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High-resolution measurement of massive-dielectron production in 800-GeV proton-beryllium collisions

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The hadronic production of dielectrons in the Υ region has been measured with a mass resolution of 0.17% using incident protons with momentum of 800 GeV/c. The cross sections of the Υ resonances are compared with the predictions of a gluon-fusion model. The dielectron continuum is also compared with the Drell-Yan prediction, and the K factor is extracted. The results on the mean transverse momentum of the resonances and that of the continuum are also presented.

The hadronic production of dileptons in the high-mass region has been a fruitful arena in which to test our knowledge of the internal structure of hadrons, since the continuum production reflects the quark and antiquark distributions in hadrons, while the Υ production reflects the gluon distribution in hadrons and is a sensitive way to study QCD higher-order processes.

We report here on a high-resolution measurement of inclusive dielectron production in proton-nucleus collisions. The Fermilab 800-GeV proton beam was incident upon beryllium targets of 55.9 or 58.7 mm in length. An invariant-mass range from 8 to 20 GeV/c^2 was studied. The apparatus was similar to that used to study hadron production with 400-GeV protons, which has been reported elsewhere,[1] and was designed so as to perform simultaneous measurement of high-p_T single-particle production and high-invariant-mass pair production of electrons, muons, and hadrons. Two powerful spectrometer magnets SM12 and SM3 gave p_T kicks of 7.5 and 0.9 GeV/c, respectively, to charged particles emerging from the target. These particles passed through the apparatus which was designed to focus only high-mass pairs on the downstream detectors and to sweep out low-momentum background particles from the aperture.

In preparation for use of the 800-GeV proton beam, a few modifications were made to the original apparatus.[2] First, the target was moved upstream by 330 cm in order to keep out acceptance centered near 90° in the proton-nucleon center-of-momentum frame. A tungsten collimator was placed at the entrance to SM12 to absorb all particles emitted at vertical angles less than 37.1 mrad. Also, carefully designed tungsten and lead baffles were installed along the walls of SM12 to absorb photons emitted by π^0's. These modifications enabled us to increase the luminosity over previous exposures by a factor of 4 without excesses of single counts in all detector elements. Our apparatus was able to operate up to a luminosity of about $1\times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The calorimeter, placed 50 m downstream of the target, consisted of an electromagnetic (EM) part and a hadronic part.[1,2] This calorimeter was used to provide fast trigger signals for the data acquisition and to distinguish electrons from hadrons in the off-line data analysis. The total thickness of the EM part was 19 radiation lengths. Events which deposited energy of more than 80 GeV in the front three modules, 13 radiation lengths, of the EM part were recorded.

Data corresponding to an integrated luminosity per nucleon of $L = 1.2\times10^{40}$ cm^{-2} were collected and analyzed, and 208 dielectron events survived after the off-line analysis cuts. The particle trajectories were reconstructed by requiring at least 3 hits on 6 multiwire proportional chambers (MWPC's) and at least 8 hits on 12 drift chambers. The momentum of each particle was determined from the trajectory emerging from SM12 under the assumption of a point target origin. This was confirmed by the measured deflection in SM3. From the cluster of the energy deposited around each trajectory in the calorimeter, the ratio of the energy deposit in the EM part to the total energy deposit was calculated for each trajectory. A particle was identified as an electron if the ratio exceeded 0.94. The rejection factor for single hadrons was estimated to be 830, while maintaining the efficiency for the dielectron events to be larger than 98%. Muons were rejected by searching for tracks in the three proportional-tube planes and two hodoscope planes behind the calorimeter.

The acceptance (fraction of events recorded at a given mass) was calculated by the Monte Carlo method. In this simulation, we simulated not only the geometrical configuration but also known effects such as multiple scattering, electron breesstrahlung, energy loss due to ionization, radiative corrections, synchrotron radiation in the magnets, the spatial resolution of the drift chambers and the efficiencies of the counters and chambers. The acceptance covered the dielectron mass range from 8 to 20 GeV/c^2, the p_T range from 0 to 4 GeV/c, the rapidity y range from -0.5 to 0.3, and the range of decay angles $-0.4 < \cos\theta^* < 0.4$ in the Gottfried-Jackson frame. A decay-angular distribution $1+\cos^2\theta^*$ for the continuum was assumed in this frame. Isotropic decay was assumed for the Υ resonance. The rapidity dependence of the Υ production expected by the fusion model[3] based on the semilocal-duality hypothesis[4] was also taken into account.

