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Evidence for $Z_c^{\pm}(3900)$ in semi-inclusive decays of b-flavored hadrons

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We present evidence for the exotic charged charmonium-like state $Z_c^\pm(3900)$ in semi-inclusive weak decays of b-flavored hadrons. The signal is correlated with a $J/\psi\pi^+\pi^-$ system in the invariant mass range 4.2−4.7 GeV and includes the sequential process b-quark hadron $\rightarrow Y(4260)+$ anything, $Y(4260) \rightarrow Z_c^\pm(3900)\pi^\mp$, $Z_c^\pm(3900) \rightarrow J/\psi\pi^\pm$. The study is based on 10.4 fb^{-1} of $p\bar{p}$ collision data collected by the D0 experiment at the Fermilab Tevatron collider.

I. INTRODUCTION

The charged charmonium-like state $Z_c^\pm(3900)$ was discovered in 2013 simultaneously by the Belle [1] and BESIII [2] collaborations in the sequential process $e^+e^- \rightarrow Y(4260)$, $Y(4260) \rightarrow Z_c^+(3900)\pi^-$, $Z_c^+(3900) \rightarrow J/\psi\pi^+$ (charge conjugate processes are implied throughout). Their fits of the $Z_c^+(3900)$ signal with an S-wave Breit-Wigner signal shape and an incoherent background gave the signal parameters $M = 3894.5 \pm 6.6 \pm 4.5$ MeV, $\Gamma = 63 \pm 34 \pm 26$ MeV and $M = 3899.0 \pm 3.6 \pm 4.9$ MeV, $\Gamma = 46 \pm 10 \pm 20$ MeV, respectively. The $Z_c^+(3900)$ cannot be a conventional quark-antiquark meson as it is charged and decays via the strong interaction to charmonium. Its minimal quark content is thus $c\bar{c}u\bar{d}$.

Since the original observation the understanding of both the $Z_c^+(3900)$ and $Y(4260)$ has evolved. The BESIII collaboration has measured [3] the $e^+e^- \rightarrow J/\psi\pi^+\pi^-$ cross section at a range of energies from 3.77 GeV to 4.60 GeV and reported that the $Y(4260)$ may consist of two states: a narrow state at about 4.22 GeV and a wider one at about 4.32 GeV above a continuum that may also be consistent with a broad resonance near 4.0 GeV. Currently the "$Y(4260)$" is believed to be composed of two states: a lower-mass narrower state denoted by the Particle Data Group (PDG) [4] as $\psi(4260)$ with mass $M = 4230 \pm 8$ MeV and width $\Gamma = 55 \pm 19$ MeV and a higher-mass broader state $\psi(4360)$ with $M = 4368 \pm 13$ MeV and $\Gamma = 96 \pm 7$ MeV.

The $Z_c^+(3900)$ is close in mass to $X(3872)$ and also close to the open-charm $D^*\overline{D}$ threshold, so it may be a "molecular" state composed of a loosely bound pair of colorless, quark-antiquark pairs containing a charm and a light quark ($c\bar{d}$) and ($\bar{c}u$), the isovector analog of the $X(3872)$. A mass enhancement is also seen in the $D^*\overline{D}$ system [5] but the fit for this channel gives a different mass and width compared to that for the $J/\psi\pi^+$ channel.

The PDG [4] assumes that it is a single resonance decaying to two final states. It lists it as $Z_c(3900)$ with $M = 3886.6 \pm 2.4$ MeV and $\Gamma = 28.2 \pm 2.6$ MeV. The spin and parity are determined to be [6] $J^P = 1^+$.

The presence of $Z_c^+(3900)$ in decays of b hadrons is unclear. It is not seen by Belle [7] in the decay $\bar{B}^0 \rightarrow (J/\psi\pi^+)K^-$ nor by LHCb [8] in the decay $B^0 \rightarrow (J/\psi\pi^+)\pi^-$. On the other hand, the $Y(4260)$ may have been seen in the decays $B \rightarrow J/\psi\pi\pi K$ by BaBar [9], so there could be production of $Z_c^+(3900)$ in b-hadron decays through the two-step process $H_b \rightarrow Y(4260)+$ anything, $Y(4260) \rightarrow Z_c^+(3900)\pi^-$, where H_b represents any hadron containing a b quark. The process may be spread over many channels and thus escape observation

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in any specific channel.

In this article we look for the presence of such two-step processes using 10.4 fb^{-1} of $p\overline{p}$ collision data collected by the D0 experiment at the Fermilab Tevatron collider.

II. D0 DETECTOR, EVENT RECONSTRUCTION AND SELECTION

The D0 detector [10] has a central tracking system consisting of a silicon microstrip tracker [11] and a central scintillating fiber tracker, both located within a 1.9T superconducting solenoidal magnet. A muon system [12] covering pseudorapidity $|\eta_{\rm det}| < 2$ [13] is located outside of the central tracking system and the liquid argon calorimeter, and consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8T toroidal magnets, followed by two similar layers after the toroids.

