Analysis of the quantum numbers J^{PC} of the $X(3872)$

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We present an analysis of angular distributions and correlations of the $X(3872)$ in the exclusive decay mode $X(3872) \to J/\psi\,\pi^+\pi^-$ with $J/\psi \to \mu^+\mu^-$. We use 780 pb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected with the CDF II detector at the Fermilab Tevatron. We derive constraints on spin, parity, and charge conjugation parity of the $X(3872)$ by comparing measured angular distributions of the decay products with predictions for different J^{PC} hypotheses. The assignments $J^{PC} = 1^{++}$ and 2^{-+} are the only ones consistent with the data.

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The recent discovery of the particle $X(3872)$ [1, 2] has revived general interest in charmonium spectroscopy. The exact nature of this particle is still unknown. At-

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tempts to explain the $X(3872)$ as a conventional bound quark-antiquark pair have shortcomings, such as deviations from mass predictions or violation of isospin conservation [3]. The close proximity of the $X(3872)$ mass to the $D^0\bar{D}^{*0}$ mass threshold has raised the question whether the $X(3872)$ is an exotic form of matter [3]. The determination of the quantum numbers spin J, parity P, and charge conjugation parity C is of vital importance for establishing the nature of the $X(3872)$. The evidence for the decay mode $X(3872) \rightarrow J/\psi\,\gamma$ [4] and the measurement of the dipion mass distribution [5], which is in agreement with the decay mode $X(3872) \rightarrow J/\psi\rho^0$, are consistent with a C-even assignment. Reference [6] observes an enhancement in the $D^0\bar{D}^0\pi^0$ mass spectrum and concludes that, if assigned to the $X(3872)$, low values for the spin quantum number are favored. Neglecting effects from model uncertainties in the dipion mass spectrum (see [5]), preliminary results from [7] favor $J^{PC} = 1^{++}$. In this Letter we report the angular distributions in the decay $X(3872) \rightarrow J/\psi\,\pi^+\pi^-$, $J/\psi \rightarrow \mu^+\mu^-$, and compare them with predictions for different J^{PC} states. The analysis is independent of any specific model of the internal structure of the $X(3872)$. We consider all allowed states up to spin two and C-odd spin three states.

We use a sample of $p\bar{p}$ collisions at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV with an integrated luminosity of 780 pb^{-1} collected with the CDF II detector at the Fermilab Tevatron. The CDF II detector [8] consists of a magnetic spectrometer surrounded by electromagnetic and hadronic calorimeters and muon detectors. The tracking system is composed of a silicon micro-strip detector [9] surrounded by an open-cell drift chamber called the central outer tracker (COT) [10]. We detect muons in planes of multi-wire drift chambers [11] in the pseudorapidity range $|\eta| \leq 1.0$. The $J/\psi \rightarrow \mu^+\mu^-$ decays used in this analysis are recorded using a dimuon trigger, which requires two oppositely charged COT tracks matched to muon chamber track segments with an invariant mass from 2.7 to 4.0 GeV/c^2.

The basic event selection is described in [2, 5], although we do not cut on the dipion mass. Additional criteria are imposed on the number of candidates per event, the transverse momentum p_T of the $X(3872)$ candidate ($>$ 6 GeV/c), the p_T of the J/ψ ($>$ 4 GeV/c), and the kinetic energy released in the $X(3872)$ decay, $Q = m(J/\psi\,\pi\pi) - m(J/\psi) - m(\pi\pi)$ ($<$ 100 MeV/c^2), where $m(J/\psi)$ is from [12]. The cuts are chosen to optimize the significance $S/\sqrt{S+B}$ of the observed signal, where S and B are the fitted number of signal and combinatorial background events in a $\pm 1.5\sigma$ window centered on the $X(3872)$ mass. The resulting distribution of the invariant $J/\psi\,\pi^+\pi^-$ mass is shown in Fig. 1.

