PROCEEDINGS OF SCIENCE

Spectroscopy (X,Y,Z) at the Tevatron

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In this article, I present studies that probe the nature of the $X(3872)$ and evidence for a new resonance, the $Y(4140)$.

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1. Motivation

In the last years evidence for new states has been found, which don't fit well into the known meson spectra, therefore named X, Y, or Z states. A number of exotic explanations for these states within the frame of the standard model have been suggested, e.g. meson molecules or four-quark states. Despite no challenge to the standard model, the study of such states can give us a deeper insight into physics in the low energy QCD region.
While the b-factories dominate the field, there are specific states, where the Tevatron collaborations can contribute or even dominate the progress to greater insight. The specific conditions at the Tevatron experiments are the result of it being a hardon machine. A great number of b-quarks are produced, but in a very challenging environment, which restricts us to decay modes with only charged particles and - perhaps even more restricting - modes that can be triggered.

2. Studies of the $X(3872)$

One of the states, that have been studied at the Tevatron collaborations is the $X(3872)$, which was discovered in 2003 by the Belle collaboration [1]. Very soon after that, both, CDF II [2] and D0 [3] were able to confirm the signal. In figure 1 the selection from D0 can be seen. The decay to $J/\psi\pi^+\pi^-$ with the J/ψ into a pair of muons can be triggered even for a prompt decay, due to good recognition of the rare muons.
In another analysis by CDF II [4], the quantum numbers J^{PC} of the $X(3872)$ have been revealed to be either 1^{++} or 2^{-+}. With these quantum numbers and a mass around 3.872 GeV/c^2 the X doesn't fit well into the charmonium spectrum - although it is not impossible that it is a charmonium. However, an exotic explanation can explain the measured properties easier.

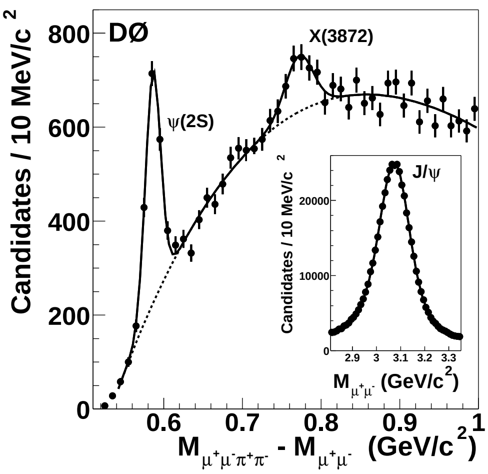

Figure 1: Invariant mass of $\mu^+\mu^-\pi^+\pi^-$ combinations at D0.

2.1 Exotic interpretations

One of the most striking properties of the $X(3872)$ is, that its mass is very close to the sum of the masses of a D^0 and a D^{*0}. This initiated the idea of a molecular state of two such mesons, described e.g. in [6] and [7]. One way to approach this idea experimentally is a very precise measurement of the masses of the $X(3872)$ and the involved meson masses.
Another possibility is a genuine four-quark state as suggested e.g. in [5]. In this case the expectation is, to have not only a single state, but two states with slightly different masses, e.g. $c\bar{c}u\bar{u}$ and $c\bar{c}d\bar{d}$. As the d and the u quark have slighly different masses, the resulting states should as well differ in their mass, leading to a modified shape of the $X(3872)$.

A recent analysis [8] performed at the CDF II experiment has tried to clarify the nature of the $X(3872)$ using the above approaches.

2.2 Data Selection

The data selection for the $X(3872)$ studies makes use of the di-muon trigger. A multivariate technique including a neural networkis used to enrich the signal contribution in the data sample. In the trainings for the neural network, simulations are used for the signal, and experimental data from a sideband in the $\mu^+\mu^-\pi^+\pi^-$ invariant mass spectrum are used to describe the background. The most important variables in the neural network are the Q value, which is dominated by the $\pi^+\pi^-$ system, the transverse momenta of the pions, the quality of the kinematic fit, and the muon identification.

The optimisation for the final cut on the neural network output is done by optimising $N_{MC}/\sqrt{N_{DATA}}$, where N_{MC} is a simulated signal, and N_{DATA} is the experimental data $\pm$ 10 MeV/c^2 around the $X(3872)$ signal. After this cut roughly 6000 $X(3872)$ particles remain in the data set.

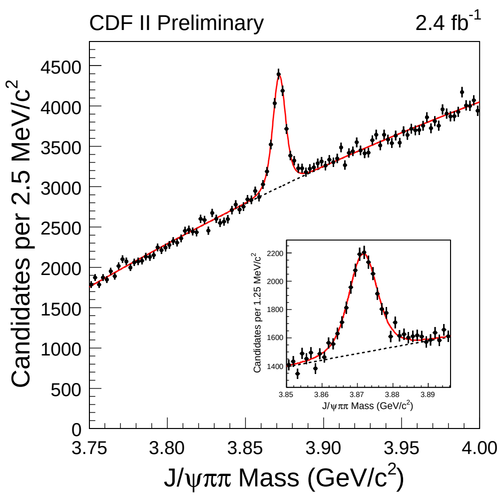

Figure 2: Selected mass spectrum.

