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The $X(3872)$ at the TeVatron

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Abstract. I report results on the $X(3872)$ from the Tevatron. Mass and other properties have been studied, with a focus on new results on the dipion mass spectrum in $X \to J/\psi\pi^+\pi^-$ decays. Dipions favor interpreting the decay as $J/\psi\rho$, implying even C-parity for the X. Modeling uncertainties do not allow distinguishing between S- and P-wave decays of the J/ψ-ρ mode. Effects of ρ-ω interference in X decay are also introduced.

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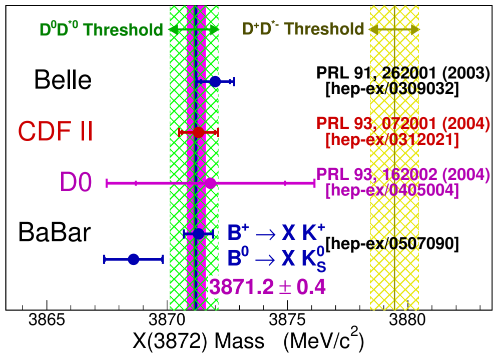
The charmonium-like $X(3872)$ stands as a major spectroscopic puzzle. Its mass and what is known of its decays makes $c\bar{c}$ assignments problematic. Exotic interpretations have been offered, notably that the X may be a D^0-$\overline{D}^{*0}$ "molecule" [1].

$X(3872) \to J/\psi\pi^+\pi^-$ was confirmed by CDF [2] and DØ [3], and is copiously produced at Fermilab's $\bar{p}p$ collider—albeit with high backgrounds. Mass measurements are compared in Fig. 1, with an average of 3871.2 ± 0.4 MeV/c^2. DØ studied other X properties by comparing the fractions of X yield in various types of subsamples to the corresponding fractions for the $\psi(2S)$ [3]. The results for 230 pb^{-1} are summarized in Fig. 1, where the subsamples are the fraction of signal which have: **a)** $p_T(J/\psi\pi\pi) > 15$ GeV, **b)** $|y(J/\psi\pi\pi)| < 1$, **c)** $\cos(\theta_\pi) < 0.4$ (π helicity angle), **d)** proper decay length $ct <$ 100 μm, **e)** no tracks with $\Delta R < 0.5$ around the candidate, **f)** $\cos(\theta_\mu) < 0.4$ (μ helicity



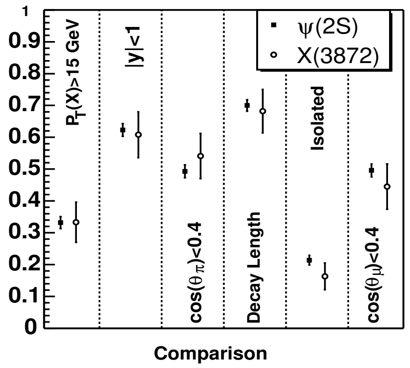


FIGURE 1. **LEFT:** Summary of X-mass measurements compared to the $D^0\overline{D}^{*0}$ and D^+D^{*-} thresholds. **RIGHT:** DØ's comparison of X production/decay properties to that of the $\psi(2S)$ [3]. The fraction of the yield surviving the listed cut is plotted (see text for descriptions).