Figure 1 shows the mass spectrum in the mass range from 8.9 to 10.8 GeV/c^2. While the Υ and Υ' are clearly seen, the Υ'' is not clear due to poor statistics. The curve superimposed on this figure represents the shape which was determined by the Monte Carlo method, including the Υ'', because the Υ'' has been confirmed by our dimuon data.[5] The shape of each resonance is not symmetric but has a tail below the peak due to radiation of real and virtual photons from the final-state electrons. The dielectron mass resolution ($\Delta m/m$) was 0.17% (standard deviation) at the resonance. This fine resolution allowed us to separate clearly the resonances from the continuum and to evaluate accurately the cross section for the Υ resonances. The branching ratio times cross section for the three resonances is

$$B\,d\sigma/dy\,|_{y=0}(\Upsilon+\Upsilon'+\Upsilon'') = 2.31\pm0.37\pm0.12\ \text{pb/nucleon}\,.$$

The first error is statistical, and the second is the uncertainty due to the normalization. The ratios $[B'd\sigma/dy(\Upsilon')]/[B\,d\sigma/dy(\Upsilon)]$ and $[B''d\sigma/dy(\Upsilon'')]/[B\,d\sigma/$

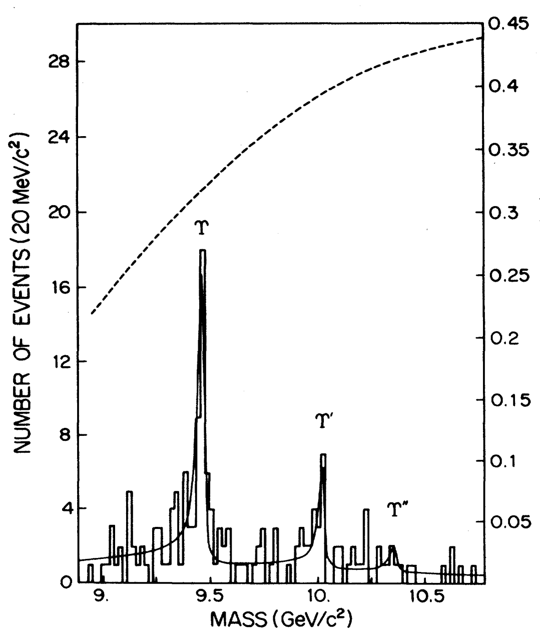

FIG. 1. The mass spectrum of dielectrons in the mass range from 8.9 to 10.8 GeV/c^2. The solid curve shows the fit with the three Υ resonances. The dashed curve shows our average acceptance.

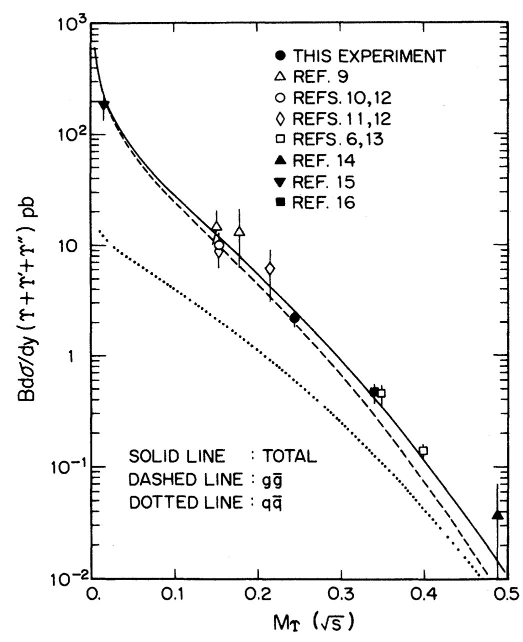

FIG. 2. The branching ratio times cross section for the Υ resonances versus $M_\Upsilon/\sqrt{s}$, together with the results of other experiments (Refs. 6 and 9–16). The solid line is the fits based on the gluon-fusion model with the EHLQ distribution of set II (Ref. 17). The dashed and dotted lines are the contributions of $g\bar{g}$ and $q\bar{q}$, respectively.

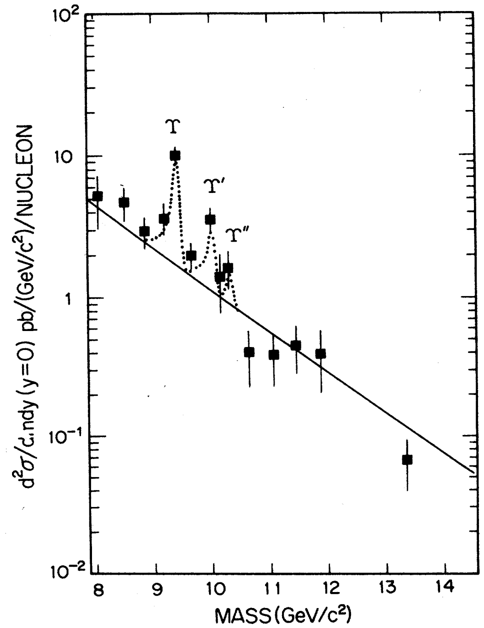

FIG. 3. The cross section of dielectron production vs the dielectron invariant mass. The solid line shows the K factor times naive Drell-Yan prediction based on the Q^2-dependent distribution of set II by EHLQ (Ref. 17).

