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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 a sum of $P_c(4440)$ and $P_c(4457)$. The significance, with the input 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 3.0σ. This is the first confirmatory evidence for these pentaquark states. We measure the ratio $N_{\rm prompt}/N_{\rm nonprompt} = 0.05 \pm 0.39$ and set an upper limit of 0.8 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 less than 0.6 at the 95% credibility level. 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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In 2015 the LHCb Collaboration announced the discovery [1] of a particle decaying to a J/ψ meson and a proton and measured its invariant mass $M = 4449.8 \pm 1.7(\text{stat}) \pm 2.5\,(\text{syst})$ MeV and width $\Gamma = 39 \pm 5\,(\text{stat}) \pm 19\,(\text{syst})$ MeV. In addition to this particle, called $P_c(4450)$, the LHCb Collaboration reported the presence of a second enhancement based on an amplitude analysis, with a mass of $4380 \pm 8\,(\text{stat}) \pm 29\,(\text{syst})$ MeV and a width of $205 \pm 18\,(\text{stat}) \pm 86\,(\text{syst})$ MeV.

Recently, using an increased dataset, the LHCb Collaboration reported the discovery of three narrow resonances [2] 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. [1]. The minimum quark content of these states, is $c\overline{c}uud$ (charge conjugation is implied throughout this paper).

The P_c states were found as resonances in the decay products of the Λ_b^0 baryon, $\Lambda_b^0 \to J/\psi p K^-$. They might also be produced in other decay channels, such as $\Lambda_b^0 \to J/\psi p K^{*-}$ or $\Lambda_b^0 \to J/\psi p \pi^-$, or in decays of other b hadrons (H_b) such as $B_c \to P_c X$, or promptly in gluon-gluon or quark-antiquark fusion. In this note we present results of a search for the inclusive production of the P_c states in $p\overline{p}$ 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. [2]. The data sample corresponds to an integrated luminosity of 10.4 fb^{-1} collected with the D0 detector in $p\overline{p}$ collisions at 1.96 TeV at the Fermilab Tevatron collider.

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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 [3–5]. A muon system, covering $|\eta| < 2$ [6], 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 [7]. 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 selection requirements detailed below were set prior to examining the data, based on the previous D0 analyses of heavy quark hadron production and decays [8]. Although the observation of the P_c states in Refs. [1, 2] were in the decay channel $\Lambda_b^0 \to P_c^+ K^-$ with $P_c \to J/\psi p$, our analysis is 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. While the number of background events in data for the region $4.2 < M(J/\psi p) < 4.6$ GeV decreases by a factor of about 20 going from the inclusive to exclusive selections, we expect that the P_c signal would decrease by more than a factor of $\sqrt{20}$, thus leading to higher significance for the inclusive selection. We verify this expectation below.

Our J/ψ selection and displaced vertex requirements for selecting b hadrons are standard and similar to those in previous analyses. Candidate events are required to include a pair of oppositely charged muons consistent with J/ψ decay, accompanied by a third charged particle with $p_T > 2$ GeV that is assigned the proton mass. We select events with $2.92 < M(\mu^+\mu^-) < 3.25$ GeV. In a kinematic fit procedure, the dimuon invariant mass is constrained to the world-average J/ψ mass [9], and the three-track system is constrained to a common vertex.

In the coordinate system in which the z axis is aligned with the proton beam direction, we define the decay length of a particle, L_{xy}, to be the length of the vector pointing from the primary vertex to the decay vertex, projected onto the direction of the transverse momentum. To ensure that the J/ψ and the proton candidate come from the same vertex, we require the difference between the decay length measured with the two muons and with two muons and the proton candidate to be < 30 μm in the transverse plane and < 500 μm in three-dimensional space.

To select "displaced vertex" events where the $J/\psi p$ system comes from a weak decay of a b hadron, we require $L_{xy} > 250$ μm and $L_{xy}/\sigma(L_{xy}) > 3$. Background to the decay $H_b \to J/\psi p + X$ consists primarily of decays of b hadrons to J/ψ accompanied by a charged hadron h^+ that may be a kaon or a pion, misidentified as a proton, and any nonzero number of additional particles, charged or neutral, $H_b \to J/\psi h^+ + X$. The number of prompt events in the "displaced vertex" sample is negligible.

