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Precision Measurement of the X(3872) Mass in J/ psi pi + pi - Decays

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Citation: CDF Collaboration et al. "Precision Measurement of the X(3872) Mass in J/ psi pi + pi - Decays." Physical Review Letters 103.15 (2009): 152001. © 2009 The American Physical Society

As Published: http://dx.doi.org/10.1103/PhysRevLett.103.152001

Publisher: American Physical Society

Persistent URL: http://hdl.handle.net/1721.1/51893

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

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Precision Measurement of the $X(3872)$ Mass in $J/\psi\pi^+\pi^-$ Decays

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0031-9007/09/103(15)/152001(8)

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(Received 29 June 2009; published 5 October 2009)

We present an analysis of the mass of the $X(3872)$ reconstructed via its decay to $J/\psi\pi^+\pi^-$ using 2.4 fb^{-1} of integrated luminosity from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, collected with the CDF II detector at the Fermilab Tevatron. The possible existence of two nearby mass states is investigated. Within the limits of our experimental resolution the data are consistent with a single state, and having no evidence for two states we set upper limits on the mass difference between two hypothetical states for different assumed ratios of contributions to the observed peak. For equal contributions, the 95% confidence level upper limit on the mass difference is 3.6 MeV/c^2. Under the single-state model the $X(3872)$ mass is measured to be $3871.61 \pm 0.16(\text{stat}) \pm 0.19(\text{syst})\ \text{MeV}/c^2$, which is the most precise determination to date.

DOI: 10.1103/PhysRevLett.103.152001 PACS numbers: 14.40.Gx, 12.39.Mk, 13.25.Gv

The discovery of the $X(3872)$ [1,2] and many additional unexpected states [3] has revived general interest in spectroscopy in the charmonium mass region. Initial attempts to explain the $X(3872)$ as a conventional bound state of a c quark and an anti–c quark have shortcomings [4] which triggered the development of unconventional explanations. Two popular models are a molecular state composed of D^0 and $\bar{D}^{*0}$ mesons [5,6], and a four-quark state [7].

In an effort to resolve the nature of $X(3872)$, several of its properties have been measured. The first determinations of its mass [1,2,8,9] resulted in values very close to the $D^0\bar{D}^{*0}$ mass threshold. The observed width in these measurements was compatible with zero. Studies of the $X(3872)$ production properties in $p\bar{p}$ collisions [8,10] suggest that the production mechanisms are similar to those for the $\psi(2S)$ charmonium state. Several measurements constrained the quantum numbers spin (J), parity (P), and charge-conjugation parity (C) of the $X(3872)$. These include evidence for the decay modes $X(3872) \rightarrow J/\psi\gamma$, $J/\psi\omega$, and $\psi(2S)\gamma$ [11], and a measurement of the mass distribution of the dipions from the $X(3872) \rightarrow J/\psi\pi^+\pi^-$ decay [12]. These measurements indicate an even C parity. A subsequent angular analysis constrained the quantum numbers to only two possibilities, $J^{PC} = 1^{++}$ or 2^{-+} [13]. A possible further decay mode of the $X(3872)$ was identified as a peak near threshold in the $D^0\bar{D}^0\pi^0$ invariant mass spectrum [14] with a mean mass more than 3 MeV/c^2 above measurements in the $J/\psi\pi^+\pi^-$ mode. Despite efforts on both the experimental and theoretical sides, the nature of the $X(3872)$ still remains an unresolved puzzle.

A measurement of the $X(3872)$ mass with increased precision can provide crucial information for understanding its nature. Under the hypothesis of a molecular state the mass of the $X(3872)$ has to be lower than the sum of the D^0 and $\bar{D}^{*0}$ masses. The four-quark state hypothesis predicts the existence of two distinct particles that differ by the light-quark content bound to the $c\bar{c}$ quarks. These two particles should have slightly different masses, and the model of Maiani *et al.* [7] predicts a mass difference at the level of $8 \pm 3\ \text{MeV}/c^2$. Recent measurements of the difference between the $X(3872)$ mass in $B^+ \rightarrow X(3872)K^+$ and $B^0 \rightarrow X(3872)K^0$ decays [15,16] disfavor this model under the hypothesis that one state is dominantly produced in B^+ decays and the other one in B^0 decays.