In high-energy $p\overline{p}$ collisions the J/ψ can be produced both promptly, either directly or in strong interaction decays of higher-mass charmonum states, or nonpromptly in weak-interaction b-hadron decays [14–16]. Non-prompt J/ψ mesons from H_b decays are displaced from the $p\overline{p}$ interaction vertex by typically several hundred μm as a result of the long b-quark lifetime.

Events used in this analysis are collected with both single-muon and dimuon triggers. We re-use a sample of events, prepared for an earlier study, containing a nonprompt J/ψ and a pair of oppositely charged particles consistent with coming from a displaced decay vertex. For this previously used data sample, the event selection requirement that the decay vertex be separated from the primary vertex with a significance of more than 3σ precludes extension of the current study to include the prompt production of $Z_c^+(3900)$ and $Y(4260)$. Unless indicated otherwise, we assume the hadrons to be pions and select events in the mass range $4.1 < m(J/\psi\pi^+\pi^-) < 5.0$ GeV that includes the $Y(4260)$ states and is high enough for production of the $Z_c^+(3900)$, but low enough to exclude fully reconstructed direct decays of b hadrons to final states $J/\psi h^+h^-$ where h stands for a pion, a kaon, or a proton.

Candidate events are selected by requiring a pair of oppositely charged muons and a charged particle with p_T above 1 GeV 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 [4]. To select final states originating from b-hadron decays, the $J/\psi + 1$ track vertex is required to be displaced from the $p\overline{p}$ interaction vertex in the transverse plane by at least 5σ and the transverse impact parameter [17] significance $IP/\sigma(IP)$ of the hadronic track is required to be greater than 2σ.

For accepted $J/\psi + 1$ track combinations, another track, with an opposite charge to the first track and with $p_T > 0.8$ GeV, is added to form a common $J/\psi+2$ tracks system. The second track must have an IP significance greater than 1σ and its contribution to the χ^2 of the $J/\psi + 2$ tracks vertex [18] must be less than six. The cosine of the angle in the transverse plane between the momentum vector and decay path of the $J/\psi + 2$ tracks system is required to be greater than 0.9.

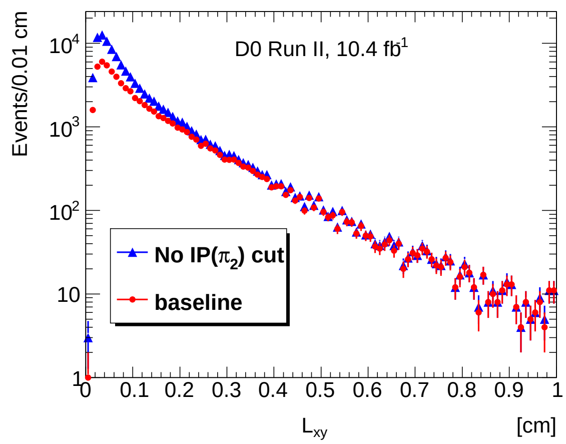

FIG. 1: The $J/\psi\pi^+\pi^-$ decay length in the transverse plane for accepted candidates in the range $4.2 < m(J/\psi\pi^+\pi^-) < 4.7$ GeV and for the case when the IP cut on the second pion is removed.

For the accepted $J/\psi + 2$ tracks combinations we calculate the $J/\psi\pi^+\pi^-$ invariant mass by assigning the pion mass to both hadronic tracks. We correct the muon momenta by constraining $m(\mu^+\mu^-)$ to the world average J/ψ meson mass [4]. The sample includes events in which the hadronic pair comes from decays $K^* \to K\pi$ or $\phi \to KK$. We remove such events by vetoing the mass combinations $0.81 < m(\pi K) < 0.97$ GeV, $0.81 < m(K\pi) < 0.97$ GeV, and $1.01 < m(KK) < 1.03$ GeV. We also veto photon conversions by removing events with $m(\pi^+\pi^-) < 0.35$ GeV. Multiple candidates per event are allowed but their rate is negligible.

The transverse decay length distribution of the $J/\psi\pi^+\pi^-$ system $L_{\rm xy}$ is shown in Fig. 1. With the average resolution of 0.0057 cm most of the prompt events would be contained at $L_{\rm xy} < 0.025$ cm. The distribution confirms that prompt background has been strongly suppressed and that the selected $J/\psi+2$ tracks combinations originate predominantly from partially reconstructed vertices of b-hadron decays.