To suppress combinatorial background, we select events with relatively low hadronic activity around the $J/\psi p$ candidate. In the b-quark fragmentation process, the b hadron carries a large fraction of the parent quark momentum. Also, in a decay $H_b \to J/\psi h + X$, the $J/\psi h$ subsystem carries a large fraction of the H_b momentum. We define the *Isolation*, $\mathcal{I}$, as the ratio of the P_c candidate momentum to the sum of the momentum of the P_c and the momenta of all other reconstructed charged particles within a cone of radius [6] $\Delta R = 1.0$ about the direction of the P_c momentum and require $\mathcal{I} > 0.5$. This requirement rejects 11% of the candidates.

We set an upper limit on the $J/\psi p$ transverse momentum at 12 GeV. This restriction is based upon the fact that the p_T distribution of Λ_b^0's is softer than that for B mesons [10], and on our expectation that a P_c signal has a dominant contribution from Λ_b^0 decays.

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

The resulting "displaced vertex" sample contains 68007 events.

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 background described by a series of Chebyshev polynomials of the first kind. At around 4.45 GeV, the mass resolution is 12 MeV.

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 also assume the relative contribution of the two yields for the inclusive production of P_c to be equal to the LHCb value, $f = N(4440)/(N(4440) + N(4457)) = 0.68 \pm 0.08\,(\text{stat}) \pm 0.05\,(\text{syst})$. 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 $[3/2^-, 1/2^-]$ [11]. In the compact diquark model, the J^P of $P_c(4440)$ and $P_c(4457)$ are $[3/2^+, 5/2^+]$ [12].

With background parametrized by a second-order polynomial, the fit, shown in Fig. 1, gives a total of $N = 523 \pm 145$ signal events. The statistical significance, based on the increase of the likelihood with respect to

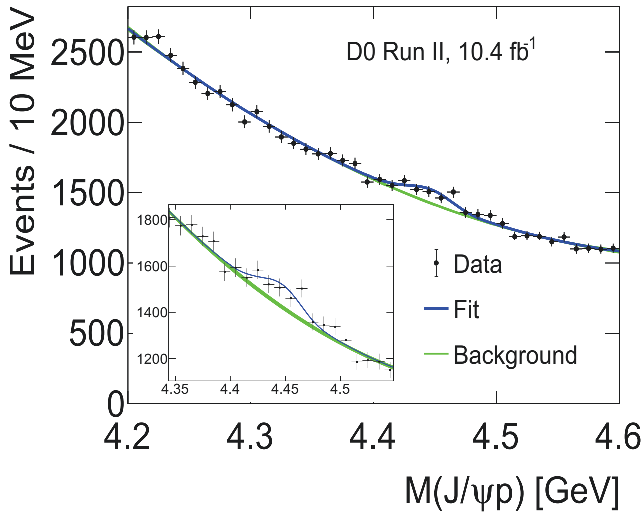

FIG. 1: (color online) Invariant mass distribution of $J/\psi p$ "displaced vertex" candidates with a superimposed fit that includes an incoherent sum of two Breit-Wigner resonances with parameters set to the values reported in Ref. [2] and the background modeled with a second-order Chebyshev polynomial (green band). The uncertainty in the background is represented by the width of the line.

the fit with no signal, $S = \sqrt{-2\Delta \ln \mathcal{L}}$, is $S = 3.6\sigma$, and $\chi^2/ndof$=31.2/36. This is the baseline fit and measurement.

For a third-order polynomial background, the results are $N = 467 \pm 153$, $S = 3.1\sigma$, and $\chi^2/ndof$=29.8/35. The improvement in χ^2 is less than the penalty [13] for an additional parameter and thus justifies the choice of the fit with the second-order polynomial background as the baseline.

We test the sensitivity to altering single parameters or pairs of parameters with these auxiliary fits:

- With fixed parameters for the signal mass and width and the ratio of the two yields allowed to vary, the fit with the second-order polynomial background yields $N = 499 \pm 147$ signal events with $f = 0.46^{+0.28}_{-0.36}$, showing a preference for the presence of both resonances. The statistical significance is $S = 3.7\sigma$ and the fit quality is $\chi^2/ndof$=30.8/35.

- When one width is allowed to vary, with the other set to the LHCb value, the results are $\Gamma(4440) = 86^{+92}_{-49}$ MeV, $S = 3.9\sigma$, $\chi^2/ndof = 28.8/35$, and $\Gamma(4457) = 0^{+58}_{-0}$ MeV, $S = 3.6\sigma$, $\chi^2/ndof = 31.2/35$.

- A fit allowing for varying $M(4440)$ and the other four parameters set to the LHCb values, gives $M(4440) = 4426^{+8}_{-10}$ MeV, $N = 668 \pm 179$, $S = 4.0\sigma$, and $\chi^2/ndof = 28.5/35$.