In this Letter we report a study of the mass of the $X(3872)$ resonance produced in $p\bar{p}$ collisions. We consider the conjecture that the structure observed in our data is composed of two different states with distinct masses; but failing to discern any evidence for this possibility we set an upper limit on the mass difference between two hypothetical states. In light of this result we perform a precision measurement of the $X(3872)$ mass, the main result of this Letter.

The data were collected by the CDF II detector at the Fermilab Tevatron $p\bar{p}$ collider between February 2002 and August 2007, and correspond to an integrated luminosity of 2.4 fb^{-1}. The CDF II detector [17] consists of a magnetic spectrometer surrounded by electromagnetic and hadronic calorimeters and muon detectors. The tracking system is immersed in a 1.4 T axial magnetic field and is composed of a silicon microstrip detector [18] surrounded by an open-cell drift chamber (COT) [19]. It extends out to a radius of 138 cm with up to 96 position measurements in the COT, and achieves a transverse momentum resolution of $\sigma(p_T)/p_T \approx 0.15\% p_T/(\text{GeV}/c)$. We detect muons in planes of multiwire drift chambers and scintillators [20] in the pseudorapidity range $|\eta| \leq 1.0$. Events with $J/\psi \rightarrow \mu^+\mu^-$ decays are recorded using a dimuon trigger, which requires two oppositely charged COT tracks matched to muon chamber track segments. The reconstructed invariant mass of a dimuon pair is required to be between 2.7 and 4.0 GeV/c^2.

To reconstruct $X(3872)$ candidates we first build J/ψ candidates by combining pairs of oppositely charged muon candidates with a transverse momentum, p_T, larger than 1.5 GeV/c. The $X(3872)$ candidates are formed by combining J/ψ candidates in the invariant mass range from 2.95 to 3.25 GeV/c^2 with pairs of oppositely charged tracks, each with $p_T > 0.4\ \text{GeV}/c$ and assigned the pion mass. We require that all four tracks have at least 10 COT and 2 silicon hits. For the resulting $X(3872)$ candidates with $p_T > 3.5\ \text{GeV}/c$, we perform a kinematic fit in which the tracks are constrained to originate from a common vertex and the dimuon invariant mass is constrained to the world average J/ψ mass [21]. Candidates having a kinematic fit of good quality are selected in a broad invariant mass range containing, in addition to $X(3872)$ candidates, also $\psi(2S)$ candidates that decay to the same final state. The $\psi(2S)$ serves as a valuable control sample.

Several discriminating quantities are combined by a neural network into a single selection variable. The individual quantities are transformed such that linear dependences on the invariant mass are removed. The most important inputs to the neural network are the Q value of the decay, defined as $Q = m_{J/\psi\pi^+\pi^-} - m_{\pi^+\pi^-} - m_{J/\psi}$, the transverse momenta of the two pions, the quality of the kinematic fit of the $X(3872)$ candidate, and muon identification quantities. The offline muon identification is based on the matching of tracks found in the tracking system to track segments in the muon system and on the energy deposited in the calorimeter by the muon-candidates. For the training of the neural network, a background sample is extracted from data, selecting events in regions of the $J/\psi\pi^+\pi^-$ mass away from the $X(3872)$ and $\psi(2S)$ signals, mainly consisting of J/ψ particles combined with two random tracks. For the signal sample we use simulated $X(3872)$ events. In the simulation we generate a single $X(3872)$ per event using the momentum distribution of the $\psi(2S)$, which is then decayed using the EVTGEN package [22]. Each event is then passed through a detector simulation based on the GEANT3 package [23] and a trigger simulation, and is reconstructed with the same code as for real data. The simulation is in good agreement with the data as verified with several kinematic quantities. The final selection places a requirement on the neural network output and the number of candidates per event. Using wrong-sign candidates, where the two pion candidates have the same charge, we verify that the selection does not create an artificial excess in the mass spectrum. The invariant mass distribution of the selected candidates in the $X(3872)$ mass region is shown in Fig. 1. The sample contains about 6000 $X(3872)$ signal events.