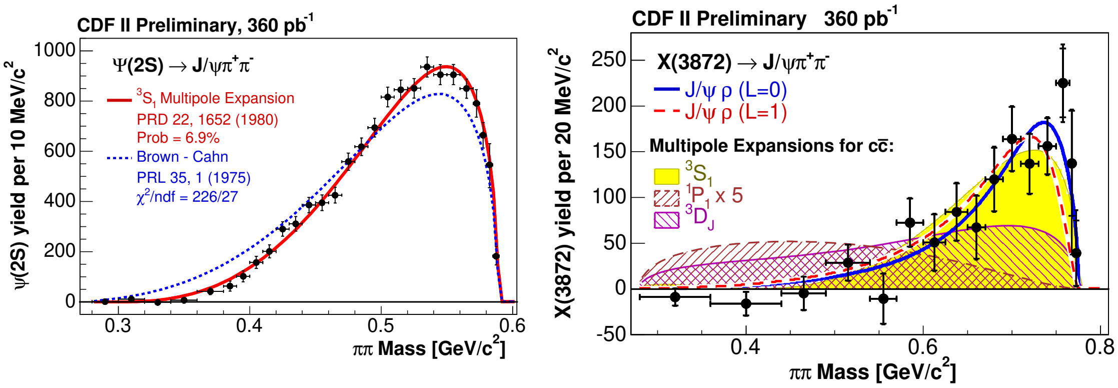


FIGURE 2. LEFT: The $\psi(2S)$ dipion mass spectrum with fits of $^3S_1$ multipole expansion and an older calculation of Brown and Cahn. **RIGHT:** The $X(3872)$ dipion mass spectrum with fits of multipole expansion predictions for C-odd charmonia, and of $X \to J/\psi\rho$ for $L = 0$ and 1 using a relativistic Breit-Wigner with Blatt-Weisskopf factors ($R_\rho = 0.3$ and $R_X = 1.0$ fm).

angle). In all cases the X results are compatible with those of the $\psi(2S)$. CDF used the proper decay length ct to quantify the fraction of X's that come from b-hadrons, versus those that are promptly produced. Using 220 pb^{-1}, CDF finds the fraction of X's from b-decays is $16.1 \pm 4.9 \pm 2.0\%$, in contrast to $28.3 \pm 1.0 \pm 0.7\%$ of $\psi(2S)$'s [4]. The X fraction is somewhat lower than the $\psi(2S)$'s, but within $\sim 2\sigma$. From these perspectives the X is compatible with the $\psi(2S)$. The large X-production at the Tevatron is indicative to some of a charmonium character [5]. Naïvely one expects production of a fragile D^0-$\overline{D}^{*0}$ molecule, bound by an MeV or less, to be suppressed. It may, however, be sufficient to accommodate these features if the X merely has a significant $c\bar{c}$ "core."

Another property is the dipion mass spectrum. If the X has even C-parity, the dipions are (to lowest L) in a 1^{--} isovector state, and dominated by the ρ^0. An odd-C state produces 0^{++} dipions, for which QCD multipole expansion predictions exist for $c\bar{c}$.

CDF used 360 pb^{-1} ($\sim$1.3k X's) to measure the $\pi\pi$-spectrum [6, 7]. The sample is divided into $m_{\pi\pi}$ "slices" and fitted for $X(3872)$ and $\psi(2S)$ yields. After modest efficiency corrections, the spectra of Fig. 2 were obtained. The $\psi(2S)$ is a good reference signal and is well modeled by multipole predictions [8]. Also in Fig. 2 are multipole fits to the X for the C-odd $c\bar{c}$ states. The $^1P_1$ and ^3D_J fits are unacceptable. The $^3S_1$ is an excellent fit to the X, but no $^3S_1$ $c\bar{c}$ is available for assignment in this mass region.

Earlier this spring CDF provided $J/\psi\rho$ fits using a simple non-relativistic Breit-Wigner sculpted by phase space [6]. Good agreement was obtained (36% probability). About the same time Belle released new dipion data fit with a more sophisticated ρ model [9], which included the effects of angular momentum L for the J/ψ-ρ system. The phase-space factor of the J/ψ momentum in the X rest frame, k^*, generalizes to $(k^*)^{2L+1}$, thereby turning off the mass spectrum at the upper kinematic limit ($k^* \to 0$) faster for $L = 1$ than for $L = 0$. Belle obtained a good fit for S-wave decay, but only a 0.1% probability for $L = 1$. Thus the latter case was strongly disfavored, and in conjunction with angular information, Belle argued for a 1^{++} assignment for the X [9]. The above CDF fit for $J/\psi\rho$ was implicitly for $L = 0$; and the CDF fit using Belle's

$L=1$ model also yields 0.1% probability. The implication is, however, not robust.

