Production of J/ψ via ψ' and χ Decay in 300 GeV/c Proton- and $\pi^{\pm}$-Nucleon Interactions

L. Antoniazzi,[3] M. Arenton,[9] Z. Cao,[8] T. Chen,[5] S. Conetti,[4] B. Cox,[9] S. Delchamps,[3] L. Fortney,[2] K. Guffey,[7] M. Haire,[4] P. Iaonnou,[1] C. M. Jenkins,[3] D. J. Judd,[7] C. Kourkoumelis,[1] A. Manousakis-Katsikakis,[1] J. Kuzminski,[4] T. LeCompte,[6] A. Marchionni,[4] M. He,[8] P. O. Mazur,[3] C. T. Murphy,[3] P. Pramantiotis,[1] R. Rameika,[3] L. K. Resvanis,[1] M. Rosati,[4] J. Rosen,[6] C. Shen,[8] Q. Shen,[2] A. Simard,[4] R. P. Smith,[3] L. Spiegel,[3] D. G. Stairs,[4] Y. Tan,[6] R. J. Tesarek,[2] T. Turkington,[2] L. Turnbull,[7] F. Turkot,[3] S. Tzamarias,[6] G. Voulgaris,[1] D. E. Wagoner,[7] C. Wang,[8] W. Yang,[3] N. Yao,[5] N. Zhang,[8] X. Zhang,[8] G. Zioulas,[4] and B. Zou[2]
(E705 Collaboration)

[1]*University of Athens, Athens, Greece*
[2]*Duke University, Durham, North Carolina 27706*
[3]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[4]*McGill University, Montreal, PQ, Canada H3A 2T8*
[5]*Nanjing University, Nanjing, People's Republic of China*
[6]*Northwestern University, Evanston, Illinois 60208*
[7]*Prairie View A&M University, Prairie View, Texas 77445*
[8]*Shandong University, Jinan, Shandong, People's Republic of China*
[9]*University of Virginia, Charlottesville, Virginia 22901*

(Received 21 May 1992; revised manuscript received 21 October 1992)

The production of the χ_1 and χ_2 states of charmonium has been observed in 300 GeV/c $\pi^{\pm}N$ and pN interactions. The fraction of the total inclusive J/ψ production due to radiative χ decay has been determined to be 0.40 ± 0.04, 0.37 ± 0.03, and 0.30 ± 0.04 for the π^+, π^-, and proton data, respectively. Total cross sections for χ_1 and χ_2 production of $131\pm18\pm14$ and $188\pm30\pm21$ nb/nucleon in the 300 GeV/c π^-N interactions have been obtained. By measuring the contributions to the J/ψ production due to both ψ' and radiative χ decay, the cross sections for direct J/ψ production have been determined to be 97 ± 14, 102 ± 14, and 89 ± 12 nb/nucleon for π^+, π^-, and protons, respectively.

PACS numbers: 13.85.Ni, 13.40.Hq, 14.40.Gx

A considerable fraction [1] of the $J^{PC}=1^{--}$ J/ψ's produced in hadronic interactions results from the production of the $J^{PC}=1^{++}$ (χ_1) and 2^{++} (χ_2) states of charmonium followed by their radiative decays into $\gamma\psi$. The $J^{PC}=0^{++}$ (χ_0) state has a small branching ratio to J/ψ and is not expected to contribute appreciably to J/ψ production. In the color singlet model [2], the direct production of the J/ψ must proceed (because of conservation of angular momentum, charge conjugation, and parity) by three gluon or quark annihilation processes. Alternatively, within the color singlet model, the production of J/ψ's can proceed indirectly via production of the χ states with relatively large cross sections by the two gluon fusion, followed by the decay of the χ states into final states containing J/ψ's. A second production process is provided by the color evaporation model [3] in which the $c\bar{c}$ pair is initially produced in a colored, unbound state and the final noncolored singlet state is reached via the emission of a gluon. Therefore, an important facet of the untangling of the hadronic production mechanisms for hidden charm states is the determination of the fraction of the J/ψ production resulting from decays of the χ states. In order to ascertain the formation mechanisms for these charmonium states and, ultimately, to extract the gluon structure functions from the study of their production by various beam types, we have performed an experiment to measure the fraction of J/ψ arising from the χ radiative decays. In the process, we have determined the cross section for production of the χ states, by combining our measurement of the J/ψ cross section together with our high-statistics measurement of the ratio of $(\chi_1+\chi_2)/\psi$ production and a previous measurement [4] of the ratios of χ_1/ψ and χ_2/ψ production.