2.3 Mass Measurement

An unbinned likelihood fit is performed with a Voigt function as signal, and a polynomial function for background. The natural width in the Voigt function is fixed to the BABAR/Belle result, while the Gaussian part is fixed to detector simulations. Additionally an overall width scale factor is applied.

The systematic uncertainty for the mass is estimated by looking into the variations of the $\Psi(2S)$ mass with the momentum of its daughters. This method yields one hundred keV/c^2 for the $\Psi(2S)$, which is multiplied with the Q value ratio of the $X(3872)$ to the $\Psi(2S)$ to estimate the uncertainty for the $X(3872)$. The final result for the $X(3872)$ mass is

$$\mathrm{m}[X(3872)] = 3871.16 \pm 0.16\ (stat)\ \pm 0.19\ (sys)\ \mathrm{MeV/c^2}$$

This is so far the most precise measurement of the $X(3872)$ mass, as can be seen in figure 2.3. With the current world average masses for the D^0 and D^{*0} mesons, the molecular state is still possible.

2.4 Test for two separate states

To test the possibility of two states, a detailed analysis of the shape of the $X(3872)$ is performed. Toy Monte Carlo simulations are used to determine for which mass difference between two states, the scale parameter in the signal fit would yield the measured one or less, in maximal 5% or 10% of the cases.

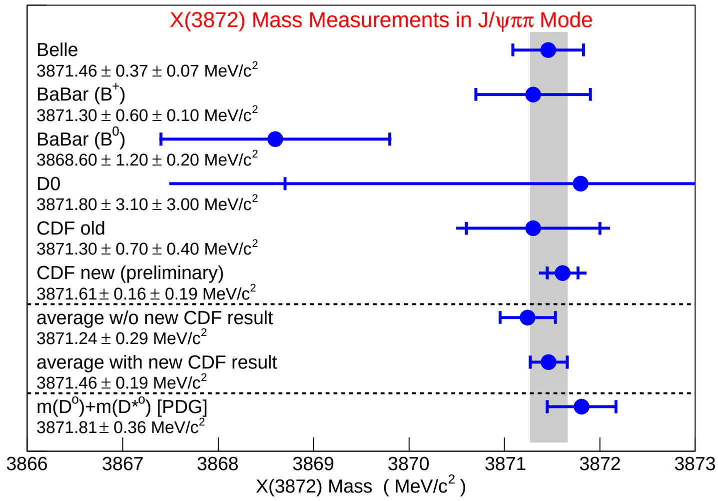

Figure 3: Mass measurement of the $X(3872)$ and the sum of D^0 and D^{*0}.

This is as well done for different production cross sections for the two states. The results of this study can be seen in figure 4. If both states have the same production cross section as one would expect in case of the four-quark model for the $X(3872)$, the 90% limit of the mass difference is 3.2 MeV/c^2, and the 95% limit is 3.6 MeV/c^2.
The model of [5] predicts a difference of Δm = 8 $\pm$ 3 MeV/c^2. The described measurement challenges this interpretation strongly.

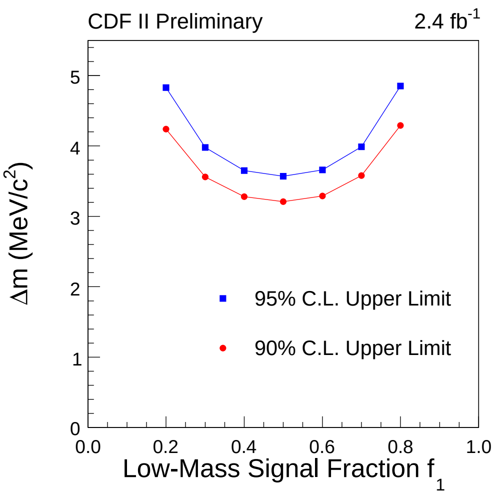

Figure 4: Limit on the mass difference of two potential states forming the $X(3872)$.

3. Evidence for $Y(4140)$

Motivated by the $Y(3930)$ decaying into $J/\psi\ \omega$ close at the kinematic threshold, a search [9] for a similar particle decaying into $J/\psi\ \phi$ has been performed with the CDF II experiment. By searching in exclusive reconstructed B^+ to $J/\psi\ \phi\ K^+$ decays, a strong reduction of background can be achieved.