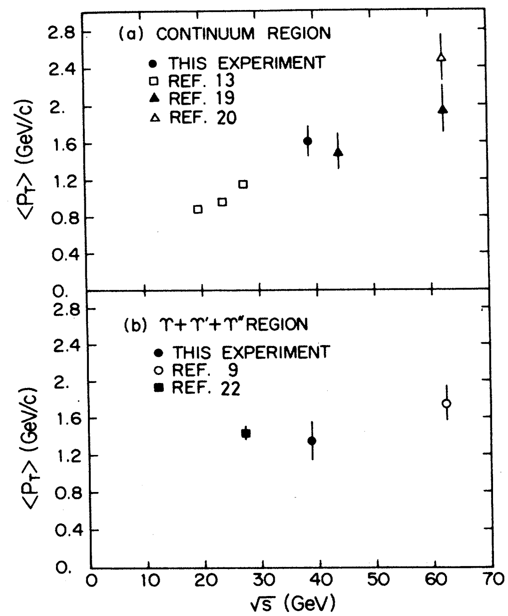

FIG. 4. (a) The mean transverse momentum of the continuum vs $\sqrt{s}$ for $m/\sqrt{s}=0.22$, and (b) that of the Υ resonances.

$dy(\Upsilon)]$ are 0.31 ± 0.11 and 0.09 ± 0.06, respectively. These ratios are consistent with the results obtained at 400 GeV.[6] Using the world-average branching ratios,[7] the production ratios $[d\sigma/dy(\Upsilon')]/[d\sigma/dy(\Upsilon)]$ and $[d\sigma/dy(\Upsilon'')]/[d\sigma/dy(\Upsilon)]$ are 0.50 ± 0.21 and 0.08 ± 0.06, respectively, while the prediction by Baier and Ruckl[8] based on the fusion model gives a value of less than 0.3 for the ratio $[d\sigma/dy(\Upsilon')]/[d\sigma/dy(\Upsilon)]\,|_{y=0}$.

Our results for $B\,d\sigma/dy\,|_{y=0}(\Upsilon+\Upsilon'+\Upsilon'')$ is shown in Fig. 2, together with the results of other experiments,[6,9-16] as a function of $M_\Upsilon/\sqrt{s}$. The theoretical prediction based on the fusion model shows that the $M_\Upsilon/\sqrt{s}$ dependence of Υ production is sensitive to the shape of the gluon distribution function. The data in Fig. 2 were fitted with the prediction by the fusion model[3] by using the Q^2-dependent gluon distribution given by Eichten, Hinchliffe, Lane, and Quigg (EHLQ).[17] Because this prediction is based on the semilocal duality hypothesis,[4] the normalization factor was the fitting parameter. The χ^2/(degrees of freedom)'s were 12.1/10 and 6.96/10 for set I and set II of the EHLQ distribution, respectively.

The dielectron differential mass spectrum is given in Fig. 3. The spectrum of the continuum from 8 to 15 GeV/c^2 was compared with the Drell-Yan prediction[18] to determine the K factor, i.e., the ratio of the measured cross section to the naive prediction. Using the EHLQ quark distribution,[17] the K factors are evaluated to be 3.13 ± 0.29 and 2.33 ± 0.23 for set I and set II, respectively. This difference is mainly due to the difference on the distribution of sea quarks. The observed ratio of the resonance to the continuum $[B\,d\sigma/dy(\Upsilon+\Upsilon'+\Upsilon'')]/[d\sigma/dm\,dy(\text{continuum};\ m=9.46\text{ GeV})]$ is estimated to be (1.34 ± 0.24) and (1.35 ± 0.25) GeV by fitting the continuum with the EHLQ distribution of set I and set II including the K factor, respectively.

The mean transverse momentum $\langle p_T \rangle$ of the continuum is also evaluated to be 1.61 ± 0.16 GeV/c. Since our data have an average value of $m/\sqrt{s}=0.22$, our results and those of other experiments in the same region of $m/\sqrt{s}$ are plotted as a function of $\sqrt{s}$ in Fig. 4(a).[13,19,20] As predicted by the QCD correction to the Drell-Yan process,[21] the $\langle p_T \rangle$ goes up as the collision energy increases. The $\langle p_T \rangle$ of the Υ resonance is 1.35 ± 0.21 GeV/c and is shown in Fig. 4(b).[19,22] This figure shows that the $\langle p_T \rangle$ is already large at the small $\sqrt{s}$ and is constant in the range of 28 GeV $< \sqrt{s} <$ 62 GeV.

In summary, we have measured the hadronic production of dielectrons in the Υ region at 800 GeV with a mass resolution of 0.17%. The production ratios of three Υ resonances are consistent with the data obtained at 400 GeV, but are somewhat large compared with the prediction based on the gluon-fusion model. The K factors are also extracted by using the Q^2-dependent EHLQ quark distribution. The mean transverse momentum $\langle p_T \rangle$ of the Υ's is consistent with no energy dependence.

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