Before we perform a mass measurement, we test whether the signal is consistent with a single state or we have evidence for more than one state. In the test we perform a binned maximum-likelihood fit to the mass distribution in data, where we describe the combinatorial background by a second-order polynomial, and the signal by a nonrelativistic Breit-Wigner function convolved with a resolution function determined from simulated events and parametrized by the sum of two Gaussians. The core Gaussian, with a width of 3.2 MeV$/c^2$, accounts for two thirds of the resolution function; the second Gaussian has about twice the width. In the fit we fix the width of the Breit-Wigner function to $\Gamma = 1.34$ MeV$/c^2$, our average of the widths measured in $J/\psi\pi^+\pi^-$ decays [1,15]. The uncertainty on Γ of 0.64 MeV$/c^2$ is taken into account in the hypothesis test described below. As a test statistic we introduce a factor t that scales the intrinsic and resolution widths of the signal shape. The value of t determined by the fit to the data is then compared to the distribution of t from an ensemble of simulated experiments that assume a single state. Based on this comparison the consistency of the data with the single-state hypothesis is evaluated. The pseudoexperiments are generated using the same fit model as in data. As several quantities are known only with limited precision, we vary those in the sample generation according to their uncertainties. The varied parameters include background shape parameters, the number of signal and background events, the width of the Breit-Wigner function, and the overall width of the resolution function. From a comparison of the $\psi(2S)$ signal in the data to that of simulated events we observe that the simulation underestimates the resolution by about 5%. The samples were generated with a resolution corrected for this discrepancy.

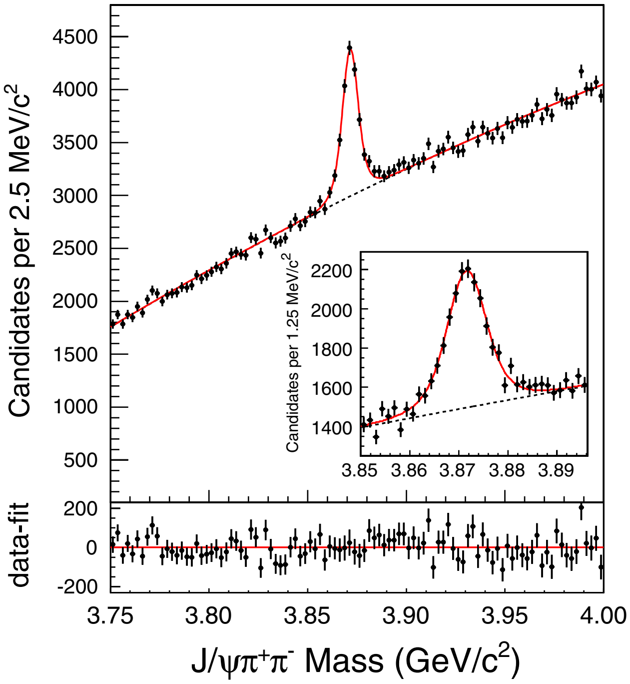

FIG. 1 (color online). Invariant mass distribution of the $X(3872)$ candidates. The points show the data distribution, the full line is the projection of the unbinned maximum-likelihood fit, and the dashed line corresponds to the background part of the fit. The inset shows an enlargement of the region around the $X(3872)$ peak. Residuals of the data with respect to the fit are displayed below the mass plot.

