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Limit on Υ Muoproduction at 209 GeV

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We present the dimuon mass spectrum from 102 678 three-muon final states produced by muon interactions within a magnetized steel calorimeter. The data place a 90%-confidence-level upper limit on the production of Υ states by muons: $\sigma(\mu N \to \mu \Upsilon X)B(\Upsilon \to \mu^+\mu^-) < 22\times 10^{-39}$ cm^2, consistent with a photon-gluon-fusion model calculation.

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We report a limit on Υ production by 209-GeV muons in the Berkeley-Fermilab-Princeton multimuon spectrometer at Fermilab.[1] An integrated luminosity of 0.78×10^{39} cm^{-2}, corresponding to 75% of the full data sample, has yielded 102 678 trimuon final states, including 6693 ± 355 examples of J/ψ and ψ' production. In every event, all three outgoing muons are fully momentum analyzed and are subjected to an energy-conserving one-constraint fit using calorimetric measurement of the associated shower energy.

No limit on Υ production by real or virtual photons has been published. A conference report[2] based on results from the Bologna-CERN-Dubna-Munich-Saclay (BCDMS) experiment presents the limit $\sigma(\mu N \to \Upsilon X)B(\Upsilon \to \mu^+\mu^-) < (6\pm 3)\times 10^{-39}$ cm^2 (at 90% confidence level) for ~275-GeV muons, where the error is systematic. This limit is based on 761 multimuon events corresponding to an integrated luminosity[2] of 0.7×10^{39} cm^{-2}. A third muon was observed in 11% of these events. No calorimetric information was available. With 48% Υ acceptance, the BCDMS limit corresponds to ≤2 Υ candidates (at 90% confidence level). In total, the experiment observed 24 events between 8 and 12 GeV/c^2 in dimuon mass. These were compared to a calculated background of 30 electromagnetic tridents in the same region.

We have calculated the expected Υ rates using a photon-gluon-fusion (γGF) model[3] which accounts[4] for most of the published features[1] of ψ muoproduction. It uses a Bethe-Heitler diagram for heavy-quark–pair production with the nuclear photon replaced by a gluon. Additional soft-gluon exchanges needed to conserve color are assumed not to affect the kinematics. With a distribution $G(x) = 3(1-x)^5/x$ in gluon momentum fraction x, a bottom quark mass $m_b = 4.7$ GeV/c^2, a bottom quark charge $|q_b| = \frac{1}{3}$, and a strong-coupling constant $\alpha_s = 1.5/\ln(4m_{b\bar{b}}^{\,2})$, where $m_{b\bar{b}}$ is the mass in GeV/c^2 of the produced quark pair, the model predicts Υ muoproduction cross sections of 0.13×10^{-36} cm^2 at 209 GeV and 0.28×10^{-36} cm^2 at 275 GeV. With $B(\Upsilon \to \mu^+\mu^-) = (3.1\pm 0.9)\%$,[5] the expected values of $B\sigma$ are $(4.0\pm 1.2)\times 10^{-39}$ and $(8.7\pm 2.5)\times 10^{-39}$ cm^2, respectively. The BCDMS upper limit is (70 ± 40)% of the latter cross section.

Figure 1 displays the spectrum in dimuon mass $M_{\mu^+\mu^-}$ from this experiment. Events below 5 GeV/c^2 in $M_{\mu^+\mu^-}$ are reconstructed and momentum fitted as described in Ref. 1. Above 5 GeV/

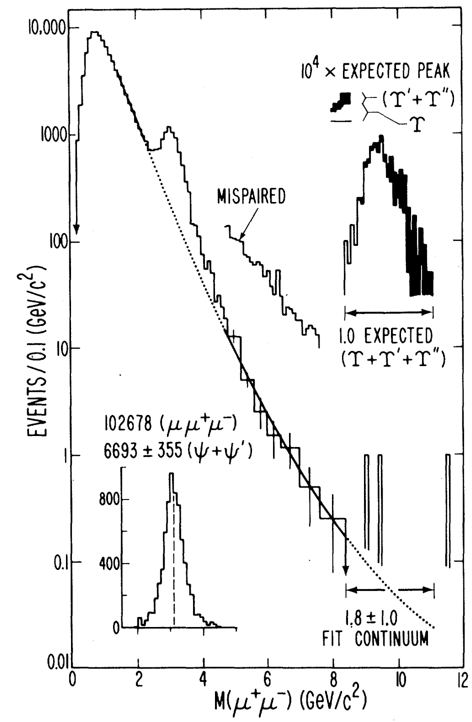

FIG. 1. Spectrum of 102 678 dimuon masses from 75% of the trimuon data. The background is fitted by $\exp(a+bM+cM^2)$ in the regions of the solid curve with a χ^2 of 13.7 for 14 degrees of freedom, and is extrapolated along the dotted curve. The "mispaired" histogram segment illustrates the appearance of the mass spectrum if the alternative muon-pairing choice is made. The background-subtracted ψ peak is shown in the lower corner; the expected peak from 10^4 times the Monte Carlo–simulated Υ, Υ', and Υ'' sample is shown in the upper corner, with the contribution from Υ' and Υ'' in black.

c^2, the analysis of all events was checked by a hand reconstruction which was blind to the invariant mass. At all masses the assignment of beam-sign secondary muons either to the scattered muon or to the produced muon pair is the critical decision in the analysis. Incorrect pairing of muons from ψ or muon trident production can cause events which properly belong in the low-mass region to be misinterpreted as having a higher mass. Our muon-pairing algorithm was selected primarily to minimize this problem. The scattered muon is chosen to be the one with the smaller value of the square of its scattering angle divided by its scattered energy. The algorithm is 89% efficient in reconstructing Υ's generated by the Monte Carlo simulation described below. The alternative choice for the scattered muon would produce more than a one-order-of-magnitude exaggeration of the high-mass continuum near the Υ, as shown by the "mispaired" histogram segment in Fig. 1. We emphasize that the muon-pairing algorithm can be optimized only if all three final-state muons are momentum analyzed.

