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

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We present a study of the inclusive production in \( p \bar{p} \) 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 values, is 3.3\( \sigma \). This is the first confirmatory evidence for these pentaquark states. We measure 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 \( J/\psi \) meson and a proton and measured its invariant mass \( M = 4449.8 \pm 1.7 \) (stat) \( \pm 2.5 \) (syst) MeV and width \( \Gamma = 39 \pm 5 \) (stat) \( \pm 19 \) (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 \( \pm 8 \) (stat) \( \pm 29 \) (syst) MeV and a width of 205 \( \pm 18 \) (stat) \( \pm 86 \) (syst) MeV.

Recently, using an increased dataset, the LHCb Collab...
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 [3]. 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.

While not restricting the search to the exclusive channel used in Ref. [2], we optimise the criteria for events with the $A_0^0$ decay containing $J/\psi p$ in the final state. Candidate events are required to include a pair of oppositely charged muons consistent with $J/\psi$ 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 $J/\psi$ mass [5], and the three-track system is constrained to a common vertex. The invariant mass of the $J/\psi p$ candidate is limited to the range $4.2 < M(J/\psi p) < 4.6$ GeV.

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 $J/\psi$ 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 $< 30 \mu$m in the transverse plane and $< 500 \mu$m 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 $L_{xy} > 250 \mu$m and $L_{xy}/\sigma(L_{xy}) > 3$. Background to the decay $H_b \rightarrow J/\psi p + X$ consists primarily of decays of $b$ hadrons to $J/\psi$ 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, $H_b \rightarrow J/\psi h^+ + X$. The number of prompt events in the “displaced vertex” sample is negligible.

We define the Isolation, $I$, 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 $|\Delta R| = 1.0$, about the direction of the $P_c$ momentum and require $I > 0.5$.

To further enhance the signal, we use the fact that the average $p_T$ of the $A_0^0$ baryon is lower than the average $p_T$ of $B$ mesons and we add a requirement $6 < p_T(J/\psi p) < 12$ GeV. Also, the lower limit of 2 GeV on the transverse momentum on the proton candidate enhances the decays of $A_0^0$ over decays of other $b$ hadrons by a factor of $\approx 2$. The resulting “displaced vertex” sample shown in Fig. [7] 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 in the range 4.2–4.6 GeV. 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.

We treat the signal 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, $f = N(4440)/(N(4440) + N(4457)) = 0.68 \pm 0.08$ (stat) $\pm 0.05$ (syst). Our assumption of an incoherent sum of the $P_c$ states is based on the unlikely case that two states so close in mass would have the same $J^P$ values. At around 4.45 GeV, the mass resolution is 12 MeV.

![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 second-order Chebyshev polynomial background (green band). The uncertainty in the background is represented by the width of the line.](image-url)
The signal yield, statistical significance, and parameters altered by one standard deviation and the others from Table 1 of Ref. [2], we obtain the results shown in Table I. In all cases, the significance is above 3.4σ, the signal yield is equal or greater than 427 events, and the fit quality is $\chi^2/ndof < 31.9/36$.

We explore the sensitivity of the signal yield, statistical significance and fit quality to the parameters in the parameter space of the two resonances observed in Ref. [2]. By altering one parameter at a time by ±1σ (calculated as a sum in quadrature of the statistical and systematic uncertainties from Table 1 of Ref. [2]), we obtain the results shown in Table I. In all cases, the significance is above 3.4σ, the signal yield is equal or greater than 427 events, and the fit quality is $\chi^2/ndof < 31.9/36$.

| Parameter          | N   | $S(\sigma)$ | $\chi^2$ |
|--------------------|-----|-------------|----------|
| $M(4440) - \sigma$ | 546 | 3.6         | 31.6     |
| $M(4440) + \sigma$| 505 | 3.7         | 31.1     |
| $M(4457) - \sigma$| 504 | 3.5         | 31.9     |
| $M(4457) + \sigma$| 571 | 3.8         | 30.0     |
| $\Gamma(4440) - \sigma$| 427 | 3.4         | 31.3     |
| $\Gamma(4440) + \sigma$| 600 | 3.7         | 30.3     |
| $\Gamma(4457) - \sigma$| 513 | 3.6         | 31.3     |
| $\Gamma(4457) + \sigma$| 545 | 3.6         | 31.2     |
| $f - \sigma$       | 518 | 3.7         | 30.9     |
| $f + \sigma$       | 520 | 3.5         | 31.2     |
| Baseline           | 523 | 3.6         | 31.2     |