3.1 Data selection

Again the J/ψ decays to two muons allowing for triggering. Candidates for ϕs are formed of two kaon candidates. Then B^+ candidates are formed from the combination of J/ψ, ϕ, and kaon candidates. A cut based selection is performed to enrich the signal. The most important variables are the decay length of the B^+ and the particle identification for the kaons.

The final data sample contains 75 ± 10 B^+ mesons, estimated using a Gaussian fit for the signal contribution and a first order polynomial for the background as can be seen in figure 5.
For the search for substructure in the $J/\psi\ \phi$ combinations, B^+ candidates with a mass closer than $\pm 3\ \sigma$ (17.7 MeV/c^2) of the resolution around the true B^+ mass are taken. As cross check the distribution of the ϕ candidates from B^+ candidates in the signal B^+ region less the ϕ candidates from the B^+ sideband is viewed, which confirms, that the final state $J/\psi\ K^+K^-K^+$ is well described as $J/\psi\ \phi\ K^+$.

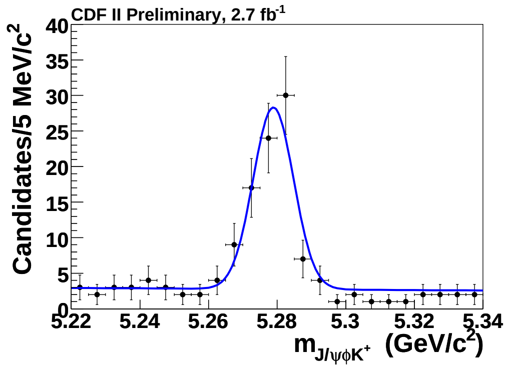

Figure 5: Experimental data selection of B^+ candidates.

3.2 Mass and width

73 candidates can be found in the spectrum shown in figure 6 of the invariant mass difference

$$\Delta \mathrm{M} = \mathrm{m}(\mu^+\mu^-[K^+K^-]_{\phi candidate}) - \mathrm{m}(\mu^+\mu^-)$$

up to 1.56 GeV/c^2. The spectrum is only analysed up to that point to avoid background contributions from the decay of B_s mesons to $\Psi(2S)\ \phi$ and $\Psi(2S)$ to $J/\psi\ \pi^+\pi^-$. A likelihood fit on the spectrum is performed. The non-peaking contribution in this spectrum is modeled by a 3 body-phase space function.
The signal contribution from the potential new resonance Y is modeled by a relativistic Breit-Wiegner function convoluted with a Gaussian. The width of the Gaussian is fixed to 1.7 MeV/c^2 from Monte Carlo simulation studies.
The systematic uncertainty for the mass and width is estimated by using a flat distribution as an alternative background model. In this way, we get a mass of 4143.0 ± 2.9 (stat) $\pm$ 1.2 (sys) MeV/c^2 and a width of $11.7^{+8.3}_{-5.0}$ MeV/c^2.

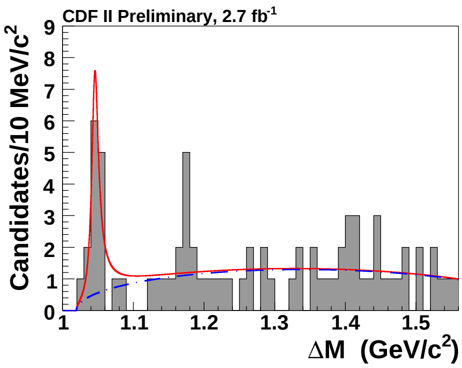

Figure 6: Spectrum of $\Delta\mathrm{M} = \mathrm{m}(\mu^+\mu^-[K^+K^-]_{\phi candidate}) - \mathrm{m}(\mu^+\mu^-)$.

3.3 Significance

To estimate the significance of the new found resonance, we calculate two times the negative log-likelihood ratio $-2L$ and perform a p-value study to get the probability of such a big difference in $-2L$ for fits with and without a signal contribution anywhere in the considered mass window of the spectrum in toy simulations based on only the background contribution.

The significance with a flat background model is smaller than for the three-body phase-space, and gives a significance of 3.8 σ. According to the usual conventions, we claim evidence for this new state.

4. Summary

The most recent study of the $X(3872)$ at the CDF II experiment challenges the two-state hypothesis, which follows from the four-quark state assumption, strongly.
The measurement of the mass of the $X(3872)$ is still consistent with an interpretation of the $X(3872)$ as a molecular state formed from D^0 and D^{*0} mesons. The uncertainty on the $X(3872)$ mass is now so little, that for further study of that interpretation more precise measurements of the D^0 mass is necessary.
We have found evidence for an exotic charmonium-like state decaying to $J/\psi\ \phi$ with a mass of 4143.0 ± 3.1 MeV/c^2. Due to the similarity to the $Y(3930)$ we call it $Y(4140)$.

The studies show, that the Tevatron experiments can contribute in the area of the new and exciting X, Y, and Z states, raising hope for more contributions in this field in the future.

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