- A fit for the case of the lowest mass value of the lower resonance, taken as the central value minus one standard deviation obtained as a sum in quadrature of the statistical and systematic uncertainties, and the highest mass value of the higher resonance, obtained in a similar way by shifting upwards the LHCb value according to its uncertainty, gives $N = 606 \pm 158$, $S = 3.8\sigma$, and $\chi^2/ndof = 30.4/36$.

- A fit for the case of the highest mass value of the lower resonance and the lowest mass value of the higher resonance gives $N = 493 \pm 140$, $S = 3.6\sigma$, and $\chi^2/ndof = 31.6/36$.

To search for the $P_c(4312)$ state in the "displaced vertex" sample, we perform a fit in the reconstructed mass range 4.22-4.40 GeV, with the signal mass and width set to the values of 4311.9 MeV and 9.8 MeV reported in Ref. [2]. The mass resolution is 9 MeV. The best fit, with the second-order Chebyshev polynomial background gives $N = 42 \pm 132$ events. The fit quality is $\chi^2/ndof = 14.3/18$. The ratio of the yield of the $P_c(4312)$ to the sum of $P_c(4440)$ and $P_c(4457)$ is less than 0.6 at the 95% credibility level, with the Bayesian prior for negative values of the ratio set to zero. This result 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 218,251 "primary vertex" events, the fit assuming an incoherent sum of the $P_c(4440)$ and $P_c(4457)$ resonances with fixed LHCb parameters and a second-order polynomial background gives $N = 188 \pm 263$ events with $S = 0.71\sigma$ and $\chi^2/ndof = 34.3/36$. The fit is shown in Fig. 2.

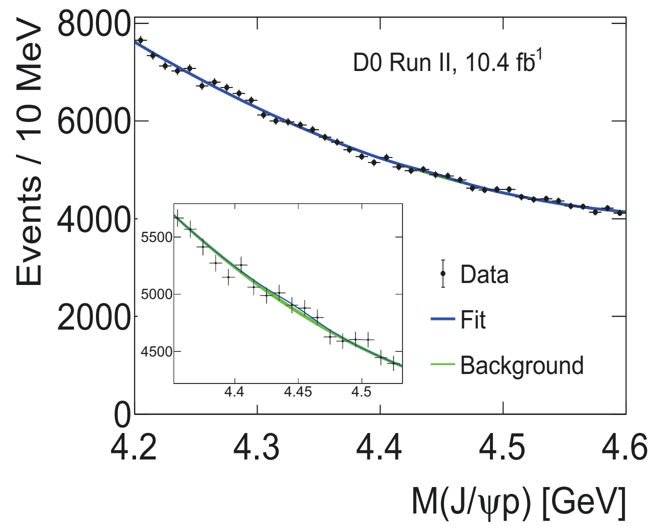

FIG. 2: (color online) Invariant mass distribution of "primary vertex" $J/\psi p$ candidates. The fit includes an incoherent sum of two Breit-Wigner resonances with all parameters set to the values reported in Ref. [2] and the background modeled with a second-order Chebyshev polynomial (green $\pm 1\sigma$ 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 $N = 488 \pm 139$, $S = 3.5\sigma$, $\chi^2/ndof = 31.9/35$ and $N = 561 \pm 153$, $S = 3.7\sigma$, $\chi^2/ndof = 30.7/35$, respectively.

- Background shape

  We assign a symmetric uncertainty equal to the difference between the results obtained using the 2nd and 3rd order polynomial.

- LHCb resonance parameters

  We explore the sensitivity of the signal yield to the location in the parameter space of the two resonances observed in Ref. [2] by randomly altering all five parameters using the LHCb statistical and systematic uncertainties from Table 1 of Ref. [2]. 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. [2] 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 93 events.

TABLE I: Systematic uncertainties in the combined $P_c(4440)$ and $P_c(4457)$ signal yield for "displaced vertex" (Fig. 1) and "primary vertex" (Fig. 2).

Source	Displaced vertex	Primary vertex
Mass resolution	± 37	± 12
Background shape	± 56	± 18
LHCb resonance parameters	± 64	–
Total (sum in quadrature)	± 93	± 22

To propagate the systematic uncertainties, we evaluate the p-value for the background-only hypothesis to give N fitted signal events using the method of Ref. [14]. We then convolve the distribution of such p-values as a function of N with a Gaussian with width $\sigma_N = 93$ to get a p-value of 0.00116, corresponding to a significance of 3.0 σ.

