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Measurement of the Dipion Mass Spectrum in $X(3872) \to J/\psi\,\pi^+\pi^-$ Decays

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We measure the dipion mass spectrum in $X(3872) \to J/\psi\,\pi^+\pi^-$ decays using 360 pb^{-1} of $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV collected with the CDF II detector. The spectrum is fit with predictions for odd C-parity ($^3S_1$, $^1P_1$, and ^3D_J) charmonia decaying to $J/\psi\,\pi^+\pi^-$, as well as even C-parity states in which the pions are from ρ^0 decay. The latter case also encompasses exotic interpretations, such as a $D^0\overline{D}^{*0}$ molecule. Only the $^3S_1$ and $J/\psi\,\rho$ hypotheses are compatible with our data. Since $^3S_1$ is untenable on other grounds, decay via $J/\psi\,\rho$ is favored, which implies $C = +1$ for the $X(3872)$. Models for different J/ψ-ρ angular momenta L are considered. Flexibility in the models, especially the introduction of ρ-ω interference, enable good descriptions of our data for both $L = 0$ and 1.

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The charmonium-like $X(3872)$ stands as a major spectroscopic puzzle. Its mass [1, 2, 3, 4] and what is known of its decays make assignments to the normal spectrum of $c\bar{c}$ states problematic [5, 6]. Its remarkable proximity to the $D^0\overline{D}^{*0}$ mass—indistinguishable within uncertainties—has fueled speculations that it is a loosely bound deuteron-like $D^0\overline{D}^{*0}$ "molecule", *i.e.* a $(u\bar{c})$-$(c\bar{u})$ system [1, 7]. Although a molecule is prominent among exotic interpretations, others have been proffered [8]. Non-$q\bar{q}$ mesons are allowed within QCD, but an unequivocal example remains elusive. Even as a conventional meson, the $X(3872)$ remains interesting as the $c\bar{c}$ spectrum

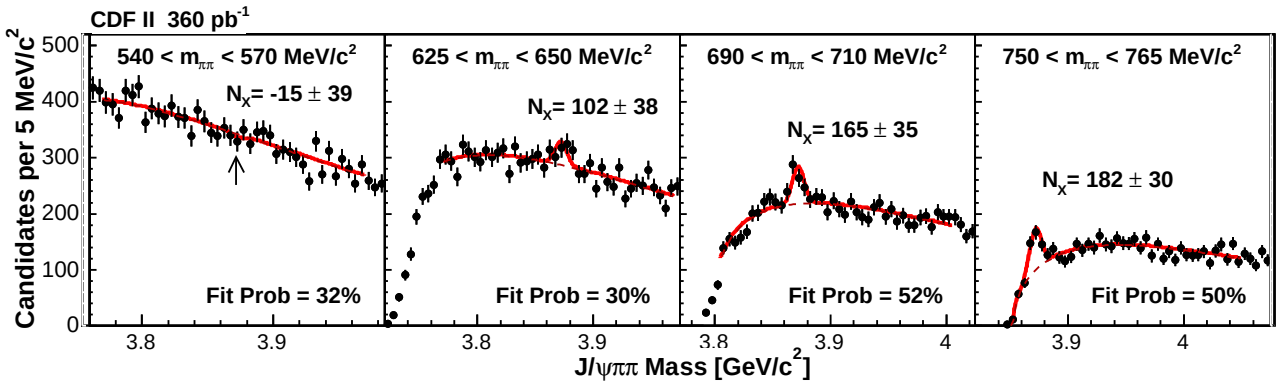

FIG. 1: Examples of "slices" in dipion mass $m_{\pi\pi}$ of the $J/\psi\,\pi^+\pi^-$ mass distributions, and their $X(3872)$ fits. The raw yields N_X prior to efficiency corrections are quoted, and the arrow in the first panel marks the $X(3872)$ mass.

above the $\psi(3770)$ is not well known.

Insight into the $X(3872)$ is offered by the dipion mass spectrum in $X \to J/\psi\,\pi^+\pi^-$. Belle observed a preference for high $\pi\pi$-masses, contrary to expectations for triplet-D $c\bar{c}$-states [9]—the naïve interpretation. Belle noted that $X \to J/\psi\,\rho^0$ decay—isospin violating for charmonium—produces high masses, and thus may be a hint for a $D^0\overline{D}^{*0}$ molecule. Dipion spectra have been published [1, 10]; and a preliminary analysis partially based on $\pi\pi$ masses argues for a $J^{PC} = 1^{++}$ assignment [6], consistent with that expected for a $D^0\overline{D}^{*0}$ molecule.

