chi^2/ndof = 20/17$. We conclude that the Chebyshev polynomial background model is adequate for our data.

We treat the signal near 4.45 GeV as an incoherent sum of the $P_c(4440)$ and $P_c(4457)$ Breit-Wigner resonances, with the mass and width parameters equal to the LHCb values. We allow the relative contribution of the two yields, $f = N(4440)/(N(4440) + N(4457))$ to vary. Our assumption of an incoherent sum of the P_c states is based on the theoretical predictions that these two states have different J^P values. They have been widely discussed as $\Sigma_c\bar{D}^*$ molecules or compact diquark structures. In the molecular picture, the J^P of the $P_c(4440)$ and $P_c(4457)$ can be $[1/2^-, 3/2^-]$ or $[3/2^-, 1/2^-]$ [19]. In the compact diquark model, the J^P of $P_c(4440)$ and $P_c(4457)$ are $[3/2^+, 5/2^+]$ [20].

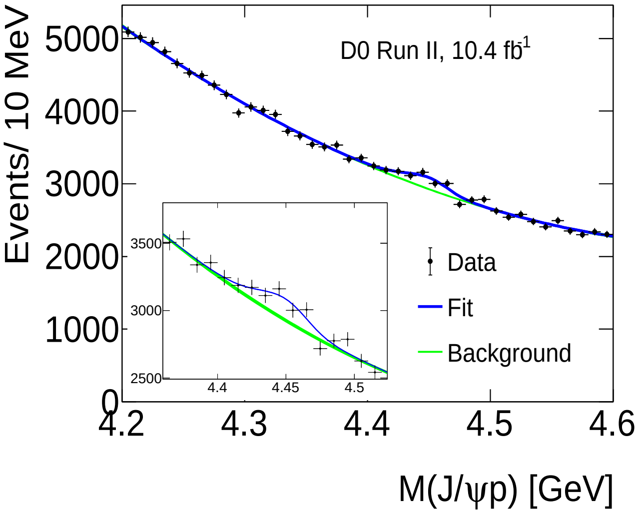

FIG. 2: (color online) Invariant mass distribution of $J/\psi p$ "displaced vertex" candidates with a superimposed fit that includes an incoherent sum of two Breit-Wigner resonances with parameters set to the values reported in Ref. [7]. The ratio of the yields of the two states is allowed to vary and background is modeled with a second-order Chebyshev polynomial (green band). The uncertainty in the background is represented by the width of the line.

With the baseline background parametrization, the fit, shown in Fig. 2, gives a total of $N = 830 \pm 206$ signal events, The fraction $f = 0.61 \pm 0.23$ is in agreement with the LHCb value of 0.677. The probability for background to fluctuate above the observed signal, based on the increase of the likelihood with respect to the fit with no signal $-2\Delta\ln\mathcal{L}$ of 17.0 for two degrees of freedom [21], with an assumed positivity constraint, is 0.000102. The corresponding statistical significance is $S = 3.7\sigma$, and the fit quality is χ^2/ndof=36.4/35. This is the baseline fit and measurement.

For a third-order Chebyshev polynomial background, the results are $N = 789 \pm 215$, $f = 0.62 \pm 0.24$, $S = 3.7\sigma$, and χ^2/ndof=36.0/34. With the ARGUS function of the form $Argus(m, m_0, s, p) \propto m \cdot [1 - (m/m_0)^2]^p \cdot \exp[s \cdot (1 - (m/m_0)^2)]$, the fit results are $N = 735 \pm 200$, $f = 0.63 \pm 0.26$, $S = 3.7\sigma$, and χ^2/ndof=36.3/34. In both cases the improvement in χ^2 is less than the penalty [22] for an additional parameter and thus justifies the choice of the fit with the second-order Chebyshev polynomial background as the baseline.

We test the sensitivity to altering single parameters or pairs of parameters with these auxiliary fits. In these fits, the fraction f is set to the LHCb value of 0.677. In all cases the significances differ by no more than 0.1σ relative to the baseline fit.

