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SEARCH FOR η_b AT CDF

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The $\eta_b(1S)$ is the $J^{PC} = 0^{-+}$ $b\bar{b}$ ground state, and has not yet been experimentally observed. Theorists have recently suggested that it could be observed at the Fermilab Tevatron through its decay to $J/\psi J/\psi$, if not in the 1992-96 ("Run 1") dataset, then in Run 2. This article describes a search for this particle at CDF in Run 1 using this decay channel. A small cluster is seen, with 7 events where 1.8 events are expected from background. The statistical significance is estimated to be 2.2σ, and an upper limit is set on the product of cross section and branching fractions.

1. Introduction

The application of the non-relativistic QCD (NRQCD) framework[1] to understanding the bound states of heavy quarks and antiquarks was spurred, in part, by the CDF observation of what was then deemed an anomalously large direct $\psi(2S)$ cross section compared to prior theoretical models.[2] Subsequent models have taken into account higher-order effects than those explicit in the earlier models, and isolate non-perturbative effects into experimentally-determined, universal coefficients which relate predictions across different quarkonia species. Predictions concerning bottomonia are considered the most reliable, and with this in mind theorists[3,4] have analyzed the CDF bottomonia cross section measurements.[5,6] Braaten *et al.*[4] predict the η_b cross section to be roughly three to six times that of $\Upsilon(1S)$. The authors propose finding this particle through its decay into two J/ψ's; the branching fraction of this mode, however, can only be estimated to be between 7×10^{-5} and 7×10^{-3}. Experimental tests of these theoretical calculations will have to wait for the observation of other decay modes; on the other hand, the upper reaches of the cross section and branching fraction expectations suggest the possibility that η_b could be observed even in the 100 pb^{-1} of Run 1 data.

The η_b mass is also an important test of NRQCD. For the present purpose of finding it, a range of predictions, including early potential models[7] as well as later lattice calculations with NRQCD,[8,9,10] is used to define a search window spanning 100 MeV/c^2 below the $\Upsilon(1S)$ mass of 9460 MeV/c^2.[11] This search window incorporates the effect of the expected CDF mass resolution for $J/\psi J/\psi$ decays of about 10 MeV/c^2.

2. Reconstruction

The CDF detector has been described elsewhere.[12] The search for $\eta_b \rightarrow J/\psi J/\psi$ decays begins by reconstructing one of the J/ψ's through its decay to an oppositely charged pair of identified muons. Muon candidates are accepted from any of the central muon detector systems, which cover roughly pseudorapidity $|\eta| < 1$, and must be reconstructed in the silicon microstrip detector (SVX) and central drift chamber (CTC). The requirement that a muon reaches the muon chambers results in an implicit minimum p_T of about 1.5 GeV/c, where p_T is the momentum measured in the plane transverse to the beam.

The other ("non-leading") J/ψ is then reconstructed. In order to increase the acceptance for signal events, only one muon is required to be identified in the muon chambers; the other muon, designated the "fourth track," is only required to be reconstructed in the SVX and CTC. The four tracks are then constrained to come from a common vertex, and mass constraints to the world average J/ψ mass[11] are applied to both muon pairs. Since the η_b is only directly produced in the $p\overline{p}$ interaction and decays promptly, the four-track vertex is further constrained to lie close to the beam. The χ^2 probability of the four tracks forming a single vertex lying close to the beam must exceed 1%.

The p_T threshold on the fourth track is set by maximizing S^2/B, where S and B are models of the signal and background yields as a function of the threshold. The signal model is based on a simulation of η_b production and decay. The production model is flat in rapidity y and follows the p_T spectrum of $\Upsilon(1S)$ production as measured at CDF.[5] The angular distribution of the muons is derived taking the J^{PC} of the η_b and J/ψ mesons into account. The background model is a sample of events where the vertex constraint has been relaxed; this sample is expected to be rich in the dominant background, which consists of $B \rightarrow J/\psi X$ decays, with the other b hadron decaying semileptonically. As shown in Fig. 1(left), the maximum S^2/B is achieved with the p_T threshold set at 0.8 GeV/c.

The dominant b hadron background can be further reduced by imposing an isolation requirement, an upper threshold on the scalar sum of p_T's of tracks in $(\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}) < 0.4$ cones around the J/ψ candidate directions, excluding the four muons. The background model is the same as before, while the signal model consists of $\Upsilon(1S) \to \mu\mu$ decays, where the muon directions are used in place of the J/ψ directions. The maximum S^2/B, as shown in Fig. 1(right), is achieved with an upper threshold of 1.8 GeV/c.

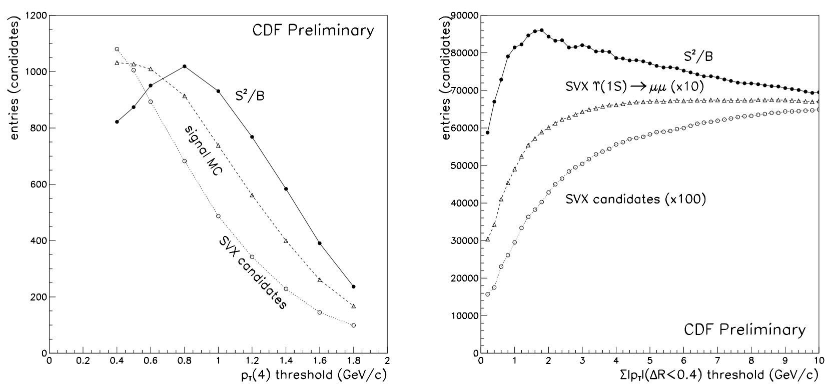

Figure 1. Selection optimizations for fourth track p_T (left) and isolation (right). The dashed line with triangles show the yield for the signal model, the dotted with circles the yield for the background model, and the solid line shows S^2/B.