At the Tevatron, large $X(3872)$ samples are available, albeit with high backgrounds. Previously, we have measured the X mass and confirmed the propensity for high $\pi\pi$ masses [2]. We also have made a preliminary measurement of the inclusive production fraction arising from b hadrons [11]. Here we measure the $\pi\pi$ mass spectrum.

We use a sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV collected with the Collider Detector at Fermilab (CDF II) between February 2002 and August 2004. The detector is described in detail elsewhere [12], and only the most relevant components for this analysis are summarized here. The central tracking system is immersed in a 1.4 T solenoidal magnetic field for the measurement of charged particle momenta p_T transverse to the beamline. It is composed of six layers of silicon-strip detectors (L00 [13] and SVX [14]) surrounded by an open-cell drift chamber called the Central Outer Tracker (COT) [15]. The active volume of the COT is a 3.1 m long cylinder with 8 superlayers of 12 wires each. The outermost detection system is planes of multi-layer drift chambers for detecting muons [16]. The Central Muon system (CMU) covers $|\eta| \leq 0.6$, where pseudorapidity $\eta \equiv -\ln[\tan(\theta/2)]$ and θ is the angle of the particle with respect to the direction of the proton beam. Additional chambers (CMX) extend the muon coverage to $|\eta| = 1.0$.

A dimuon trigger is used to obtain a $J/\psi \to \mu^+\mu^-$ sample. At Level 1 of a three-level trigger system, the eXtremely Fast Tracker (XFT) [17] uses COT information to select tracks based on p_T. XFT tracks with $p_T \geq 1.5$ (2.0) GeV/c are extrapolated to the CMU (CMX) chambers and compared with the positions of muon-chamber tracks. The event passes Level 1 if two or more XFT tracks are matched to muon tracks. Opposite-charge and opening-angle cuts are imposed at Level 2. At Level 3, full COT tracking information is used to reconstruct $\mu^+\mu^-$ candidates. Events with candidates from 2.7 to 4.0 GeV/c^2 in mass are recorded for further analysis.

This analysis [18] is based on an integrated luminosity of 360 pb^{-1}. Candidate selection follows Ref. [2] with two exceptions (see below). After constraining $\mu^+\mu^-$ candidates to a common vertex, the dimuon mass must be within 60 MeV/c^2 ($\sim$ 4 standard deviations) of the J/ψ mass [19]. This one degree-of-freedom (DoF) fit must have $\chi^2 < 15$. Pairs of charged tracks, each with $p_T \geq 0.4$ GeV/c and assumed to be pions, are fit with the $\mu^+\mu^-$ tracks to a common vertex. In this fit, the dimuon mass is constrained to the J/ψ mass, and we demand $\chi^2 < 25$ (6 DoF). We reduce combinatorial backgrounds by requiring $p_T(J/\psi) \geq 4$ GeV/c and $\Delta R \leq 0.7$ for both pions, where $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$, $\Delta\phi$ is the difference in azimuthal angle between the $J/\psi\,\pi\pi$ system and the pion, and $\Delta\eta$ is the difference in pseudorapidity. The mass range for the sample includes both $X(3872)$ and $\psi(2S)$ signals [2]; the latter is used as a control sample.

We depart from Ref. [2] by dropping a cut on the number of candidates allowed per event. This removes a possible bias and improves the X signal at high $\pi\pi$ masses. We also add fiducial criteria: $p_T(J/\psi\,\pi\pi) > 6\,\mathrm{GeV}/c$ and $|\eta(J/\psi\,\pi\pi)| < 0.6$. This eliminates the region of rapidly changing efficiency and sacrifices $\sim 25\%$ of the $\psi(2S)$ yield, leaving 11500 ± 220 $\psi(2S)$ mesons. We have 1260 ± 130 $X(3872)$ candidates for $m_{\pi\pi} > 500\,\mathrm{MeV}/c^2$ [2].

To extract $dN/dm_{\pi\pi}$ spectra, we divide the sample into "slices" of $m_{\pi\pi}$ and fit each $J/\psi\,\pi^+\pi^-$ mass distribution for the signal per slice. The $J/\psi\,\pi^+\pi^-$ mass fits use a Gaussian for the $X(3872)$ signal and an exponential times power law for the background. We also fit the

$\psi(2S)$ control signal in the same way, but use two Gaussians for the better defined shape arising from the larger $\psi(2S)$ signal. As slices may have small signals—or none at all—we inhibit the fit from latching onto fluctuations by fixing the position and width of the signal to values from full-sample fits. Sample slices are shown in Fig. 1.