To obtain the acceptance A of the "displaced-vertex" selection for H_b decay events leading to $P_c(4450)$, 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 $N_{\rm displaced} = 20186 \pm 551$ and $N_{\rm primary} = 5924 \pm 359$. In a similar study [15] we estimated the systematic uncertainty of the acceptance A due to differences between different H_b decays to be $\pm 2\%$ of its nominal value. Our result, including the systematic uncertainty, is $A = 0.77 \pm 0.05$.

Using the total number of events of $P_c(4440)$ and $P_c(4457)$ with a "displaced vertex" and the number of decays $B^+ \to J/\psi K^+$ we obtain the ratio $(H_b \to P_c + X)/(B^+ \to J/\psi K^+) = 0.03 \pm 0.01$.

Using the results of the mass fits to the "displaced-vertex" and "primary vertex" subsamples we can obtain acceptance-corrected yields of prompt and non-prompt production and their ratio. The total yield of the nonprompt production is $N_{\rm nonprompt} = N_{\rm displaced}/A = 677 \pm 207$ (stat + syst). The net number of prompt events is $N_{\rm prompt} = N_{\rm primary} - (1 - A) \times N_{\rm nonprompt} = 34 \pm 267$. In calculating the uncertainty on the total prompt yield, we add the statistical and the systematic uncertainty components in quadrature. We obtain the ratio $N_{\rm prompt}/N_{\rm nonprompt} = 0.05 \pm 0.39$. Assuming Gaussian uncertainties and setting the Bayesian prior for negative values of the ratio to zero, we obtain an upper limit of 0.8 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 outlined below. As in the baseline fit, the signal parameters are set to the LHCb values and the background is modeled by the second-order Chebyshev polynomial.

The signal is present in the entire rapidity range of $(-2, 2)$. 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 144 ± 72, 140 ± 80, and 242 ± 94, respectively.

When we increase the upper limit on the $J/\psi p$ p_T to 14 GeV, the signal yield is increased by 17% to 615 ± 172 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 remains unchanged at 3.6σ.

The baseline sample contains negligible background from processes other than $H_b \to J/\psi h^+ + X$. When the requirements on the quality of the decay vertex are removed and the only rejection of prompt production is the condition $L_{xy}/\sigma(L_{xy}) > 3$ for the J/ψ vertex, the number of accepted events increases by a factor of two. There are additional backgrounds due to prompt production of J/ψ, to $H_b \to J/\psi + X$ decays with the hadron h coming from the primary vertex, and to non-J/ψ dimuon events. This looser selection also has more $H_b \to J/\psi h^+ + X$ decays, including additional signal events. The results of a fit with the signal parameters set to the LHCb values and with a second-order polynomial background, are $N = 784 \pm 207$, $S = 3.8\sigma$, $\chi^2/ndof = 35.3/36$.

Since the $P_c(4450)$ was originally observed in the $\Lambda_b^0 \to J/\psi p K^-$ channel we should expect to see some indication of it in that exclusive channel. We have examined a subsidiary sample in which we require that there is an additional negative track, assigned to be a kaon, with a good probability to be connected to the $J/\psi p$ vertex, and constrain the $J/\psi p K^-$ mass to be in the Λ_b mass region. A fit to this sample gives a reduction in the number of signal events by a factor of 6.5 relative to the baseline fit while the background is reduced by a factor of 19. The statistical significance drops from 3.6σ to 2.3σ, as expected from the reduction in the size of the sample and the decrease in the signal to $\sqrt{\text{background}}$ ratio.

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. [2]. This is the first confirmatory evidence for these pentaquark states. The statistical significance of the pentaquark signal with parameters set to the LHCb values is 3.6σ. 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 parameters for the $P_c(4440)$ and $P_c(4457)$ is 3.0σ.

The ratio of the P_c signal yield to the number of events of the decay of the same topology, $B^+ \to J/\psi K^+$, is 0.03 ± 0.01.

There is no evidence of prompt production of the $P_c(4450)$ states. We find $N_{\text{prompt}}/N_{\text{nonprompt}} = 0.05 \pm 0.39$ and obtain an upper limit of 0.8 at the 95% credibility level.

We find no evidence for the state $P_c(4312)$. The ratio of the yield of the $P_c(4312)$ to the sum of $P_c(4440)$ and $P_c(4457)$ $R = N(4312)/(N(4440) + N(4457))$ is less than 0.6 at the 95% credibility level, consistent with the value measured by LHCb.

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