Our experiment, Fermilab E705, was performed with 300 GeV/c $\pi^{\pm}$, proton, and antiproton beams incident on a 5-cm-radius, 33-cm-long ^{7}Li target (0.21 radiation length; 0.24 and 0.175 interaction length for protons and pions, respectively) in the P-West High Intensity Laboratory at Fermilab. The beam particles were tagged with two gas Cherenkov counters operated in the threshold mode; the 300 GeV/c negative beam was 98% π^- and 2% antiprotons and the positive beam was 55% protons and 45% π^+. A small charged K contamination (estimated to be less than 6% of the total beam flux) was present in both the positive and negative beams.

The χ states produced by the four beam types were observed via their radiative decays

$$
\begin{aligned}
p^{\pm},\pi^{\pm}N &\to \chi_1,\chi_2 \\
&\qquad \hookrightarrow J/\psi+\gamma \\
&\qquad\qquad \hookrightarrow \mu^+\mu^-
\end{aligned}
$$

using a large-aperture open-geometry spectrometer [5], an element of which was a large electromagnetic (EM) detector [6] composed of a main array of approximately 400 lead (PbO) and scintillating (BaO loaded with Ce_2O_3) glass elements together with a photon preconverter for photon identification, and position and energy measurement. This choice of EM detector offered a reasonable compromise between the need to operate at high rates without significant radiation damage and the desire to maintain good photon energy resolution for photons of quite low energy (down to 2 GeV).

An equally important aspect of the spectrometer was a two-level dimuon trigger. The first level required that two or more muons penetrate 0.40 m of Cu, 3.7 m of steel, and 0.91 m of shielding concrete, causing appropriate triple coincidences between the elements of three banks of scintillation counters placed at various depths in the absorbing material. The second level consisted of a trigger processor [7] which processed hits from drift chambers downstream of the spectrometer analysis magnet to find tracks pointing at the muon counter triple coincidences. These tracks were used to form a crude dimuon mass under the assumption that each track originated in the target. All events passing a mass cut of 2.4 GeV/c^2 were written to tape. The suppression of the total cross section by this trigger system was approximately a factor of 3×10^{-4}. Over 140 million dimuon triggers were accumulated in this manner at interaction rates of up to 1.5 MHz.

The mass spectra of all opposite-charge muon pairs obtained by these triggers are shown in Fig. 1 for the four different beam types, $p^{\pm}$ and $\pi^{\pm}$. A clear J/ψ signal is seen with the expected resolution of $\sigma\approx60$ MeV/c^2 in each of the four spectra. Differential and total cross sections for production of the J/ψ and ψ' as measured in this experiment are given in Ref. [8] for the four beam types.

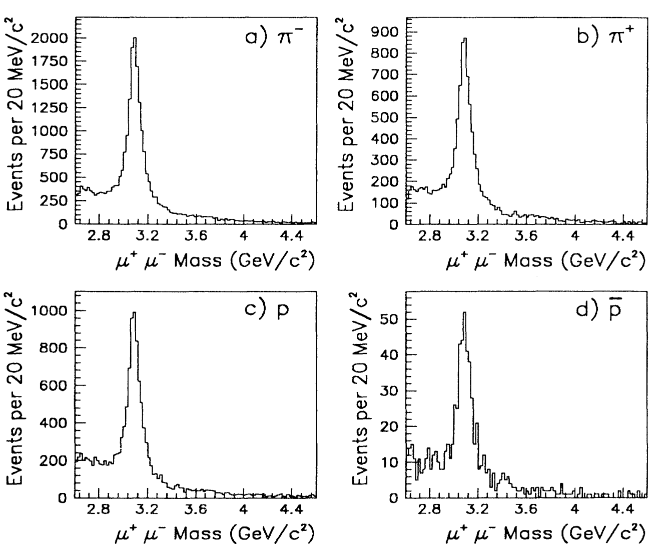

FIG. 1. E705 $\mu^+\mu^-$ mass spectra for (a) π^-, (b) π^+, (c) proton, and (d) antiproton ^{7}Li interactions at 300 GeV/c.

