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Evidence of the simultaneous production of J/ψ and Υ mesons

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We report evidence for the simultaneous production of J/ψ and Υ mesons in 8.1 fb^{-1} of data collected at $\sqrt{s}$ =1.96 TeV by the D0 experiment at the Fermilab $p\bar{p}$ Tevatron Collider. We observe 21 candidate events in data and estimate $14.5 \pm 4.6(\text{stat}) \pm 3.4(\text{syst})$ signal events in the J/ψ mass window $2.88 < M_{\mu\mu} < 3.32$ GeV/c^2 and Υ mass window $9.1 < M_{\mu\mu} < 10.2$ GeV/c^2. This corresponds to 3.5 standard deviation evidence.

Results for Summer 2015 Conferences

The importance of multiple parton interactions in hadron-hadron collisions as a background to processes such as Higgs production or various new phenomena has been often underestimated in the past. Recent data [1–8] on double parton interactions have attracted considerable theoretical attention [9–13].

In this analysis we search for simultaneous production of J/ψ and Υ mesons in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The production of two quarkonium states can be used to probe the interplay of perturbative and non-perturbative phenomena in quantum chromodynamics (QCD) and for searches for new bound states of hadronic matter such as tetraquarks [9, 14].

In $p\bar{p}$ collisions, there are three main production mechanisms for J/ψ mesons: prompt production (directly at the interaction point); as a radiative decay product of promptly produced heavier charmonium states such as the $^3P_1$ state χ_{1c} and the $^3P_2$ state χ_{2c}; and non-prompt B hadron decays. Υ mesons are only produced promptly, either directly or as a decay product of higher mass states, such as χ_{1b} or χ_{2b}.

Prompt heavy quarkonium production is described by three types of models: the color-singlet (CS) model [15]; the color evaporation model [16] with a follow-up soft color interaction model [17]; and the color-octet (CO) model [18]. At Tevatron and LHC energies, it is dominated by gluon fusion, $gg \to J/\psi(\Upsilon) + X$ [9, 19].

The production of J/ψ and Υ mesons is expected to be dominated by double parton (DP) interactions involving the collisions of two pairs of partons within the colliding beam particles. The simultanteous production through single parton (SP) interactions is suppressed by additional powers of α_s and by the small size of the allowable color octet matrix elements [10]. The DP process is estimated in Ref. [13] to contribute 97% of the total J/ψ + Υ production at the Tevatron. In this analysis we neglect the small SP process. Due to the dominance of gg scattering in the $p\bar{p}$ initial state, the spatial distribution of gluons in a proton [20] will be directly probed by the DP scattering rate, which represents simultaneous, independent parton interactions. In contrast, the existing DP studies involving vector bosons and jets probe the spatial distributions of quark-quark or quark-gluon initial states [1–5].

The analysis is based on a data sample collected by the D0 experiment at the Tevatron, which corresponds to an integrated luminosity of 8.1 ± 0.5 fb^{-1} [21]. The J/ψ and Υ mesons are fully reconstructed via their decay $J/\psi(\Upsilon) \to \mu^+\mu^-$. The muons in both cases are required to have transverse momenta $p_T^\mu > 2$ GeV/c and pseudorapidity $|\eta^\mu| < 2.0$ [22].

The D0 detector is a general purpose detector described in detail elsewhere [23]. The two sub-detectors used to trigger and reconstruct muon final states are the muon and the central tracking systems. The central tracking system, used to reconstruct charged particle tracks, consists of the inner silicon microstrip tracker (SMT) [24] and outer central fiber tracker (CFT) detector both placed inside a 1.9 T solenoidal magnet. The solenoidal magnet is located inside the central calorimeter. The muon detector [25] is the outermost detector system surrounding the calorimeters, consisting of three layers of drift tubes and two to three layers of plastic scintillators, one inside the 1.8 T iron toroidal magnets and two outside. The luminosity is measured using plastic scintillation counters surrounding the beams at small polar angles [21].

We require events to pass at least one of a set of low-p_T di-muon triggers. Identification of muons starts with requiring hits at least in the muon detector in the layer in front of the toroids [26]. The identification further proceeds by matching the hits in the muon system to a charged particle track reconstructed by the central tracking system. The track is required to have at least one hit in the SMT and at least two hits in the CFT detectors. To suppress cosmic rays, the muon candidates must satisfy strict timing requirements. Their separation at the distance of the closest approach to the beam line has to be less than 0.5 cm and their matching tracks have to pass within 2 cm of the interaction vertex along the beam axis. We require two oppositely charged muons, isolated in the calorimeter and tracking detectors [27] and with good matching of the tracks in the inner tracking and those in the muon detector, to be within the mass ranges $2.4 < M_{\mu\mu} < 4.2$ GeV and $8 < M_{\mu\mu} < 12$ GeV. The mass windows are chosen to be large enough to provide determination of backgrounds on either side of the J/ψ or Υ peaks. Events that have a pair of such muons in each of the two invariant mass windows are identified as J/ψ and Υ simultaneous production candidates. Background events are mainly due to random combinations of muons from $\pi^\pm$, $K^\pm$ decays (decay background), and continuous non-resonant $\mu^+\mu^-$ Drell-Yan (DY) production. In the case of $J/\psi + \Upsilon$ production, there is also a background where one muon pair results from a genuine J/ψ or Υ decay and the other pair is a non-resonant combination of muons $(J/\psi(\Upsilon) + \mu\mu)$.