III. FIT RESULTS

Our study is focused on the $J/\psi\pi^+$ system around the $Z_c^+(3900)$ mass. As mentioned above, the production of $Z_c^+(3900)$ may occur through a sequential process with an intermediate $Y(4260)$, e.g., $B^+ \to Y(4260)K^+$, $Y(4260) \to Z_c^+(3900)\pi^-$. To test this possibility, we

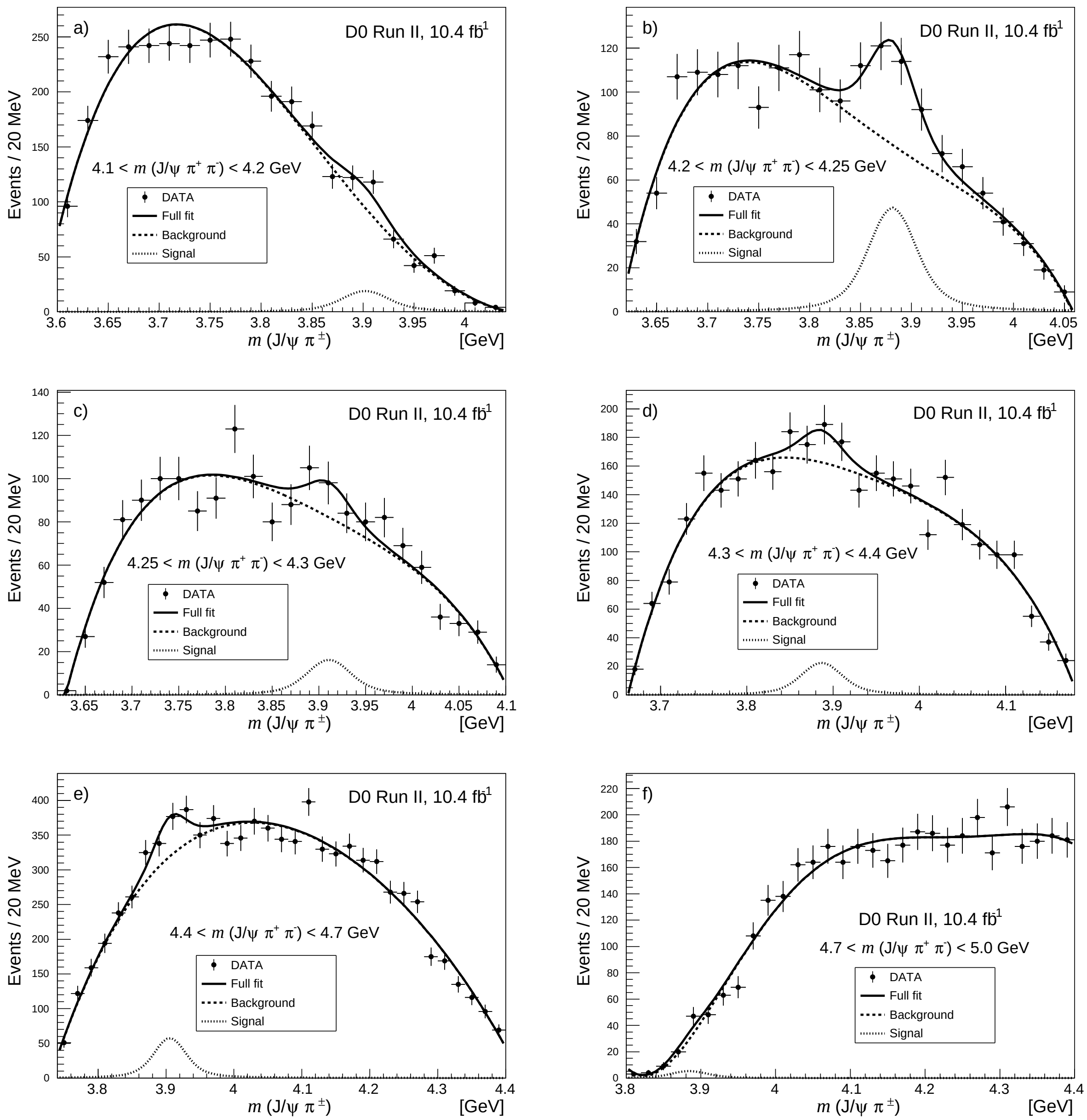

FIG. 2: The invariant mass distribution of $J/\psi\pi^+$ candidates in six ranges of $m(J/\psi\pi^+\pi^-)$ as indicated. The solid lines show the results of the fit. The dashed lines show the combinatorial background and the dotted lines indicate the signal contributions.

select events in the mass range $4.1 < m(J/\psi\pi^+\pi^-) < 5.0$ GeV. We construct the mass $m(J/\psi\pi^+)$ by combining the J/ψ with either of the two pion candidates and, following Refs. [1] and [2], selecting the higher-mass combination. We fit the resulting $m(J/\psi\pi^+)$ distribution to the sum of a resonant signal represented by a relativistic S-wave Breit-Wigner function with a width fixed to $\Gamma = 28.2$ MeV [4] smeared with the D0 mass resolution of $\sigma = 17 \pm 2$ MeV and a mass that is allowed to vary freely, and an incoherent background. Background is mainly due to b-hadron decays to a J/ψ, with a random hadron coming from the same multi-body decay. For the background shape we use Chebyshev polynomials of the first kind. The fitting range is chosen so as to obtain an acceptable fit while avoiding regions where the background function becomes negative.