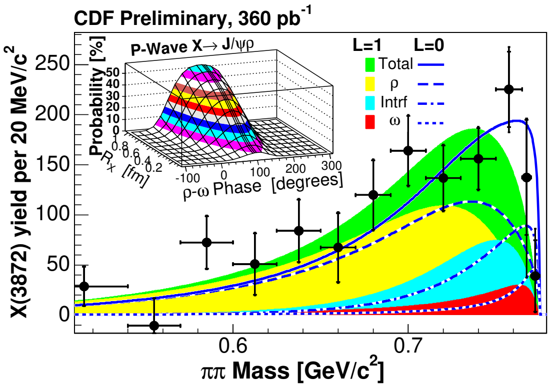
Breit-Wigner formulations are often modified by Blatt-Weisskopf form factors [10]. The centrifugal modification to $(k^*)^{2L+1}$ tends to be too strong, and for $L=1$ it is multiplied by $f_{1i}(k_*) \propto (1+R_i k_*)^{-\frac{1}{2}}$, where R_i is a "radius" of meson-i. Specifically, CDF's $J/\psi\rho$ model is: $dN/dm_{\pi\pi} \propto k_*^{2L+1} f_{LX}^2(k_*)|B_\rho|^2$ for angular momentum L. The ρ propagator $B_\rho \propto \sqrt{m_{\pi\pi}\Gamma_\rho(m_{\pi\pi})}/[m_\rho^2 - m_{\pi\pi}^2 - im_\rho\Gamma_\rho(m_{\pi\pi})]$, where $\Gamma_\rho(m_{\pi\pi}) = \Gamma_0\left[q_*/q_0\right]^3 \times [m_\rho/m_{\pi\pi}][f_{1\rho}(q_*)/f_{1\rho}(q_0)]^2$, q_* is the π momentum in the $\pi\pi$ rest-frame, and $q_0 \equiv q_*(m_\rho)$. The ρ parameters m_ρ and Γ_0 are taken from the PDG. The $L=0$ factor is $f_{0i}(x)=1$. The f_{1i} factors require two uncertain parameters, R_X and R_ρ. For light mesons, like the ρ, values ~ 0.3 fm are usually found, whereas for charm mesons larger radii ~ 1 fm are often used [11]. Choosing these values for R_ρ and R_X, CDF obtains the fits in Fig. 2 (Right). The $L=0$ fit has an excellent probability of 55%. While the $L=1$ probability is not quantitatively as good, it is a respectable 7.7%. This P-wave fit is sensitive to the R_i's, whereby the probability can be increased by lowering R_ρ and/or raising R_X. We conclude that flexibility in the fit model can accommodate either L.

Other modeling uncertainties may arise, for example, the effects of ρ-ω interference. Belle reported $X \to J/\psi\pi^+\pi^-\pi^0$, and interprets it as decay via a virtual ω. As such, they find the ratio of $J/\psi\omega$ to $J/\psi\rho$ branching ratios $\mathscr{R}_{3/2}$ is 1.0 ± 0.5 [12]. Although $\omega \to \pi^+\pi^-$ is nominally negligible here, its interference effects may not be.

$dN_{2\pi}/dm_{\pi\pi}$ is generalized by replacing $|B_\rho|^2$ with $|A_\rho B_\rho + e^{i\phi}A_\omega B_{\omega 2\pi}|^2$ where A_ρ and A_ω are X-decay amplitudes via ρ and ω, and ϕ is the relative phase. The form for $B_{\omega 2\pi}$ is identical to B_ρ except ρ parameters are replaced by ω ones, including the $\omega \to \pi\pi$ branching ratio. The size of $|A_\omega/A_\rho|$ is established by the relationship between $\mathscr{R}_{3/2}$ and the integrals of $dN_{2\pi}/dm_{\pi\pi}$ and $dN_{3\pi}/dm_{3\pi} \propto |A_\omega B_{\omega 3\pi}|^2$ for $X \to J/\psi\pi^+\pi^-\pi^0$. The $B_{\omega 3\pi}$ follows $B_{\omega 2\pi}$ except the numerator contains $\Gamma_{\omega 3\pi}(m_{\pi\pi})$. While $\Gamma_{\omega 2\pi}(m_{\pi\pi})$ follows $\Gamma_\rho(m_{\pi\pi})$, a different form for $\Gamma_{\omega 3\pi}(m_{3\pi})$ is adapted from the SND experiment studying $e^+e^- \to \pi^+\pi^-\pi^0$ [13]. They model $\omega \to \pi^+\pi^-\pi^0$ by virtual $\rho\pi$ decays and use the ω matrix-element $|\vec{q}_{\pi^+} \times \vec{q}_{\pi^-}|^2$, where $\vec{q}_{\pi^{+/-}}$ are the momenta for the $\pi^{+/-}$.