To simulate the decays of $X(3872)$ states with specific J^{PC} assumptions, we first generate phase space decays of $X(3872) \rightarrow J/\psi\,\pi^+\pi^-$, $J/\psi \rightarrow \mu^+\mu^-$. Detector effects are included using parameterized efficiencies and acceptances. This sample is weighted according to each specific J^{PC} hypothesis using the corresponding matrix element $\mathcal{M}_{tot}$ described below.

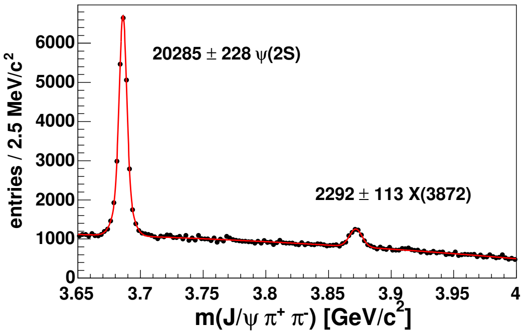

FIG. 1: The $J/\psi\,\pi^+\pi^-$ mass spectrum after optimizing the selection cuts, fitted by a double Gaussian function for the $\psi(2S)$ (left), a Gaussian function for the $X(3872)$ (right), and a second order polynomial for the combinatorial background.

The decay of the narrow $X(3872)$ is modeled as the sequential two-body decay chain X(3872) $\rightarrow J/\psi\ (\pi^+\pi^-)$, $J/\psi \rightarrow \mu^+\mu^-$ and the decay of the intermediate $(\pi^+\pi^-)$ state to $\pi^+\pi^-$. Assuming low relative angular momentum between the pions and conservation of C parity, the intermediate pion state can be in either a relative S-wave $((\pi\pi)_S)$ or a P-wave (ρ^0) state. $\mathcal{M}_{tot}$ is formed by the product of a matrix element $\mathcal{M}_i$ for each decay and a term $T(m(\pi\pi))$, which describes the mass dependence of the intermediate $(\pi^+\pi^-)$ system. Due to the very narrow width of the intermediate J/ψ, we can neglect the J/ψ mass dependence.

With fixed helicities the angular dependence of a two-body decay amplitude is given by the Wigner function $D^{J_i}_{\lambda_i,\lambda_{i,1}-\lambda_{i,2}}$ [13, 14], where J_i and λ_i are the spin and helicity of the decaying particle, and $\lambda_{i,1}$ and $\lambda_{i,2}$ are the helicities of the child particles in the parent rest frame. The function is multiplied by two Clebsch-Gordan coefficients, coupling the spins of the child particles to their summed spin S_i, and S_i with their relative angular momentum L_i to J_i.

In general, in the X(3872)$\rightarrow J/\psi\ (\pi^+\pi^-)$ decay there is more than one combination to form J from L and S in a parity-conserving way. Of the independent amplitudes corresponding to these combinations, only the ones with lowest L, assumed to be dominant, are taken into account. If more than one amplitude remains, mixing parameters are introduced to describe the physical state. Since the virtual photon in the $J/\psi \rightarrow \mu^+\mu^-$ decay can be treated as transverse, helicity combinations with $\lambda_{\mu^+} - \lambda_{\mu^-} = 0$ are neglected.

The dependence of $\mathcal{M}_{tot}$ on the dipion mass has model ambiguities. Therefore, we do not use the information from $m(\pi\pi)$ to distinguish between different J^{PC} hypotheses. The influence of the $m(\pi\pi)$ model on the angular distributions via acceptance effects is very small. Nevertheless we choose for all J^{PC} hypotheses the same model for the $m(\pi\pi)$-dependent terms, which agrees with the $m(\pi\pi)$ spectrum measurement. In this way, no hypothesis is rejected due to a wrong $m(\pi\pi)$ model. In detail, we fix $T(m(\pi\pi))$ to a relativistic Breit-Wigner formula with mass and width of a ρ^0 [12]. Following [5], we also fix the momentum dependence of the matrix element of the $(\pi^+\pi^-) \to \pi^+\pi^-$ decay to $k^* \cdot f_1(k^*)$, where k^* is the magnitude of the three-momentum of one of the pions in the $(\pi^+\pi^-)$ rest frame and $f_1(k^*)$ is a Blatt-Weisskopf form factor [15] to counter the divergence for rising k^*. This form factor has the effective size r of the particle as a free parameter which we set to a common choice of $r = 1$ fm.