- When one width is allowed to vary, with the other set to the LHCb value, the results are $\Gamma(4440) = 32^{+67}_{-27}$ MeV and $\chi^2/\text{ndof} = 36.2/35$, and $\Gamma(4457) = 0^{+35}_{-0}$ MeV and $\chi^2/\text{ndof} = 36.4/35$.
- A fit allowing the mass of the lower resonance to vary and the other four parameters set to the LHCb values, gives $M(4440) = 4443^{+8}_{-9}$ MeV and $\chi^2/\text{ndof} = 36.4/35$.
- A fit in which the mass of the lower resonance is taken as the LHCb central value minus one standard deviation, obtained as the sum in quadrature of the statistical and systematic uncertainties, and the mass of the higher resonance is similarly shifted up by 1σ, gives $N = 905 \pm 224$ and $\chi^2/\text{ndof} = 37.6/36$.
- A fit in which the lower mass is shifted up by 1σ and the higher mass is shifted down by 1σ gives $N = 805 \pm 140$ and $\chi^2/\text{ndof} = 36.3/36$.

To search for the $P_c(4312)$ state in the "displaced vertex" sample, we perform a fit in the reconstructed mass range 4.22-4.44 GeV, with the signal mass and width set to the values of 4311.9 MeV and 9.8 MeV reported in Ref. [7]. The mass resolution is 9 MeV. The best fit, shown in Fig. 3, with the second-order Chebyshev polynomial background gives $N = 151 \pm 186$ events. The fit quality is $\chi^2/\text{ndof} = 15.5/18$. The ratio of the yield of the $P_c(4312)$ to the sum of $P_c(4440)$ and $P_c(4457)$ at 0.18±0.22 is consistent with the LHCb reported ratio of $0.18 \pm 0.06\,(\text{stat})^{+0.21}_{-0.06}\,(\text{syst})$ for the exclusive decay $\Lambda_b^0 \to J/\psi p K^-$.

For the complementary sample of 451,696 "primary vertex" events obtained by reversing the requirement on

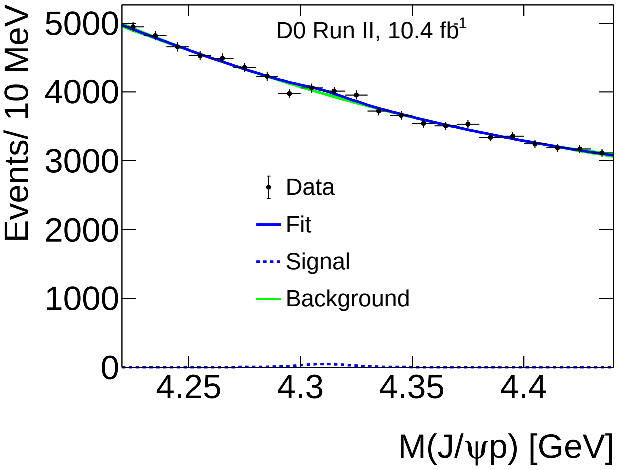

FIG. 3: (color online) Invariant mass distribution of $J/\psi p$ candidates in the vicinity of the $P_c(4312)$. The fit includes a single Breit-Wigner resonance with mass and width fixed to the values of 4311.9 MeV and 9.8 MeV reported in Ref. [7] (dotted blue) and a second-order Chebyshev polynomial background (green $\pm 1\sigma$ band).

the separation of the $J/\psi p$ vertex from the primary vertex, the fit assuming an incoherent sum of the $P_c(4440)$ and $P_c(4457)$ resonances with fixed LHCb parameters for the masses and widths and a free ratio f and a second-order polynomial background gives $N = 421 \pm 410$ events and $\chi^2/\text{ndof} = 49.2/35$. The fit is shown in Fig. 4.

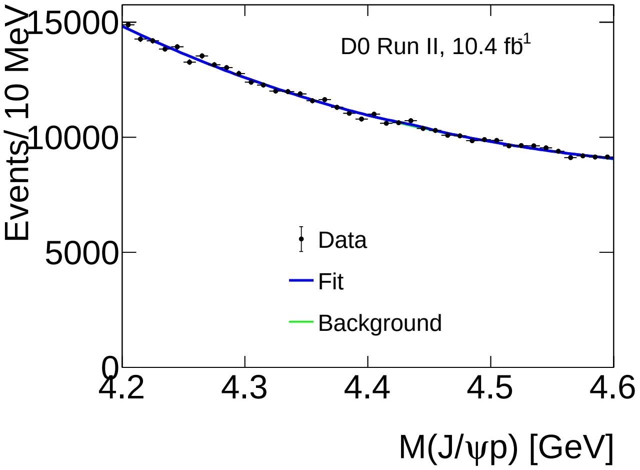

FIG. 4: (color online) Invariant mass distribution of "primary vertex" $J/\psi p$ candidates. The fit includes an incoherent sum of two Breit-Wigner resonances with mass and width parameters set to the values reported in Ref. [7] and the background modeled with a second-order Chebyshev polynomial (green $\pm 1\sigma$ band).