In the data, 21 events pass the selection criteria for $J/\psi+\Upsilon$ in the J/ψ mass window $2.88 < M_{\mu\mu} < 3.32$ GeV/c^2 and Υ mass window $9.1 < M_{\mu\mu} < 10.2$ GeV/c^2. Fig. 1 shows the distribution of the two dimuon masses $(M_{\mu\mu}(J/\psi, \Upsilon))$ in these and surrounding mass regions. We estimate the accidental and $J/\psi(\Upsilon) + \mu\mu$ backgrounds using the same technique as in [6]. We fit a two-dimensional distribution of the $M_{\mu\mu}(J/\psi)$ vs. $M_{\mu\mu}(\Upsilon)$ and estimate the amount of $J/\psi + \Upsilon$(1S,2S,3S) signal to be $N_{sig} = 14.5 \pm 4.6(\text{stat}) \pm 3.4(\text{syst})$. The probability of the observed number of events to have arisen from the background is 2.5×10^{-4} corresponding to 3.5 standard deviation evidence for the double quarkonium production. The distribution of the azimuthal angle between the J/ψ and Υ candidates, $\Delta\phi(J/\psi, \Upsilon)$

after the subtraction of backgrounds is shown in Fig. 2. The data $\Delta\phi(J/\psi, \Upsilon)$ distribution is consistent with DP MC model, which is flat [10], substantiating our assumption that the DP process is the dominant contribution to the selected data.

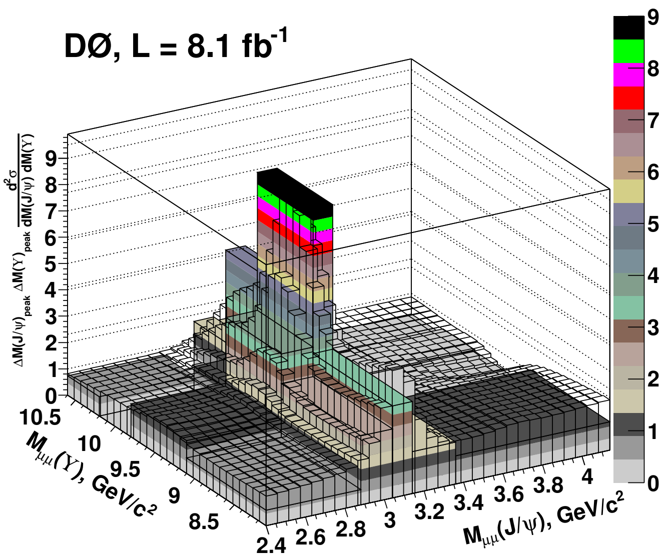

FIG. 1: (color online) Dimuon invariant mass distribution in data for two muon pairs, $M_{\mu\mu}(J/\psi)$, $M_{\mu\mu}(\Upsilon)$, after the selection criteria. This double differential distribution is normalized such that the content of the highest bin represents the actual number of events observed in that bin. Also shown is the two-dimensional fit surface.

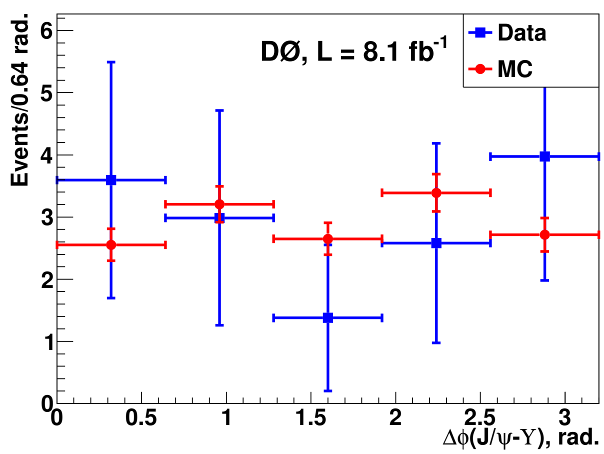

FIG. 2: (color online) The distribution of the azimuthal angle between the J/ψ and Υ candidates, $\Delta\phi(J/\psi, \Upsilon)$, in data after background subtraction and in DP MC. MC is normalized to the integrated luminosity.

In conclusion, we have seen the first evidence of simultaneous production of J/ψ and Υ(1S,2S,3S) mesons with the significance of 3.5 standard deviations. The distribution of the azimuthal angle between the J/ψ and Υ candidates is consistent with the DP scattering MC model. We are continuing this analysis to determine the simultaneous DP cross cross section for $J/\psi + \Upsilon$ production, and to measure the effective cross section which probes the spatial distribution of the initial state partons.

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