A weight is formed from the square of the total matrix element $\mathcal{M}_{tot}$ by averaging over all initial state helicities assuming unpolarized $X(3872)$ production, incoherently summing over all final state helicities, and coherently summing over all intermediate state helicities.

The decay is described by the decay angles θ_X, $\theta_{J/\psi}$, $\phi_{J/\psi}$, $\theta_{\pi\pi}$, $\phi_{\pi\pi}$, and $\Delta\Phi$, as defined in Fig. 2. For unpolarized $X(3872)$ production and because of rotational symmetry, the J^{PC} of the $X(3872)$ and the $(\pi^+\pi^-)$ system affect the distribution of only four variables: $m(\pi\pi)$, $\cos(\theta_{J/\psi})$, $\cos(\theta_{\pi\pi})$, and $\Delta\Phi$.

The angular distributions are analyzed with a three-dimensional fit to take into account their correlations. From simulation studies, the optimal binning is determined to be three bins in $||\Delta\Phi - \pi| - \frac{\pi}{2}|$, and two bins in each of $|\cos(\theta_{J/\psi})|$ and $|\cos(\theta_{\pi\pi})|$, where absolute values are used to exploit final state charge symmetry. The invariant $J/\psi\,\pi^+\pi^-$ mass spectrum is fitted in each of the resulting 12 bins in a mass window of ± 110 MeV/c^2 around the $X(3872)$ position using a binned maximum likelihood fit, where the bin width is 2.5 MeV/c^2. The distribution is described by a Gaussian function for the $X(3872)$ and a second order polynomial for the background. The position and width of the Gaussian function describing the $X(3872)$ are first determined from a fit to the full invariant mass spectrum and are then fixed in the subsequent fits. We compare the fitted yield as a function of the angular variables with the predictions for different J^{PC} assignments by forming a χ^2 based on statistical uncertainties of the measurement. We determine the normalization of the simulated distributions from the measurement so that 11 degrees of freedom remain.

The decay amplitude for the state with $J^{PC} = 1^{-+}$ consists of three LS-terms with the same L value; the $J^{PC} = 2^{-+}$ state has an amplitude with two LS-terms (see Tab. I). Neither of the 1^{-+} terms describes the data alone, so we fit for a mixed state by minimizing the χ^2. For the 2^{-+} state, the amplitude for $S = 1$ is sufficient to describe the data.

Table I shows the χ^2 for each J^{PC} assignment. We find that only the assignments $J^{PC} = 1^{++}$ and 2^{-+} are able to describe the data. All other states are rejected by more than three standard deviations (χ^2 prob. $\leq 2.7 \times 10^{-3}$). Figure 3 shows the measurement and the expected distribution for four of the assignments.