The systematic uncertainties in the signal yield for fixed mass and width are evaluated as follows:

- Mass resolution

  We assign the uncertainty in the signal yields due to uncertainty in the mass resolution as half of the difference of the results obtained by changing the resolution between 10 MeV and 14 MeV. The fit results for the "displaced vertex" sample are $N = 795 \pm 196$ and $N = 869 \pm 222$, respectively.

- Background shape

  We assign a symmetric uncertainty equal to the difference of 95 events between the highest and lowest yields obtained using the three background models.

- LHCb resonance parameters

  We explore the sensitivity of the signal yield to the parameters of the two resonances observed in Ref. [7] by randomly altering all five parameters using the LHCb statistical and systematic uncertainties from Table 1 of Ref. [7]. We simultaneously vary the statististical deviations according to Gaussian distributions in an unlimited range and the systematic deviations within $\pm 1\sigma$ assuming uniform distributions. The choice of the range allowed for the systematic uncertainties is based on the fact the LHCb uncertainties are maximum deviations from multiple alternate fits. The parameter uncertainties reported in Ref. [7] assume that the $P_c(4440)$ and $P_c(4457)$ have the same J^P and interfere with an arbitrary phase, thus overestimating the uncertainties for the case of states of different J^P. The standard deviation of 100 such random alterations is taken as the systematic uncertainty due to the LHCb resonance parameters.

The systematic uncertainties are shown in Table I. The total systematic uncertainty on the "displaced vertex" event yield, taken as the sum in quadrature, is 128 events.

TABLE I: Systematic uncertainties in the combined $P_c(4440)$ and $P_c(4457)$ signal yield for "displaced vertex" (Fig. 2) and "primary vertex" (Fig. 4).

Source	Displaced vertex	Primary vertex
Mass resolution	±37	±22
Background shape	±95	±139
LHCb resonance parameters	±77	–
Total (sum in quadrature)	±128	±141

To propagate the systematic uncertainties we evaluate the p-value for the background-only hypothesis to give N fitted signal events assuming a Gaussian distribution. We then convolve the distribution of such p-values as a function of N with a normalized Gaussian function with a mean of 830 and width $\sigma_N = 128$ to get a significance of 3.2 σ.

To obtain the acceptance A of the "displaced-vertex" selection for H_b decay events leading to the P_c states, defined as $N_{\rm displaced}/(N_{\rm displaced}+N_{\rm primary})$, we use candidates for the decay $B^+ \to J/\psi K^+$ assuming that the distributions of the decay length and its uncertainty for the B^+ decay are a good representation for the average b hadron. All the event selection criteria are the same as for the P_c candidates, except that the upper limit on p_T of the $J/\psi h^+$ system is removed. We find the fitted numbers of B^+ decays $N_{\rm displaced} = 46688 \pm 350$ and $N_{\rm primary} = 12752 \pm 765$, and the corresponding acceptance of 0.78. Relative to the B^+ case, the Λ_b mean lifetime is 10% lower and its mean p_T is about 10% lower so that the slope of the transverse decay length, $L_{\rm xy}$, distribution is larger than that for B^+ by 20%. Assuming that our sample is dominated by Λ_b, and assuming an exponential distribution of $L_{\rm xy}$, we obtain the acceptance of $A = 0.73{\pm}0.05$.

Using the results of the mass fits to the "displaced-vertex" and "primary vertex" subsamples we can obtain acceptance-corrected yields of prompt and nonprompt production and their ratio.

The "displaced-vertex" signal includes events (≈10%) with a proton candidate that originates from the primary vertex. Such events include cases where the proton candidate is "prompt" but the J/ψ originates from an H_b decay. Thus, the fraction of the true prompt production of $J/\psi p$ is less than 10%. It is accounted for as an additional source of uncertainty in the calculation of prompt and nonprompt yield but has a negligible impact compared to other sources.