We perform binned maximum-likelihood fits to the $J/\psi\pi^+$ mass distribution in six $J/\psi\pi^+\pi^-$ mass intervals of varying size, chosen to align with the $Y(4260)$ states. These intervals, (4.1$-$4.2), (4.2$-$4.25), (4.25$-$4.3), (4.3$-$4.4), (4.4$-$4.7), and (4.7$-$5.0) GeV, contain roughly equal numbers of signal plus background events. In each interval we represent the background contribution by a Chebyshev polynomial whose order

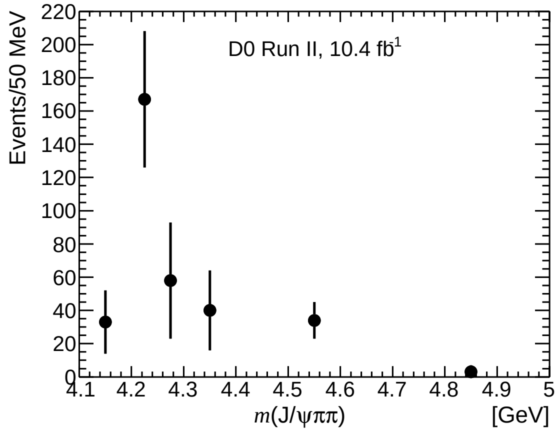

FIG. 3: The $Z_c^+(3900)$ signal yield per 50 MeV for the six intervals of $m(J/\psi\pi^+\pi^-)$: 4.1−4.2, 4.2−4.25, 4.25−4.3, 4.3−4.4, 4.4−4.7, and 4.7−5.0 GeV. The points are placed at the bin centers.

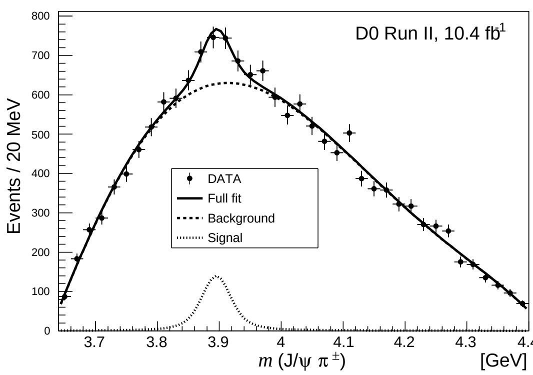

FIG. 4: The invariant mass distribution of $J/\psi\pi^+$ candidates in the range $4.2 < m(J/\psi\pi^+\pi^-) < 4.7$ GeV. The solid line shows the result of the fit. The dashed line show the combinatorial background parametrized with the fifth-order Chebyshev polynomial and the dotted line indicates the signal contribution.

is chosen to minimize the Aikake Information Criterion (AIC) [19]. For a fit with p free parameters to a distribution in n bins the AIC is defined as $AIC = \chi^2 + 2p + 2p(p+1)/(n-p-1)$. We use fourth-order polynomials in all bins except (4.7−5.0) GeV where we use a fifth-order polynomial.

As shown in Fig. 2, we see a clear enhancement near the $Z_c^+(3900)$ mass for events in the range $4.20 < m(J/\psi\pi^+\pi^-) < 4.25$ GeV, consistent with coming from the $\psi(4260)$ (recall that the $\psi(4260)$ mass is 4230 ± 8 MeV [4]), and smaller enhancements in other ranges between 4.2 GeV and 4.7 GeV. We find no significant signal in the bin $4.1 < m(J/\psi\pi^+\pi^-) < 4.2$ GeV or $4.7 < m(J/\psi\pi^+\pi^-) < 5.0$ GeV. The resulting differential distribution of the signal yield is shown in Fig. 3. We note the presence of a $Z_c^+(3900)$ signal with a statistical significance greater than 3σ in the $4.4 < m(J/\psi\pi^+\pi^-) < 4.7$ GeV region above the $\psi(4360)$ signal [3], indicating some contribution from a non-$Y(4260)$ $J/\psi\pi^+\pi^-$ combination. The measured signal masses are consistent with each other (with a p-value of 0.1).