The resulting mass distribution is shown in Fig. 2. Since the mass resolution is about 10 MeV/c^2, the signal is expected to be mostly contained in 4 bins ($\pm 2\sigma_m$) out of the 10-bin search window. A small cluster of 7 events, of which 1.8 are expected to be background based on the sidebands, is seen on the upper side of the search window. The probability that the background can mimic this cluster, assuming a Poisson variation in the observed sideband level, is calculated to be 1.5%, or about 2.2σ. A simple unbinned likelihood fit yields a mass of $9445 \pm 6(stat)$ MeV/c^2 for the cluster, or about 15 MeV/c^2 below the $\Upsilon(1S)$ mass. Energy loss corrections have not been applied but may be expected to be several MeV/c^2.

The robustness of the cluster has been checked by varying the selection criteria and observing the expected behavior. Furthermore, the analysis has been repeated without the mass constraint on the non-leading muon

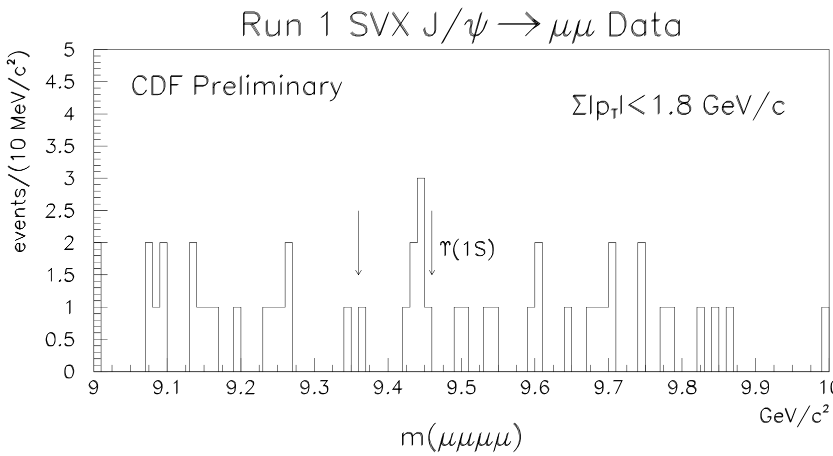

Figure 2. Mass distribution after selection. Arrows delimit the 100 MeV/c^2 search window, the upper side of which is set by the world-average $\Upsilon(1S)$ mass.

pair to confirm that they cluster around the J/ψ mass, as expected for η_b decay. An analysis using $J/\psi \to ee$ decays has also been performed, but the yield is too small to draw any firm conclusions.

3. Production Rate Limit

In light of the small cluster, an upper limit is calculated for η_b production and decay to $J/\psi J/\psi$,

$$\sigma_{\eta_b}(|y| < 0.4)B(\eta_b \to J/\psi J/\psi)[B(J/\psi \to \mu\mu)]^2 = \frac{N}{LA_{MC}\epsilon_{trig}\epsilon_{rec}} \quad (1)$$

where N is the number of events observed, L is the integrated luminosity of the data sample, A_{MC} is the acceptance calculated with simulation, and ϵ_{trig} and ϵ_{rec} are the trigger and reconstruction efficiencies not included in the simulation.

Additional selection criteria are necessary in order to reliably quantify the acceptance and efficiencies, and are chosen to follow those of the published Run 1 $B^+ \to J/\psi K^+$ cross section[13] wherever possible. Only data taken between 1994 and 1996 ("Run 1B") are used. Stricter requirements on the acceptance are applied, including limiting the identified muons to those found in the most central muon chambers, which cover $|\eta| < 0.6$. No isolation requirement is used. One event, with mass 9.45 GeV/c^2, remains in the search window after the additional requirements. Neglecting background, the 95% C.L. unified upper limit[14] on Eq. 1 is thus 18 pb.

The major systematic uncertainties arise from the luminosity calculation ($\pm 7\%$), J/ψ trigger simulation ($\pm 6\%$), measured $\Upsilon(1S)$ production cross section ($\pm 4\%$), CTC tracking efficiency ($\pm 3.6\%$), and muon reconstruction efficiency ($\pm 3.1\%$). The total relative systematic uncertainty is $\pm 11\%$.

The upper limit on the product of cross section and branching fractions lies above the 0.02 to 4 pb range expected from the aforementioned NRQCD predictions as well as previously measured branching fractions.[11] If the single event which survives the tighter criteria is assumed to be signal, the central value of the product is 3.5 pb, which is just within the upper expected range.

4. Conclusion

A search has been made for the η_b through its decay into two J/ψ's in Run 1 $J/\psi \to \mu\mu$ data. A small cluster is observed, with 7 events in the search window where 1.8 background events are expected based upon the mass sidebands. The probability that the background could mimic the cluster is assessed to be 1.5%, or about 2.2σ. A simple fit to the mass distribution gives $9445 \pm 6(stat)$ MeV/c^2 as the mass of the cluster, where the error is only statistical. The mass difference relative to $\Upsilon(1S)$ is on the low side of the theoretical expectation. Since the cluster is small, a 95% C.L. upper limit on $\sigma_{\eta_b}(|y| < 0.4)B(\eta_b \to J/\psi J/\psi)[B(J/\psi \to \mu\mu)]^2$ is calculated, giving 18 pb with an 11% relative systematic uncertainty. This limit is above the theoretical range of 0.02 to 4 pb, though the single event which survives the more restrictive cuts is consistent with the upper part of that range. Confirmation of this signal is already being pursued in Run 2 data, where the extended SVX coverage and lower p_T threshold for the upgraded central muon trigger improves the prospect of gathering a large sample of η_b decays at CDF in the near future.

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