The total yield of the nonprompt production is $N_{\rm nonprompt} = N_{\rm displaced}/A = 1136 \pm 282$ (stat + syst). The net number of prompt events is $N_{\rm prompt} = N_{\rm primary} - (1-A) \times N_{\rm nonprompt} = 114 \pm 430$. In calculating the uncertainty on the total prompt yield, we add the statistical and the systematic uncertainty components in quadrature. We obtain the ratio $N_{\rm prompt}/N_{\rm nonprompt} = 0.1 \pm 0.4$. Assuming Gaussian uncertainties and setting the Bayesian prior for negative values of the ratio to zero, we obtain an upper limit of 0.9 at the 95% credibility level.

To test the robustness of the signal in the "displaced vertex" data, we performed fits for various alternative selection criteria. As in the baseline fit, the signal mass and width parameters are set to the LHCb values, the fraction f is allowed to vary, and the background is modeled by the second-order Chebyshev polynomial. The signal is present in the entire rapidity range of $(-2, 2)$ with yields expected for b-hadron decays. The results for the three regions of $|y|$ of the $J/\psi p$ rapidity, $|y| < 0.9$, $0.9 < |y| < 1.3$, and $|y| > 1.3$ are 247 ± 111, 234 ± 116, and 347 ± 134, respectively. When we increase the upper limit on the $J/\psi p$ p_T to 14 GeV, the signal yield is increased by 10% to $915{\pm}243$ while the background is increased by 40%. This is in agreement with the expectation, due to the difference in the p_T distributions of the Λ_b^0 baryons and B mesons. The statistical significance of the signal is slightly lowered to 3.3σ. For the upper limits of 11 GeV and 13 GeV, the signal yields are 532 ± 174 and 825 ± 230 events, with corresponding statistical significances of 2.7σ and 3.3σ. Within statistical fluctuations the variation of these significances with the p_T limit conforms to our expectations.

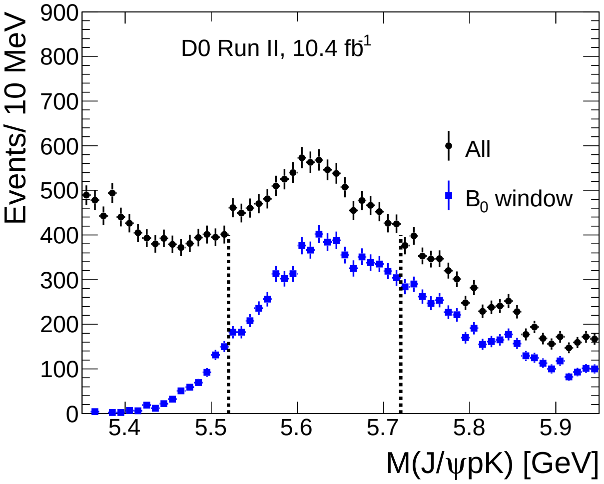

FIG. 5: (color online) The invariant mass distribution of $\Lambda_b^0 \to J/\psi p K^-$ candidates. Also shown (in blue) is the mass distribution for events in the B_d^0 mass window. The vertical lines indicate the Λ_b^0 mass window.

Since the $P_c(4450)$ states were originally observed in the $\Lambda_b^0 \to J/\psi p K^-$ channel we should expect to see some indication of them in that exclusive channel. We have examined a subsidiary sample in which we require that there is an additional negative track with a transverse momentum $p_T > 0.7$ GeV assigned to be a kaon. The addition to the χ^2 of the vertex fit is required to be less than six. To select events with a displaced vertex, we require the $J/\psi p K^-$ vertex to be displaced in the transverse plane from the $p\bar{p}$ interaction vertex by at least 3σ and we apply a constraint on the pointing angle [23] of $\alpha < 0.06$ radians. The mass distribution for accepted candidates is shown in Fig. 5. The Λ_b^0 signal region is defined as 5.52–5.72 GeV, corresponding approximately to ±2.5 standard deviations of our mass resolution. There is a large peaking background from fully reconstructed 3-body decays of B mesons treated as $J/\psi p K^-$, and a falling background mainly due to multibody H_b decays.