We then perform a fit to the data in the mass range $4.2 < m(J/\psi\pi^+\pi^-) < 4.7$ GeV. The AIC test gives similar results using the fifth- and fourth-order polynomial as background while the χ^2 test prefers the fifth-order polynomial (p-value of 0.18 vs 0.066). The fit using the fifth-order polynomial background shown in Fig. 4 yields $N = 502 \pm 92$ (stat) signal events, $M = 3895.0 \pm 5.2$ (stat) MeV, and a statistical significance of $S = 5.6\sigma$. The fit using the fourth-order polynomial gives $N = 608 \pm 82$, $M = 3895.7 \pm 4.6$ MeV, and $S = 7.7\sigma$. The statistical significance of the signal is defined as $S = \sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\max})}$, where $\mathcal{L}_{\max}$ and $\mathcal{L}_0$ are likelihood values for the best-fit signal yield and for the signal yield fixed to zero. In the following we choose the fit using the fifth-order polynomial as the baseline. A χ^2 test of the fit quality gives the χ^2 over the number of degrees of freedom (ndf) $\chi^2/\text{ndf} = 36.8/30$.

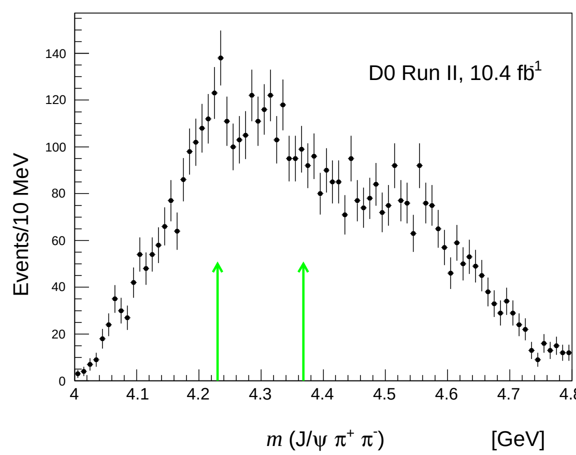

FIG. 5: The invariant mass $J/\psi\pi^+\pi^-$ distribution for events near the $Z_c^+(3900)$ peak, $3.83 < m(J/\psi\pi) < 3.95$ GeV. The arrows indicate the masses of $\psi(4260)$ and $\psi(4360)$.

The distribution of $m(J/\psi\pi^+\pi^-)$ for events in the $Z_c^+(3900)$ peak range, defined as $3.83 < m(J/\psi\pi^+) < 3.95$ GeV, is shown in Fig. 5. There is an enhancement corresponding to $\psi(4260)$, also seen in Fig. 3, supporting the assumption that the decay of this neutral state is a contributing source of the $Z_c^+(3900)$ signal.

IV. CROSS-CHECKS

In an alternative approach, we perform a simultaneous fit to the four subsamples of the $m(J/\psi\pi^+\pi^-)$ in the 4.2−4.7 GeV range, allowing for separate free parameters of the fourth-order Chebyshev polynomial background and free signal yields but using a common free signal mass parameter. The fitted mass is 3889.6 ± 9.8 MeV, and the number of signal events is 444 ± 149, in agreement with the baseline result, and the quality of the fit is $\chi^2/\mathrm{ndf} = 53.3/81$.

We divide the sample into two ranges of the p_T of the pion from the $Z_c^+(3900)$ decay, $p_T(\pi) < 1.5$ GeV and $p_T(\pi) > 1.5$ GeV, and fit them separately. The fitted yields are 202 ± 51 and 319 ± 72 events and the masses are 3906.6 ± 10.0 MeV and 3896.1 ± 6.7 MeV, respectively.

Fits to the three $Z_c^+(3900)$ pseudorapidity ranges $|\eta| < 0.9$, $0.9 < |\eta| < 1.3$ and $1.3 < |\eta| < 2.0$ containing similar numbers of events give the signal yields of 195 ± 57, 155 ± 52, and 163 ± 48 and mass values of 3902.8 ± 7.3 MeV, 3906.4 ± 11.2, and 3887.8 ± 8.8 MeV. The signal to background ratios in the three $|\eta|$ regions are consistent with being the same, as would be expected from the fact that both signal and the dominant backgrounds arise from the decays of b hadrons.

To test the sensitivity of the results to the fit quality requirements, we define a control sample by selecting events with the fit quality of the $J/\psi + 1$ track vertex in the range $10 < \chi^2 < 20$. The fitted yield in the control sample is 10 ± 25 events, consistent with no signal.

Due to the limited muon momentum resolution, our selection of the J/ψ mass window passes some non-J/ψ dimuons while rejecting a fraction of genuine J/ψ's. The non-J/ψ background includes sequential decays $b \to c\mu X$, $c \to s\mu X$, and semileptonic b-hadron decays accompanied by a muon track originating from a charged pion or kaon decay in flight. We estimate the fraction of non-J/ψ background in our baseline sample at 9% and the dimuon mass cut efficiency for J/ψ at 94%. A fit to the $m(J/\psi\pi^+)$ spectrum when the J/ψ mass window is expanded to 2.8–3.4 GeV yields 530 ± 100 $Z_c^+(3900)$ signal events, 6% more than in the baseline analysis, in agreement with expectation.