The fitted $dN/dm_{\pi\pi}$ yield is corrected for detector and selection efficiencies determined by Monte Carlo simulation. Only the efficiencies relative to other $m_{\pi\pi}$ slices are needed. An important input affecting the efficiency is the production p_T spectrum. For the $X(3872)$, there is no *a priori* model, and we rely upon data. The generated spectra, exponentials raised to a quadratic polynomial in p_T, are adjusted until the simulation, after detector and reconstruction effects, reproduces the respective $X(3872)$ or $\psi(2S)$ spectra of the data. We use a parameterization of the well-known $m_{\pi\pi}$ shape of the $\psi(2S)$ for both states.

Uncertainties on our spectra are dominated by statistics, but we examined two sources of systematic effects: the fits for signal yields and the efficiency corrections.

To check the yield stability, we changed the width of the $J/\psi\,\pi^+\pi^-$ fit range of 200 MeV/c^2 by $\pm$50 MeV/c^2, altered the signal and background models, and allowed the signal mean and width to float. We saw no bias in the yields, but nevertheless allotted an uncertainty based on the statistical precision to which we could observe one: 3.6 $\psi(2S)$ and 8.4 $X(3872)$ candidates per slice. The highest three X-slices—highest two for the $\psi(2S)$—are treated specially for effects near the upper kinematic limit: the background begins to turn-on under the signal, and resolution effects can distort the signal shape in the mass fit. Yield systematics are assigned to these slices based on variations in the fit model for these issues.

The other type of uncertainty is from the efficiency corrections. The $\psi(2S)$ model for $dN/dm_{\pi\pi}$ is inexact. We assign an uncertainty based on phase space as an alternate shape—including re-tuning the p_T spectrum. The ratio of the alternate correction to the nominal one quantifies the change in *shape* of the efficiency when switching from the $\psi(2S)$-like $dN/dm_{\pi\pi}$ to phase space. The ratio of efficiencies for the $\psi(2S)$ varies by $\sim$ 3% over the main region of interest, $m_{\pi\pi} > 360$ MeV/c^2, and by $\sim$ 2.5% for the $X(3872)$ above 570 MeV/c^2. For the uncertainty in the meson p_T spectra, we use alternate spectra one standard deviation steeper and shallower in their p_T fall-off based on the errors from the p_T spectrum fit to the data. We again take the ratio of the new efficiencies relative to the nominal shape to quantify the uncertainty. For the mass ranges of interest the $\psi(2S)$ variation is almost 3%, but less than 1% for the X. The p_T spectrum of the X is more poorly measured than for the $\psi(2S)$; but with higher dipion masses, the X suffers smaller variations in efficiency, and thus a smaller uncertainty.

The $dN/dm_{\pi\pi}$ spectrum for our $\psi(2S)$ control signal, after corrections and including systematic uncertainties, is shown in Fig. 2 with a scale preserving the raw fitted

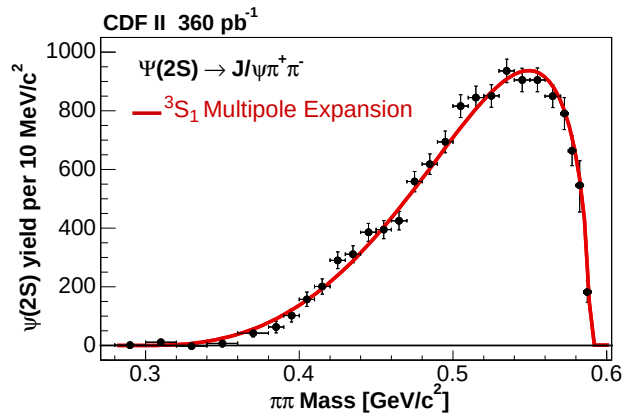

FIG. 2: The CDF dipion mass spectrum for the $\psi(2S)$ with a fit of a QCD multipole expansion calculation for $^3S_1$ [21].