The largest peaking background is due to the decay $B_d^0 \to J/\psi K^\pm \pi^\mp$. There are $8262{\pm}176$ B_d^0 events contributing to the distribution shown in Fig. 5. The mass distribution for events from the B_d^0 mass window, 5.15–5.4 GeV, treated as $J/\psi p K^-$, is shown in blue in Fig. 5. The ATLAS Collaboration presented a similar distribution in Fig. 1 of a conference report [24]. According to the ATLAS Monte Carlo estimates, the ratio of yields of $\Lambda_b \to J/\psi p K$ to $B^0 \to J/\psi K \pi$ is ≈0.2. . Hence, we can estimate the number of $\Lambda_b \to J/\psi p K$ decays in our sample to be ≈1700. According to LHCb [7] , the fit fraction for Λ_b decay to the sum of the two P_c states is $B = 0.0164$. This leads to an expected number of

$\Lambda_b \to P_c K$ events of ≈27 in our sample.

A fit to the sample within the Λ_b^0 mass region with resonance masses and widths and the ratio f set to the LHCb values is shown in Fig. 6. The fit results are $N = 82 \pm 37$ and $S = 2.3\sigma$. It should be noted that the falling background in Fig. 5 includes events that have a $J/\psi p$ pair among the decay products and may also contribute to the P_c signal. If we require that $M(pK) > 1.9$ GeV so as to remove events from $\Lambda_b \to J/\psi\Lambda^*$, as was imposed by LHCb, the yield decreases to 13 ± 14 events. The disparity between the estimated number of $\Lambda_b \to P_c K$ events and the observed number of fitted P_c events in Fig. 6, as well as the reduction in the number of fitted P_c events when the cut $M(J/\psi p K^-) > 1.9$ GeV is imposed, indicate the possibility that decays $\Lambda_b \to P_c X$ other than those with $X = K^-$ are present.

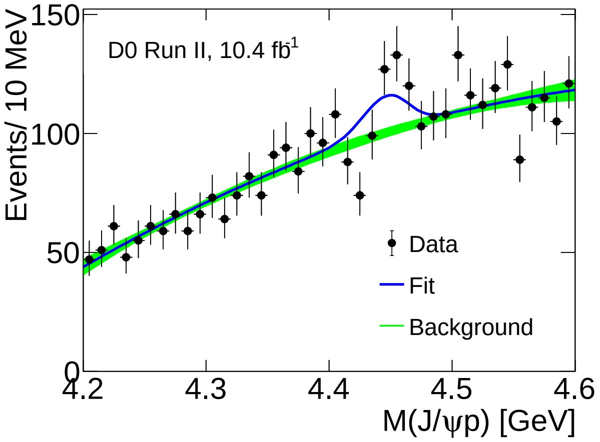

FIG. 6: (color online) The invariant mass distribution of $J/\psi p$ candidates for the candidates of the decay $\Lambda_b^0 \to J/\psi p K^-$.

In summary, we have studied the inclusive production of the J/ψ meson associated with a particle assumed to be a proton. For a subsample of events consistent with coming from decays of b hadrons, we find an enhancement in the $J/\psi p$ invariant mass consistent with a sum of resonances $P_c(4440)$ and $P_c(4457)$ reported in Ref. [7]. This is the first confirmatory evidence for these pentaquark states. The statistical significance of the pentaquark signal with mass and width parameters set to the LHCb values is 3.7σ. The total significance of the signal obtained with the input parameters set to the LHCb values and including the D0 systematic uncertainties and uncertainties in the LHCb input mass and width parameters for the $P_c(4440)$ and $P_c(4457)$ is 3.2σ. The systematic uncertainty due to the LHCb resonance parameters is conservative since Ref. [7] assumes that the $P_c(4440)$ and $P_c(4457)$ are coherent. The measured ratio $f = N(4440)/(N(4440) + N(4457))$ of 0.61 ± 0.23 is consistent with the LHCb value. The study of the semi-exclusive process $\Lambda_b \to J/\psi p X$ indicates the possibility that decays $\Lambda_b \to P_c X$ other than those with $X = K^-$ exist.

There is no evidence of prompt production of the $P_c(4450)$ states. We find $N_{\text{prompt}}/N_{\text{nonprompt}} = 0.1 \pm 0.4$ and obtain an upper limit of 0.9 at the 95% credibility level.

The ratio of the yield of the $P_c(4312)$ to the sum of $P_c(4440)$ and $P_c(4457)$ is 0.18 ± 0.22 which is consistent with the value measured by LHCb.

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