V. SYSTEMATIC UNCERTAINTIES

There are several sources of systematic uncertainties in the baseline measurement of the $Z_c^+(3900)$ mass and yield, summarized in Table I.

TABLE I: Systematic uncertainties for the $Z_c^+(3900)$ mass and yield measurements.

Systematic uncertainty	Mass (MeV)	Yield
Mass calibration	$^{+3}_{-0}$	<1
Mass resolution	< 0.1	±27
Background shape	±0.4	±53
Bin size	±1.1	±9
Signal model	±2.4	±3
Natural width variation	<0.1	±23
Total (sum in quadrature)	$-2.7, +4.0$	±64

We assign an asymmetric uncertainty of $(+3, -0)$ MeV to the $J/\psi\pi^+$ mass scale based on studies of the D0 measured mass shift compared to world-average values in several final states with a similar topology [20].

The estimate of the mass resolution is based on the dependence of the measured and simulated resolution of the released kinetic energy for decays with a similar topology. The variation of the assumed resolution by its uncertainty of ±2 MeV has a negligible effect on the measured $Z_c^+(3900)$ mass. We assign an uncertainty on the signal yield equal to half of the difference between the two extreme results.

We assess the effects of the fitting procedure and background shape as half of the difference of the results obtained with the fourth- and fifth-order Chebyshev polynomial. Similarly, we estimate the effect of bin size by comparing the results for 20 MeV and 10 MeV bins.

We assign the uncertainty in the signal model as half of the difference in the results obtained with the relativistic Breit-Wigner shapes with and without the energy dependence of the natural width.

In the analysis we set the natural width equal to the world-average value. We assign the uncertainty in the mass and yield measurement by repeating the fits with the width altered by ±2.6 MeV [4].

VI. RESULTS

A. The $Z_c(3900)$ signal yield as a function of $m(J/\psi\pi^+\pi^-)$

Table II lists the $Z_c^+(3900)$ fitted signal yields and the measured mass in the six non-overlapping intervals of the $J/\psi\pi^+\pi^-$ invariant mass between 4.1 GeV and 5.0 GeV. The $Z_c^+(3900)$ width is fixed at $\Gamma = 28.2$ MeV for these fits. The measured masses are consistent with each other and with the original results of Refs. [1] and [2], and thus we conclude that we are observing the same $Z_c^+(3900)$ state. We report the results for the range 4.2−4.7 GeV as our best measurement of the mass of the $Z_c^+(3900)$ resonance and the signal significance.

Our baseline result above allows the $Z_c^+(3900)$ mass to float but fixes its width at the world average value, and thus raises the question of whether the significance of the fit would change if the world average [4] mass were used. We have tested this by fixing the mass to $M = 3886.6$ MeV [4]. The fit gives a yield of 480 ± 91, $\chi^2/\mathrm{ndf} = 39/31$, and significance $S = 5.4\sigma$ that differ very little from our baseline result. A slightly better fit is obtained with the mass and width fixed to the PDG values [4] for just those measurements that use the final state $Z_c^{\pm,0} \to J/\psi\pi^{\pm,0}$: $M = 3893.3$ MeV and $\Gamma = 36.8$ MeV. In this case we obtain $\chi^2/\mathrm{ndf} = 35.9/31$, yield of 580 ± 104 and $S = 5.7\sigma$. We conclude that variations in the choice of Z_c^+ mass and width have only a small effect upon our conclusions.

The systematic uncertainties are taken into account in the estimate of the significance by convolving the statistical significance as a function of signal yield with a

TABLE II: $Z_c^+(3900)$ signal yields and mass measurements, fit quality, and statistical significance S in intervals of $m(J/\psi\pi^+\pi^-)$. The six measurements in non-overlapping subsamples are dominated by statistical uncertainties. There is a common asymmetric $+3, -0$ MeV mass uncertainty. The last row shows a summary result that includes statistical and systematic uncertainties.

$m(J/\psi\pi^+\pi^-)$ (GeV)	Event yield	Mass (MeV)	χ^2/ndf	S (σ)
4.1−4.2	66 ± 38	3902.2 ± 10.6	24.1/15	1.7
4.2−4.25	167 ± 41	3881.3 ± 6.1	14.6/15	4.3
4.25−4.3	58 ± 35	3910.7 ± 15.7	23.6/17	1.6
4.3−4.4	80 ± 48	3886.5 ± 13.0	26.3/19	1.8
4.4−4.7	206 ± 65	3905.7 ± 9.5	35.8/26	3.2
4.7−5.0	19 ± 25	3884.7 ± 26.6	21/22	0.4
4.2−4.7	$502 \pm 92 \pm 64$	$3895.0 \pm 5.2^{+4.0}_{-2.7}$	36.8/30	4.6

Gaussian function with a mean of 500 and width equal to the systematic uncertainty on the yield. Adding the systematic uncertainty changes the significance for the baseline fit from 5.6σ to 4.6σ.