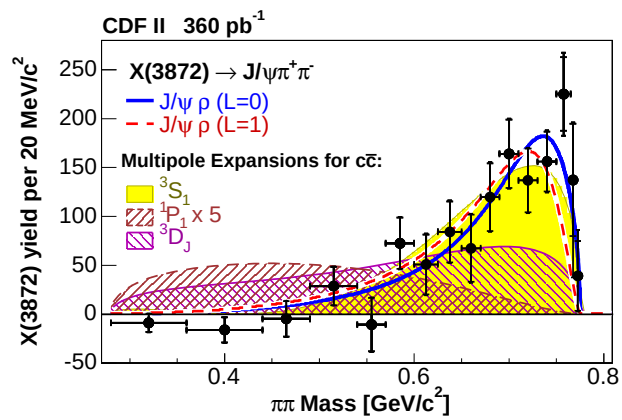

FIG. 3: The dipion mass spectrum for the $X(3872)$, and fits to various hypotheses (see text). The fitted curve for the $^1P_1$ model is scaled up by a factor of 5 for better visibility.

yield of 11 500 candidates. It agrees well with results from the BES Collaboration using a sample of 20 000 events [20]. This is reflected by the mutual agreement in fits to a QCD multipole expansion model [21]. BES obtained $-0.336 \pm 0.009 \pm 0.019$ for this model's single shape parameter "B/A," whereas our fit yields -0.342 ± 0.022 (6.9% fit probability). The systematic uncertainties are incorporated in this and later X-fits, including the $m_{\pi\pi}$ correlations in the efficiency uncertainties.

The $X(3872)$ dipion spectrum is shown in Fig. 3. We fit our data with multipole expansion calculations for C-odd $c\bar{c}$ options [22]. The ^3D_J states are a natural choice for the X according to potential models [5]. A fit of $^3D_J \to J/\psi\,\pi^+\pi^-$ [21] is unacceptable with a χ^2 of 113 for 14 DoF. The $^1P_1 \to J/\psi\,\pi^+\pi^-$ [23] fit is worse ($\chi^2/DoF = 146/14$). The $\psi(2S)$ spectrum is similar to that of the X, and indeed, our $^3S_1$ [21] fit to the X has a 28% probability. However, no new $^3S_1$ $c\bar{c}$-state can be near 3872 MeV/c^2 as the $\psi(3S)$ lies at $\sim$4040 MeV/c^2 [5].

The above C-odd states produce dipions, to lowest L

between the pions, with $J^{PC} = 0^{++}$. C-even states yield 1^{--} isovector dipions, which we associate with the ρ^0. Isospin conservation suppresses $c\bar{c}$ decays to $J/\psi\,\rho$. Thus, this mode is seen as suggestive of a $D^0\overline{D}^{*0}$ molecule [1, 7]. Even as charmonium, however, the X may break isospin by coupling to $D^0\overline{D}^{*0}$ due to its close proximity in mass.

We model $X \to J/\psi\,\rho$ by a relativistic Breit-Wigner multiplied by phase space and generalized for a J/ψ-ρ system of angular momentum L. That is, $dN/dm_{\pi\pi} \propto k_*^{2L+1} f_{LX}^2(k_*)|B_\rho|^2$, where k_* is the J/ψ momentum in the X rest-frame, $B_\rho \propto \sqrt{m_{\pi\pi}\Gamma_\rho}/[m_\rho^2 - m_{\pi\pi}^2 - i m_\rho \Gamma_\rho]$, $\Gamma_\rho(m_{\pi\pi}) = \Gamma_0\,[q_*/q_0]^3\,[m_\rho/m_{\pi\pi}][f_{1\rho}(q_*)/f_{1\rho}(q_0)]^2$, q_* is the π momentum in the ρ rest-frame, $q_0 \equiv q_*(m_\rho)$, m_ρ is 775.8 MeV/c^2, and Γ_0 is 146.4 MeV. The $f_{Li}(p)$ are $f_{0i}(p) = 1$ and $f_{1i}(p) = (1 + R_i^2 p^2)^{-\frac{1}{2}}$ [24], where R_i is a radius of interaction for meson "i." The R_i are poorly known. A common value for light mesons is 0.3 fm, but for D mesons larger values like 1 fm are often taken [25]. We use these respective values for R_ρ and R_X.

Fits with this ρ model are shown in Fig. 3 for $L = 0$ and 1. Higher L softens the fall-off at the high kinematic limit, worsening the agreement: the fit probability goes from 55% for $L = 0$ down to 7.7% for $L = 1$ [26]. The P-wave fit is somewhat disfavored, but the results are sensitive to R_X and R_ρ. The latter probability can be increased by lowering R_ρ or raising R_X.