We obtain the total uncertainty in the signal yield due to the uncertainties in the LHCb measurement, taken as the sum in quadrature of the five sources listed in Table I, to be $\sigma_N = 96$. Alternatively, we allow all five parameters that describe the signal shape to vary, constrained by Gaussian priors taken from Ref. [2]. The fitted masses, widths and ratio $f$ are in good agreement with the values in Ref. [2]. The fit yields 550±173 signal events. By comparing with the baseline fit, we deduce the uncertainty in the signal yield due to uncertainties in the signal parameters to be ±94 events, in good agreement with the estimate above.

These calculations are likely to be overly conservative. They ignore correlations among the parameters which are likely to be present. We also note that the fits in Ref. [2] assume a coherent sum of the $P_c(4440)$ and $P_c(4457)$ states with an arbitrary, fitted phase. The introduction of this phase increases the uncertainty in the fitted parameters. It is however unlikely that the two states have the same quantum numbers and thus they should be considered as an incoherent sum, leading to reduced uncertainties.

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 $f = 0.46^{+0.28}_{-0.36}$. 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 $\Gamma(4457) = 0^{+58}_{-20}$ MeV, $S = 3.6\sigma$, $\chi^2/ndof = 31.2/35$.

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 $P_c(4457)$ $R = (N(4312)/(N(4440)+N(4457)))$ 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 $0.18 \pm 0.06 (\text{stat}) - 0.06 (\text{syst})$ for the exclusive decay $N^0 \rightarrow J/\psi pK^-$. For the complementary sample of “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.

We observe the sensitivity of the signal yield, statistical significance and fit quality to the parameters in the parameter space of the two resonances observed in Ref. [2]. By altering one parameter at a time by ±1σ (calculated as a sum in quadrature of the statistical and systematic uncertainties from Table 1 of Ref. [2]), we obtain the results shown in Table I. In all cases, the significance is above 3.4σ, the signal yield is equal or greater than 427 events, and the fit quality is $\chi^2/ndof < 31.9/36$.

By altering one parameter at a time by ±1σ (calculated as a sum in quadrature of the statistical and systematic uncertainties from Table 1 of Ref. [2]), we obtain the results shown in Table I. In all cases, the significance is above 3.4σ, the signal yield is equal or greater than 427 events, and the fit quality is $\chi^2/ndof < 31.9/36$.

The fit yields $550 \pm 173$ signal events. By comparing with the baseline fit, we deduce the uncertainty in the signal yield due to uncertainties in the signal parameters to be $\pm 94$ events, in good agreement with the estimate above.

These calculations are likely to be overly conservative. They ignore correlations among the parameters which are likely to be present. We also note that the fits in Ref. [2] assume a coherent sum of the $P_c(4440)$ and $P_c(4457)$ states with an arbitrary, fitted phase. The introduction of this phase increases the uncertainty in the fitted parameters. It is however unlikely that the two states have the same quantum numbers and thus they should be considered as an incoherent sum, leading to reduced uncertainties.

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 $f = 0.46^{+0.28}_{-0.36}$. 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 $\Gamma(4457) = 0^{+58}_{-20}$ MeV, $S = 3.6\sigma$, $\chi^2/ndof = 31.2/35$.

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 $P_c(4457)$ $R = (N(4312)/(N(4440)+N(4457)))$ 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 $0.18 \pm 0.06 (\text{stat}) - 0.06 (\text{syst})$ for the exclusive decay $N^0 \rightarrow J/\psi pK^-$.

For the complementary sample of “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.

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 by ±1σ to 10 MeV and 14 MeV. The fit results for the “displaced vertex” sample are \( N = 488 \pm 139 \), \( S = 3.5\sigma \), \( \chi^2/\text{ndof} = 31.9/35 \) and \( N = 561 \pm 153 \), \( S = 3.7\sigma \), \( \chi^2/\text{ndof} = 30.7/35 \).

- **Background shape**
  We assign a symmetric uncertainty equal to the difference between the results obtained using the 2nd and 3rd order polynomial.
  