B. Normalization to $B_d^0 \to J/\psi K^*$

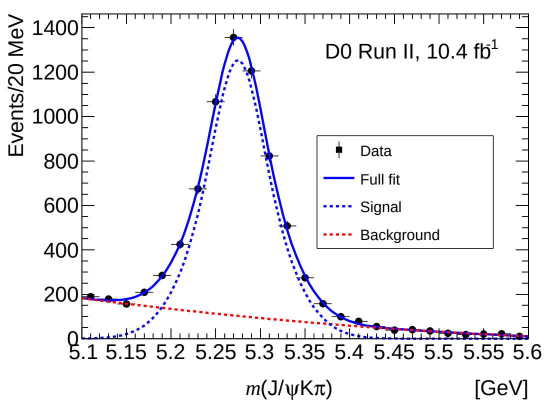

FIG. 6: The invariant mass distribution of accepted J/ψ + 2 track candidates under the $J/\psi K^\pm\pi^\mp$ hypothesis with a requirement that (at least) one of the $K^\pm\pi^\mp$ combinations is within the K^* window (see text).

We normalize the $Z_c^+(3900) \to J/\psi\pi^+$ signal in the parent $J/\psi\pi^+\pi^-$ mass range of 4.2−4.7 GeV to the number of events of the decay $B_d^0 \to J/\psi K^*$. The latter are required to satisfy the same stringent kinematic and quality cuts as applied to the $J/\psi\pi^+\pi^-$ except that the K^* veto is replaced with the requirement that at least one $K^\pm\pi^\mp$ pair is within the K^* mass window. If two such pairs are present we select the $K^\pm\pi^\mp$ combination with mass closer to the K^* mass. We fit the distribution to a sum of a signal described by a double Gaussian function and a quadratic polynomial background. We find the number of B_d^0 decays $N(B_d^0) = 5900 \pm 116$ (stat) and obtain the ratio of the observed number of events $502/5900 = 0.085 \pm 0.019$ where the uncertainty is a sum in quadrature of the statistical and systematic uncertainties (0.016 and 0.011, respectively). Since the two processes have the same topology and the kinematic restrictions assure a uniform track finding efficiency, we assume that the efficiency factors cancel out in the ratio. The invariant mass $J/\psi K\pi$ distribution and the fit results are shown in Fig. 6.

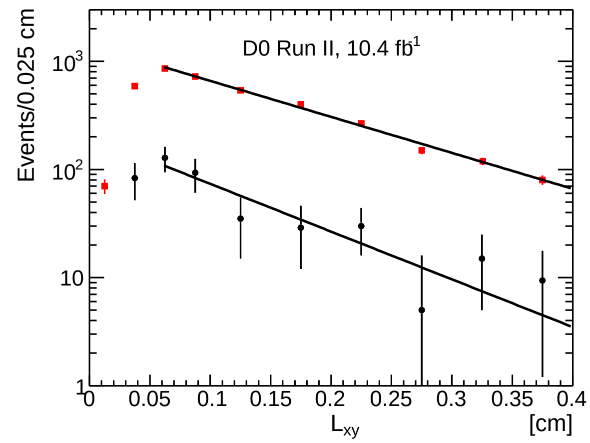

FIG. 7: The decay length distribution of $Z_c^+(3900)$ events (black circles) and $B_d^0 \to J/\psi K^*$ events (red squares).

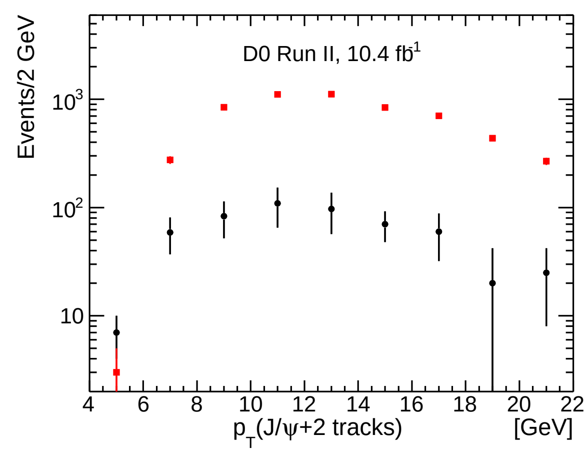

FIG. 8: The p_T of the $J/\psi\pi^+\pi^-$ parents of the $Z_c^+(3900)$ events (black circles) and of the B_d^0 in the $J/\psi K^*$ channel (red squares).