Another modeling uncertainty is the effect of ρ-ω interference. Belle reports evidence for $X \to J/\psi\,\pi^+\pi^-\pi^0$ and interprets it as decay via a virtual ω. As such, they measure the ratio of $J/\psi\,\omega$ to $J/\psi\,\rho$ branching ratios $\mathcal{R}_{3/2}$ to be $1.0 \pm 0.4 \pm 0.3$ [27]. The rate of $\omega \to \pi^+\pi^-$ is normally negligible, but its interference effects may not be.

We generalize $|B_\rho|^2$ to $|A_\rho B_\rho + e^{i\phi} A_\omega B_{\omega 2\pi}|^2$ in $dN_{2\pi}/dm_{\pi\pi}$, where A_ρ and A_ω are (positive) decay amplitudes via ρ and ω, and ϕ is their relative phase. Using $dN_{3\pi}/dm_{3\pi} \propto |A_\omega B_{\omega 3\pi}|^2$ for $J/\psi\,\pi^+\pi^-\pi^0$ [28], $\mathcal{R}_{3/2}$ determines $|A_\omega/A_\rho|$ given ϕ. We take a ϕ of 95°, the value if the only phase is from $\omega \to \pi^+\pi^-$ decaying via ρ-ω mixing [29]. Similar phases are seen in $e^+e^- \to \pi^+\pi^-$ [30]. The ω fraction is small ($< 10\%$), but interference is constructive and contributes $\sim$23% for both L, preferentially at high masses. Fits with this model are shown in Fig. 4, along with the breakdown into interference and "pure" ρ and ω parts. The probability is 19% for the S fit, and 53% for the P fit. The results are not critically dependent on $\mathcal{R}_{3/2}$: probabilities remain above 7% over a ± 1 standard deviation span of Belle's $\mathcal{R}_{3/2}$ for both L values. The P fit is sensitive to ϕ and R_X, as is shown in the inset. We conclude that there is ample flexibility in models of $X \to J/\psi\,\rho$ of either L to describe our data.

In summary, we measured the dipion mass spectrum in $X(3872) \to J/\psi\,\pi^+\pi^-$. Our spectrum is inconsistent with calculations for ${}^1P_1$ and ${}^3D_J$ charmonia. A good fit is obtained for $X \to J/\psi\,\rho^0$, an interpretation supported by recent evidence for the C-even decay $X \to J/\psi\,\gamma$ [27].

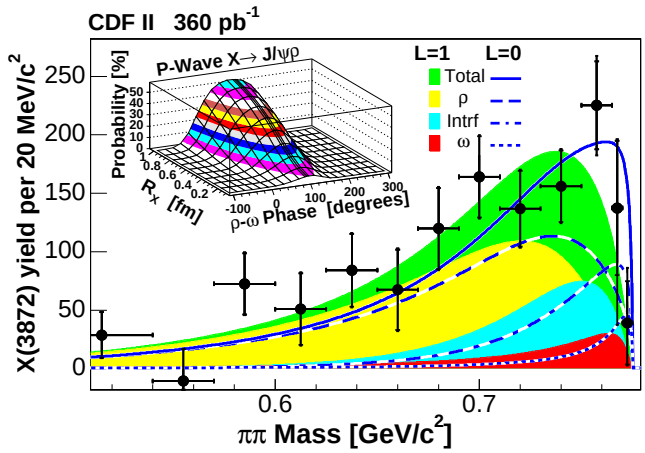

FIG. 4: A blow-up of the $X(3872)$ spectrum with $J/\psi\,\rho$ fits which include ρ-ω interference (95° phase) with relative amplitudes set by $\mathcal{R}_{3/2} = 1.0$. Fits for both $L = 0$ (lines) and 1 (shaded regions) are shown, along with their decomposition into ρ, ω, and interference terms. The inset shows $L = 1$ fit probabilities as a function of ϕ and R_X in 5% contours.

Our data are compatible with both S- and P-wave $J/\psi\,\rho$ decays, where in the latter case, this is partly due to modeling uncertainties. The P fit benefits from constructive ρ-ω interference at levels implied by the rate of $X \to J/\psi\,\pi^+\pi^-\pi^0$. The $J/\psi\,\rho$ interpretation does not by itself distinguish between C-even charmonia (e.g. 1^{++} or 2^{-+}) and exotic options like an 1^{++} $D^0\overline{D}^{*0}$ molecule.

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