J^{PC}	decay	LS	χ^2 (11 d.o.f.)	χ^2 prob.
1^{++}	$J/\psi\rho^0$	01	13.2	0.28
2^{-+}	$J/\psi\rho^0$	11,12	13.6	0.26
1^{--}	$J/\psi(\pi\pi)_S$	01	35.1	2.4×10^{-4}
2^{+-}	$J/\psi(\pi\pi)_S$	11	38.9	5.5×10^{-5}
1^{+-}	$J/\psi(\pi\pi)_S$	11	39.8	3.8×10^{-5}
2^{--}	$J/\psi(\pi\pi)_S$	21	39.8	3.8×10^{-5}
3^{+-}	$J/\psi(\pi\pi)_S$	31	39.8	3.8×10^{-5}
3^{--}	$J/\psi(\pi\pi)_S$	21	41.0	2.4×10^{-5}
2^{++}	$J/\psi\rho^0$	02	43.0	1.1×10^{-5}
1^{-+}	$J/\psi\rho^0$	10,11,12	45.4	4.1×10^{-6}
0^{-+}	$J/\psi\rho^0$	11	104	3.5×10^{-17}
0^{+-}	$J/\psi(\pi\pi)_S$	11	129	$\leq1\times10^{-20}$
0^{++}	$J/\psi\rho^0$	00	163	$\leq1\times10^{-20}$

TABLE I: Result of the $X(3872)$ angular analysis. Listed are the state, the decay mode, the L and S quantum numbers of the J/ψ-$(\pi^+\pi^-)$ system, the χ^2 with 11 degrees of freedom and the χ^2 probability.

An important cross-check of the analysis is to verify whether the correct result is obtained for the $\psi(2S)$, with known quantum numbers $J^{PC} = 1^{--}$, which decays into the same exclusive final state as the $X(3872)$. For the 1^{--} assignment, the fit probability is 1.5%. Using the $\psi(2S)$ model of Novikov and Shifman [16], which includes a small D-wave admixture in the description of the $(\pi^+\pi^-)$ system, the fit probability is 17.9%. The sensitivity to such a small admixture is only present in the high statistics $\psi(2S)$ sample. The next best model $J^{PC} = 2^{++}$ has a fit probability of 0.58%, and all other hypotheses that were tested yielded fit probabilities smaller than 2×10^{-6}.

We vary several inputs to the fitting procedure and the model of the $X(3872)$ to investigate the stability of the χ^2. Figure 4 shows the resulting χ^2 values for the different J^{PC} hypotheses for the variations investigated. The default analysis is shown as variation (1). The following effects are considered: (2)/(3) decrease/increase the fit window by 20 MeV/c^2, (4)/(5) decrease/increase the bin width to 2.0/2.86 MeV/c^2, (6)/(7) vary fixed $X(3872)$ mass by $\pm1\sigma$, (8)/(9) vary fixed $X(3872)$ width by $\pm1\sigma$.

To evaluate the contribution to the systematic uncertainty from our choice of the $m(\pi\pi)$ spectrum, the following variations are considered: (10) fix form-factor r to 0.001 fm, (11) fix form-factor r to 100.0 fm, (12) use simple phase-space for $m(\pi\pi)$.

Finally, systematic uncertainty due to details concern-

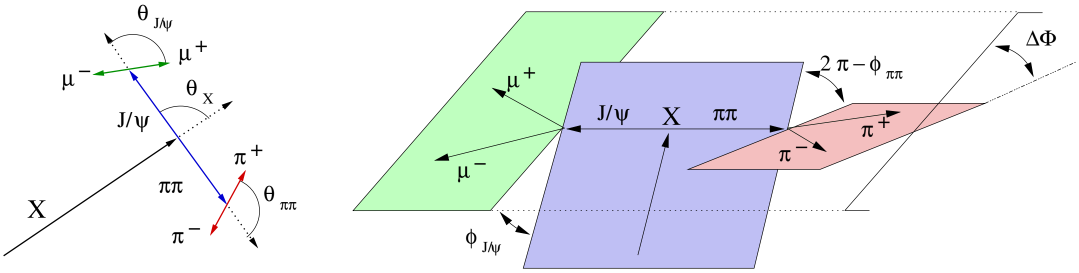

FIG. 2: Definition of the decay angles. The polar angles (θ) are calculated from the parent momenta and the child momenta in the corresponding parent rest frame.