The integral of $dN_{2\pi}/dm_{\pi\pi}$ depends upon the phase, which is *a priori* unknown. As an illustration, $|A_\omega/A_\rho|$ is determined assuming that ϕ arises completely from ρ-ω mixing, i.e. $\phi = 95°$ [14]. The $dN_{2\pi}/dm_{2\pi}$ decomposes into three parts: "pure" ρ and ω terms, and an interference cross-term. In this model with $\mathscr{R}_{3/2} = 1.0$, these fractions are, respectively, 71.0, 6.2, and 22.8% for S-wave decay, and 67.4, 8.7, 23.9% for P-wave. Fits with these fractions imposed are shown in Fig. 3 (Left). The S-wave probability has declined as the model peaks too much at high mass, but is still quite good at 19%. Increasing the amount of high masses with interference improves the P-wave fit to 53%. The $L=1$ fit is sensitive to ϕ and R_X as is seen in the inset of Fig. 3. The dependence on R_ρ is relatively weak in both cases. The overall picture from these fits is insensitive to the $\pm 1\sigma$ span of $\mathscr{R}_{3/2}$, as is seen in Fig. 3 (Right).

In summary, properties of $X(3872) \to J/\psi\pi^+\pi^-$ studied at the Tevatron are similar to those of the $\psi(2S)$. There is no viable C-odd $c\bar{c}$ assignment according to QCD multipole expansion fits to the $\pi\pi$-mass spectrum. Decay to $J/\psi\rho$ provides good fits, irrespective of the $c\bar{c}$ content. This implies the X is C-even, in-line with Belle's report of



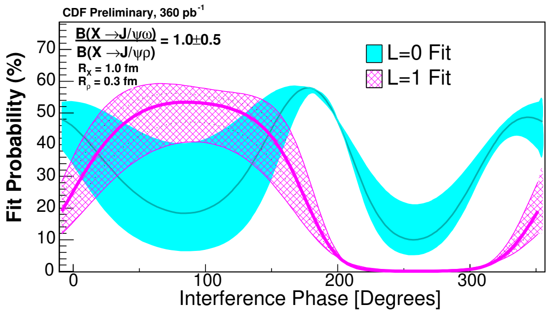


FIGURE 3. **LEFT:** Blow-up of the dipion spectrum with $J/\psi\rho$ fits for $L=0$ (lines) and 1 (shaded) including ρ-ω interference with 95° phase and sub-components set by $\mathscr{R}_{3/2}=1.0$. The decomposition into ρ, interference, and ω terms is given. The inset shows $L=1$ fit probabilities as a function of ϕ and R_X in 5% contours. **RIGHT:** $J/\psi\rho$ fit probabilities for $L=0$ (shaded) and 1 (hatched) as a function of phase. The bands span the $\pm1\sigma$ range of $\mathscr{R}_{3/2}$.

$X \to J/\psi\gamma$ [12]. Given the modeling uncertainties—especially the introduction of ρ-ω interference—the CDF spectrum can be well described by $J/\psi\rho$ decay of either $L=0$ or 1: such as from a 1^{++}—favored for a D^0-$\overline{D}^{*0}$ molecule—or a 2^{-+} state.

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