  The systematic uncertainties in the signal yield are summarized in Table II.

| Source                  | Displaced vertex | Primary vertex |
|-------------------------|------------------|----------------|
| Mass resolution         | ±37              | ±12            |
| Background shape        | ±56              | ±18            |
| Total (sum in quadrature)| ±67              | ±22            |

Adding in quadrature the uncertainty of ±96 due to the five sources listed in Table II to the estimate of the signal yield uncertainty for the “displaced-vertex” sample in Table II we obtain \( \sigma_N = 117 \). Using simulations [10], we perform a test of the null hypothesis for a range of assumed values of the signal yield \( N \). The impact of systematic effects is obtained by convolving the dependence of the \( p \)-value on \( N \), shown in Fig. 3, with a Gaussian of width \( \sigma_N = 117 \). The smeared \( p \)-value of 0.0021 and a corresponding significance of 2.8 \( \sigma \) are obtained for the measured number of signal events in data, \( N_{\text{obs}} = 523 \). In view of the potential overestimate in our application of the systematic uncertainties in Ref. [2] discussed above, we also calculate the significance corresponding to a total uncertainty equal to the sum in quadrature of the statistical and experiment-based systematic (Table II) uncertainties to obtain a \( p \)-value of 0.00047 and a significance of 3.3\( \sigma \). These results are summarized in Table III. Figure 3 enables our result to be recalculated to include future signal model uncertainties.

| Sources of uncertainties | \( \sigma_N \) (syst) | \( p \)-value | Significance |
|--------------------------|----------------------|--------------|--------------|
| D0 stat. only            | –                    | 0.00016      | 3.6\( \sigma \) |
| D0 stat. and D0 syst.    | ±67                  | 0.00047      | 3.3\( \sigma \) |
| D0 stat. and D0 syst.    | ±117                 | 0.0021       | 2.8\( \sigma \) |
| and LHCb syst.           |                      |              |              |

To obtain the acceptance \( A \) of the “displaced-vertex” selection for \( H_b \) decay events leading to \( P_c(4450) \), defined as \( N_{\text{displaced}}/(N_{\text{displaced}}+N_{\text{primary}}) \), 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 \( N_{\text{displaced}} = 20186 \pm 551 \) and \( N_{\text{primary}} = 5924 \pm 359 \), respectively. In a similar study [11] we estimated the systematic uncertainty of the acceptance \( A \) due to differences between different \( H_b \) decays to be ±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 nonprompt production and their ratio. The total yield of the nonprompt production is \( N_{\text{nonprompt}} = N_{\text{displaced}}/A = 677 \pm 207 \) (stat + syst). The net number of prompt events is \( N_{\text{prompt}} = N_{\text{primary}} - (1 - A) \times N_{\text{nonprompt}} = 34 \pm 267 \). Calculating the uncertainty on the total prompt yield, we add the statistical and the systematic uncertainty components in quadrature. We obtain the ratio \( N_{\text{prompt}}/N_{\text{nonprompt}} = 0.05 \pm 0.39 \). 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 under various alternative conditions. 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 \((-2.2, 2)\). 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 \(144 \pm 72, 140 \pm 80,\) and \(242 \pm 94,\) respectively.

When we select \(J/\psi p\) candidates in the \(p_T\) range of 7–14 GeV instead of 6–12 GeV, the signal yield is increased by 17\% to 615\pm172 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 \(A_{0}^{0}\) baryons and \(B\) mesons. The statistical significance of the signal in this case is 3.6\(\sigma\).

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 \(J/\psi\) vertex, the number of accepted events increases by a factor of two. There are additional backgrounds due to prompt production of \(J/\psi\), to \(H_b \to J/\psi + X\) decays with the hadron \(h\) coming from the primary vertex, and to non-\(J/\psi\) 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 \(N = 784 \pm 207, S = 3.8\sigma, \chi^2/ndof = 35.3/36\).

In summary, we have studied the inclusive production of the \(J/\psi\) meson associated with a hadron 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 3.6\(\sigma\). The total significance with the input parameters set to the LHCb values and including the D0 systematic uncertainties is 3.3\(\sigma\). The total significance including the effects of uncertainties in the LHCb inputs treated as fully uncorrelated is 2.8\(\sigma\).

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\pm0.01.

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 \(P_c(4457)\) is \(R = N(4312)/(N(4440) + N(4457))\) is less than 0.6 at the 95\% credibility level consistent with the value measured by LHCb.

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