Despite the care exercised in muon pairing, Monte Carlo studies show that there remains a significant contribution in the region $4.7 < M_{\mu^+\mu^-} < 8.4$ GeV/c^2 from incorrectly analyzed lower-mass events. Allowance for these effects is most reliably made by use of an empirical fit to the mass continuum. This mass region, together with the range $1.5 < M_{\mu^+\mu^-} < 2.3$ GeV/c^2, was chosen for the fit in order to exclude regions complicated by charmonium production or rapid variations in low-mass acceptance. After subtraction of the fit continuum, the ψ peak in Fig. 1 exhibits an 8.5% rms resolution, ≈ 1% larger than the Monte Carlo prediction.[1] The extrapolated continuum contains 1.8± 1.0 background events in the Υ region $8.4 < M_{\mu^+\mu^-} < 11.1$ GeV/c^2, which in fact includes two observed events. The additional event at 11.5 GeV/c^2 is interpreted as continuum background with 65% probabiltiy, or as part of the peak corresponding to known Υ states with 1% probability. With 90% confidence, there are fewer than 3.8 events above the extrapolated background.

The Monte Carlo program used to simulate Υ muoproduction is based on a routine which successfully parametrizes our ψ data.[1] It is adapted to Υ simulation by appropriately scaling the vector-meson-mass–dependent parameters. Simulated Υ mass resolution and detection efficiency are 9% (rms) and 22%, respectively. The Υ cross section is normalized to the γGF value described above. Υ, Υ', and Υ'' states are generated in the ratio 1:0.39:0.32 in agreement with recent measurements of $\Gamma_{ee}(\Upsilon):\Gamma_{ee}(\Upsilon'):\Gamma_{ee}(\Upsilon'')$.[6] Υ' and Υ'' production suffer an additional ≈ 30% suppression relative to Υ production because of threshold kinematics. The reconstructed peak corresponding to 10^4 times the expected signal is shown in Fig. 1; 1.0 events from all Υ states are expected in the data.

Our 3.8-event limit, integrated luminosity, and detection efficiency combine to set the 90%-confidence-level upper limit[7] $\sigma(\mu N \to \mu\Upsilon X)B(\Upsilon \to \mu^+\mu^-) < 22\times 10^{-39}$ cm^2. With $B(\Upsilon \to \mu^+\mu^-) = (3.1\pm 0.9)\%$,[5] we obtain the 90%-confidence-level cross-section upper limit $\sigma(\mu N \to \mu\Upsilon X) < 0.79\times 10^{-36}$ cm^2, including the error in the branching ratio. This limit lies above published predictions which use either the vector-meson dominance[8,9] or the γGF[10] models. If one ignores any γGF-model uncertainty, this result rules out the choice $|q_b| = \frac{2}{3}$ with 85% confidence. With 67% confidence, the data disfavor the existence of similar bound states of a second charge-$\frac{1}{3}$ quark in the Υ mass region.

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[3]J. P. Leveille and T. Weiler, Nucl. Phys. B147, 147 (1979), and references cited therein. In this model the fraction of bound heavy quarks in the 1S state is perhaps best regarded as a fit parameter. In agreement with ψ data (Ref. 1) we use the value $\frac{1}{6}$. See V. Barger, W. Y. Keung, and R. J. N. Phillips, University of Wisconsin Report No. 79-0776 (unpublished).

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[5]K. Berkelman, summary of DORIS results, in Proceedings of the Fifteenth Rencontre de Moriond, Les Arcs, Savoie, France, 9–21 March 1980 (to be published). If the bottom quark were to have charge $\frac{2}{3}$, a substantially larger branching ratio would be expected.

[6]T. Bohringer *et al.*, Phys. Rev. Lett. 44, 111 (1980). Because of lack of information, we simply assume that Υ' and Υ'' have the $\Upsilon \to \mu^+\mu^-$ branching ratio.

[7]Strictly speaking, our limit is on $\Sigma_V \sigma(V) B(V \to \mu^+\mu^-)$, where V runs over Υ, Υ', and Υ''. Our Υ' and Υ'' assumptions would then lead to a limit on Υ production which is 36% stronger than the limit which we have quoted.

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Measuring Quantum-Chromodynamic Anomalies in Hadronic Transitions between Quarkonium States

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It is argued that the ratio $\Gamma((\bar{Q}Q)' \to (\bar{Q}Q)\eta)/\Gamma((\bar{Q}Q)' \to (\bar{Q}Q)\pi\pi)$ of hadronic transition rates between heavy quarkonium states is calculable within quantum chromodynamics in terms of triangle anomalies in the divergence of the axial current and in the trace of the energy-momentum tensor. In the case of transitions between ψ' and J/ψ the present analysis is consistent with the data. More reliable test can be provided by experimental study of the transitions between Υ'' and Υ.

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Hadronic transitions between quarkonium levels, like $\psi' \to (J/\psi)\pi\pi$ and $\psi' \to (J/\psi)\eta$ decays, can provide an insight into gluonic physics. Indeed, the transition can be viewed as a two-step process: first, emission of soft gluons by heavy quarks, and then conversion of the gluons into light hadrons.[1] As realized first by Gottfried,[2] the gluon emission can be described by the gluon multipole expansion.[2-4] The point is that heavy quarkonium is a rather compact object in the typical hadronic scale. On the other hand, gluon conversion which effectively measures the gluon admixture in ordinary hadrons is a large-distance process and is most difficult to trace theoretically.