From data we obtain a width scale parameter value of $t = 1.052$. In Fig. 2 we show a comparison of the fitted scale parameter to the distribution obtained from simulated experiments assuming a single state. We conclude that the data are fully consistent with a single state. In the absence of evidence for two distinct states we set an upper limit on the possible mass difference between two hypothetical states. As a test statistic we use the width scale t, which is compared to expectations from samples simulated with different mass splittings. We assume that both states have the same mass shape and do not interfere. We derive upper limits as a function of the fraction f_1 of the lower lying state to the total observed signal. The resulting 90% and 95% C.L. upper limits are shown in Fig. 3. For an equal mixture of the two contributing states, the limits are $\Delta m < 3.2$ MeV$/c^2$ and $\Delta m < 3.6$ MeV$/c^2$ at 90% and 95% confidence levels, respectively. This result is complementary to other measurements [15,16] in that it does not rely on assumptions about the production of the two hypothetical states in B^+ versus B^0 decays, but depends on f_1.

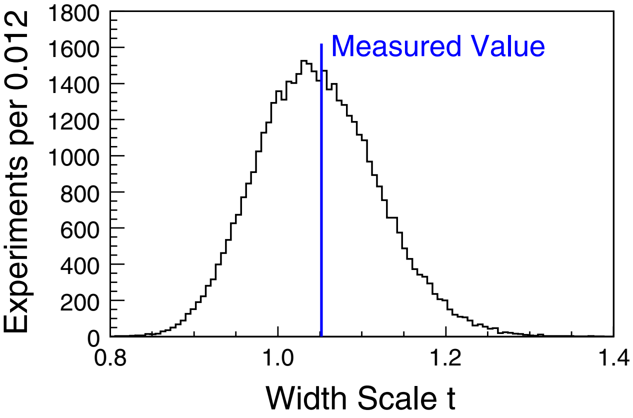

FIG. 2 (color online). Distribution of the width scale t for generated experiments using the single-state hypothesis (histogram). Also shown is the measured value from data (vertical line).

Lacking any indication of dual states we proceed to extract the mass of the $X(3872)$ by performing an unbinned maximum-likelihood fit using the same fit model as used in the previous two-state test. In this fit we fix the intrinsic width to $\Gamma = 1.34\ \mathrm{MeV}/c^2$ and the resolution parameters to their expected values. Free parameters in the fit are the mass of the $X(3872)$, the fraction of signal events in the sample, a resolution scale factor, and two parameters determining the background shape.

To check the absolute mass scale we use the nearby $\psi(2S)$ signal in the same $J/\psi\pi^+\pi^-$ invariant mass spectrum. We use the identical fit model as for the $X(3872)$, with the exception that the signal shape parameters are adjusted to the world average value of $\Gamma = 0.337\ \mathrm{MeV}/c^2$ [21] for the intrinsic width, and that resolution parameters are determined from simulated $\psi(2S)$ events. The fit yields $m_{\psi(2S)} = 3686.03 \pm 0.02(\mathrm{stat})\ \mathrm{MeV}/c^2$. While this value is consistent with the world average $\psi(2S)$ mass of $3686.09 \pm 0.03\ \mathrm{MeV}/c^2$ [21], we use the 60 keV/c^2 difference between our measurement and the world average value as an estimate of a possible uncertainty due to uncertainties both on our measurement and on the world average value.

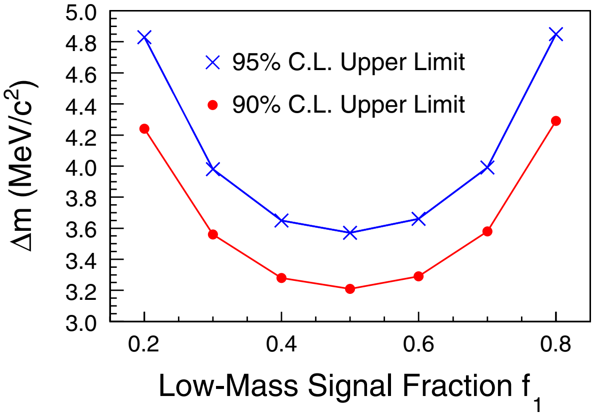

FIG. 3 (color online). The upper limit on the mass difference Δm between two states as a function of the fraction f_1 of the yield of the lower mass state.