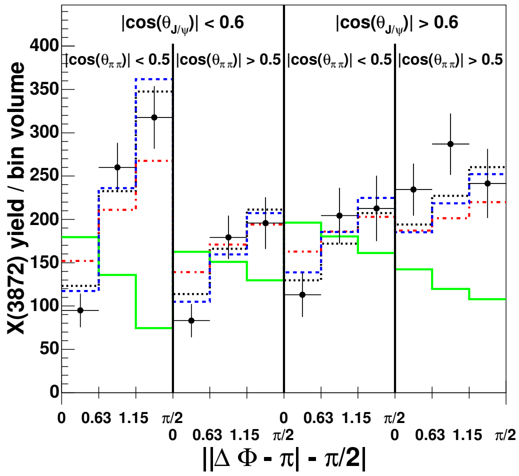

FIG. 3: Measured 3D angular distribution with acceptance corrected predictions for $J^{PC} = 0^{++}$ (solid line), 1^{++} (dotted), 2^{-+} (dashed), and 1^{--} (dash-dotted). The plot is divided into 2×2 regions, corresponding to intervals of $|\cos(\theta_{J/\psi})|$ and $|\cos(\theta_{\pi\pi})|$. Each region shows the distribution of $||\Delta\Phi - \pi| - \frac{\pi}{2}|$ in 3 bins. The bin contents have been scaled to the same bin volume.

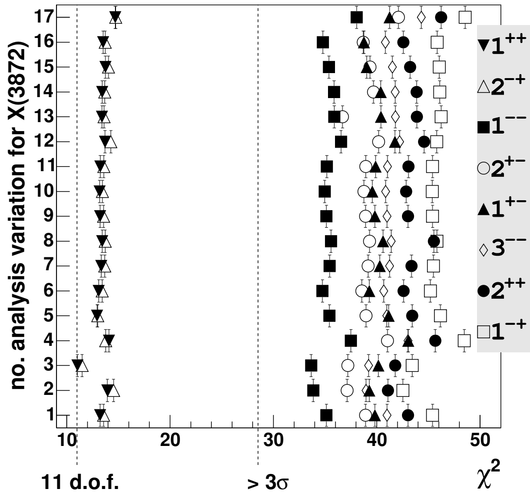

FIG. 4: Total χ^2 for different analysis variations on the y-axis, explained in the text. Vertical bars are added for visual guidance. The χ^2 values of the spin 0 states are all above 100. The 2^{--} and 3^{+-} states have the same angular distribution as the 1^{+-} state.

ing the simulation has been considered by varying distributions for (13) p_T and (14) η of the $X(3872)$, switching off (15) a p_T dependent efficiency correction for the pions, (16) a ϕ dependent correction of the COT, and (17) an effective η correction used to model the position of the generated primary vertex. All variations are consistent with 1^{++} and 2^{-+} being the only likely assignments.

A conventional explanation for the $X(3872)$ resonance is a charmonium ($c\bar{c}$) state. In this picture, the state with $J^{PC} = 1^{++}$ could be identified with the χ'_{c1} and the assignment $J^{PC} = 2^{-+}$ with the η_{c2}. An exotic interpretation is that the $X(3872)$ is a molecular state or that a significant four-quark interaction contributes to the wave-function [17]. The result of this analysis is compatible with the models of a molecular state developed by Tornqvist [18] and Swanson [19], who predict the quantum numbers $J^{PC} = 1^{++}$ for a bound $D\bar{D}^*$ state.

In summary, a spin-parity analysis of the $X(3872)$ in the final state $\mu^+\mu^-\pi^+\pi^-$ has been performed. The method of helicity amplitudes has been used to analyze $X \to J/\psi(\pi\pi)_S$ and $X \to J/\psi\rho^0$ transitions. Using a χ^2 approach to compare expected angular distributions with measured distributions, it is found that only the C-even assignments $J^{PC} = 1^{++}$ and 2^{-+}, both decaying via $J/\psi\rho^0$, describe the data. All other states are excluded at 99.7% confidence level.

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