Figure 7 shows a comparison of the decay length distribution of the $Z_c^+(3900)$ signal events, obtained by fitting $m(J/\psi\pi^+)$ in bins of the decay length, and that of the B_d^0 signal from the $B_d^0 \to J/\psi K^*$ decay. The mean lifetime of a b-hadron admixture averaged over all b species is similar to the B_d^0 lifetime, and the momentum distributions are similar. We therefore expect the decay length distribution of the two states to show general agreement. The distributions show exponential behavior $N \sim e^{-L_{\rm xy}/\Lambda}$ in the region above $L_{\rm xy} = 0.025$ cm where the efficiency is constant, with consistent coefficients of $\Lambda = 0.098 \pm 0.030$ and 0.130 ± 0.004 cm for the $Z_c^+(3900)$ and B_d^0, respectively, supporting the claim that the signal events come from b-hadron decays. The turnover at low $L_{\rm xy}$ occurs because of some events whose $L_{\rm xy}$ resolution is small, thus allowing them to pass the 5σ significance cut for lower $L_{\rm xy}$. Figure 8 compares the p_T distribution of the $J/\psi\pi^+\pi^-$ system in $Z_c^+(3900)$ events and the p_T distribution of B_d^0 in the $J/\psi K^*$ channel. The two distributions are similar, as expected for decay products of b hadrons. The average p_T of the former (12.5 GeV) is lower than the average p_T of B_d^0 (13.6 GeV) because the $J/\psi\pi^+\pi^-$ system carries less than 100% of the parent b hadron's momentum.

C. Search for the $Z_c^+(3900)$ in the decay $\bar{B}_d^0 \to J/\psi\pi^+K^-$

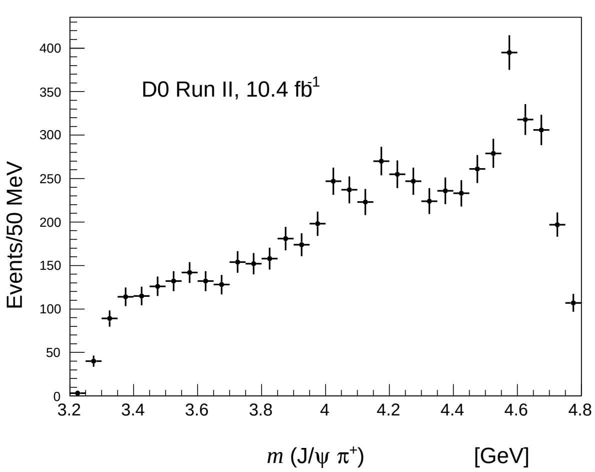

FIG. 9: Background-subtracted $J/\psi\pi^+$ invariant mass distribution in the decay $\bar{B}_d^0 \to J/\psi\pi^+K^-$ with the K^* mass range removed.

As mentioned in Section I, the Belle Collaboration [7] did not see a significant signal of the $Z_c^+(3900)$ in the decay $\bar{B}^0 \to J/\psi\pi^+K^-$. Their amplitude analysis confirmed the $Z_c(4430)$ and led to an observation of a new resonance, $Z_c(4200)$. We have studied the $J/\psi\pi^+$ mass in events consistent with this decay, excluding the events consistent with the decay $\bar{B}_d^0 \to J/\psi K^*$. The sideband-subtracted mass distribution is shown in Fig. 9. There is no indication of the $Z_c^+(3900)$ and the spectrum above 4 GeV is consistent with the resonance structures observed in Figure 8 of Ref. [7].

VII. SUMMARY AND CONCLUSIONS

In summary, our study of the semi-inclusive decays of b hadrons $H_b \to J/\psi\pi^+\pi^-$ + anything reveals a $Z_c^\pm(3900)$ signal that is correlated with the $J/\psi\pi^+\pi^-$ system in the invariant mass range 4.2−4.7 GeV. The process includes the sequential decays $H_b \to Y(4260)$ + anything, $Y(4260) \to Z_c^\pm(3900)\pi^\mp$, $Z_c^\pm(3900) \to J/\psi\pi^\pm$, where $Y(4260)$ stands for the combined signal of two neutral charmonium-like states $\psi(4260)$ and $\psi(4360)$ [4]. There is an indication that some events arise from H_b decays to an intermediate $J/\psi\pi^+\pi^-$ combination with mass above that of the $\psi(4360)$, with subsequent decay to $Z_c^\pm(3900)\pi^\mp$. The measured mass of the $Z_c^\pm(3900)$ resonance is $M = 3895.0 \pm 5.2\,({\rm stat})^{+4.0}_{-2.7}\,({\rm syst})$ MeV. The significance, including systematic uncertainties, is 4.6 standard deviations. We confirm the conclusion of Ref. [7] that there is no significant production of the $Z_c^+(3900)$ in the decay $\bar{B}_d^0 \to J/\psi\pi^+K^-$. With the present data sample we have no sensitivity to prompt production of the $Z_c^\pm(3900)$ in $p\bar{p}$ collisions.

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