Since a possible miscalibration of the momentum scale would show up as a dependence of the measured mass on momentum, we measure the $\psi(2S)$ mass as a function of several kinematic variables. We find that any tested dependence has an effect below 0.1 MeV/c^2, which is taken as an additional measure of the systematic uncertainty. This uncertainty is summed in quadrature with the systematic uncertainty on the absolute mass scale derived above. To translate the estimation of the mass-scale uncertainty from the $\psi(2S)$ to the $X(3872)$ we scale the sum by a factor of 1.6 that is modeled by a linear dependence on the mass with respect to the $J/\psi\pi^+\pi^-$ threshold. This yields a total systematic uncertainty of 0.19 MeV/c^2 attributed to the momentum scale.

To estimate the effect due to the uncertainties in the fit model, we refit the data using alternative models. These include the use of a linear function instead of a second-order polynomial for the background description, a single Gaussian function instead of a nonrelativistic Breit-Wigner function convolved with double Gaussian resolution function for the signal description, and fixing the natural width Γ to zero or to twice the nominal value. We also perform a fit in a mass window reduced by 40%. All of these modifications have a negligible effect on the fitted mass, below 20 keV/c^2, and therefore we do not assign any systematic uncertainty to the measurement due to the fit model. Because the observed decays to $D^0\bar{D}^{*0}$ may stem from a different particle we assume that the mass line shape is not distorted by them. If this were the case, as discussed in Ref. [24], it would be expected to increase the measured mass by about 150 keV/c^2.

The final mass measurement for the $X(3872)$ is $3871.61 \pm 0.16(\mathrm{stat}) \pm 0.19(\mathrm{syst})\ \mathrm{MeV}/c^2$. The measured value is in good agreement with the world average [21] and the more precise average of measurements in the $J/\psi\pi^+\pi^-$ channel including the preliminary Belle measurement [16]. It is the most precise single measurement to date and improves the precision of the latter average by about a factor of 1.5.

Our measurement is below the $D^0\bar{D}^{*0}$ mass threshold of $3871.80 \pm 0.35\ \mathrm{MeV}/c^2$ [21] by $0.19 \pm 0.43\ \mathrm{MeV}/c^2$. This implies that the interpretation of the $X(3872)$ as $D^0\bar{D}^{*0}$ molecule is still possible, although the current precision does not preclude an $X(3872)$ mass above the $D^0\bar{D}^{*0}$ mass threshold. A future increase in precision of this comparison will therefore require improvements in the precision of the D^0 and D^{*0} masses. Concerning the four-quark hypothesis, our mass splitting upper limits for two hypothetical states with relative fractions between 0.2 and 0.8 exclude the range of $8 \pm 3\ \mathrm{MeV}/c^2$ predicted in Ref. [7].

In summary, we present a new measurement of the $X(3872)$ mass using its decay to $J/\psi\pi^+\pi^-$. Our measured value of $3871.61 \pm 0.16(\mathrm{stat}) \pm 0.19(\mathrm{syst})\ \mathrm{MeV}/c^2$ supersedes that of Ref. [2], and is more than 2 times more precise than the best single measurement so far. In addition, we derive upper limits on the mass difference for the hypothesis of two $X(3872)$ states, which are predicted by some four-quark scenarios, as a function of their relative contribution to the observed signal. For an equal mixture of the two possible states, the limit is $\Delta m < 3.6\ \mathrm{MeV}/c^2$ at 95% confidence level.

We thank E. Braaten for useful discussions. We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A. P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Science and Technology Facilities Council and the Royal Society, U.K.; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

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