Approximately 32 150 $J/\psi\to\mu\mu$ candidate events with mass between 2.88 and 3.28 GeV/c^2 yielded approximately 24 440 J/ψ events in total for all four beam types (12470 ± 160, 5560 ± 90, and 6090 ± 90 J/ψ's for π^-, π^+, and proton data, respectively, after background subtraction). A selected subset of these J/ψ events was used in the search for the radiative decays of the charmonium χ states. For this measurement, the muon pairs were combined with all photons in a given event other than those from reconstructed π^0 decays. The average multiplicity of non-π^0 photons per event is 1.43 ± 1.00. The difference between the invariant mass of $\mu^+\mu^-\gamma$ and $\mu^+\mu^-$ combinations is shown in Fig. 2 for our $\pi^{\pm}N$ and pN data. Use of the mass difference spectra allows us to eliminate part of the experimental error in the mass resolution of the $\gamma\psi$ final states; the resulting mass distributions show a clear peak in the region of the χ_1-ψ and χ_2-ψ mass differences (expected values 414 and 459 MeV/c^2). The numbers of events in the χ peaks were 300 ± 35, 590 ± 50, and 250 ± 35 for the π^+, π^-, and proton data, respectively, after subtraction of background.

Uncorrelated $\gamma\psi$ backgrounds were constructed by pairing photons and J/ψ from different events, provided that both the photon and the J/ψ could have contributed to the difference mass spectra. Correlated $\gamma\psi$ backgrounds due to ψ' decays (such as $\psi'\to J/\psi\pi^0\pi^0$, $\psi\eta^0$, or $\psi\gamma\gamma$ via an intermediate χ state) were studied. In spite of the non-negligible contributions to the mass spectra below the χ states, none of these ψ' decays can kinematically generate $\gamma\psi$ combinations with mass equal to or larger

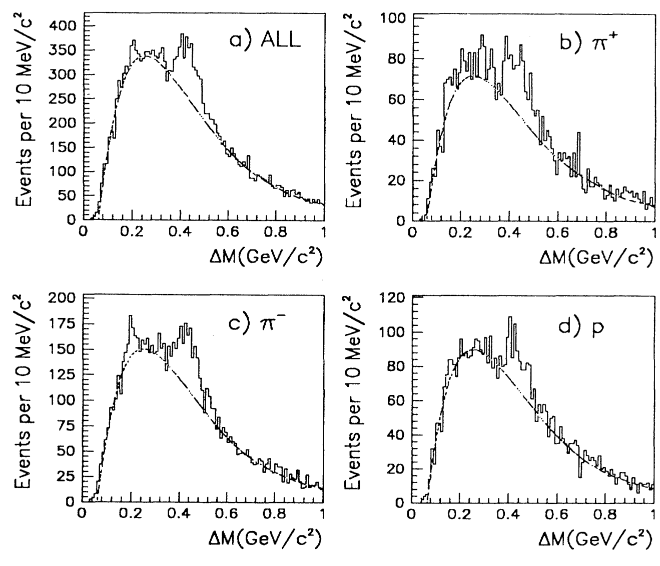

FIG. 2. E705 $M(\mu^+\mu^-\gamma)-M(\mu^+\mu^-)$ mass difference spectra for (a) all beam types, (b) π^+, (c) π^-, and (d) proton ^{7}Li interactions at 300 GeV/c. The backgrounds superimposed on the mass difference spectra are generated from pairing photons and J/ψ's from different events. ψ' decays resulting in J/ψ final states are also included in the background estimates.

than the ones corresponding to the χ_1, χ_2 states. Therefore, to avoid the uncertainties in the low mass spectrum associated with the ψ' decays or unknown $\chi(0^{++})$ or $^1P_1$ production and decay into $\gamma\psi$, the backgrounds in the χ_1 and χ_2 region have been estimated by fitting the uncorrelated background shape to the mass region above the χ peak. These background distributions are shown superimposed on the mass difference spectra in Fig. 2.

The acceptance of the electromagnetic spectrometer for the photons in the χ events was determined to be 0.60 ± 0.01 for both pion and proton data. These acceptances were calculated using a flat χ photon angular distribution and p_t and x_F distributions for χ production equal to those observed in J/ψ production [8]. Theoretical models [9] suggest the possibilities of different forms for the photon angular distribution. For a photon angular distribution of $1-\frac{1}{3}\cos\theta^2$ (corresponding to the maximum excursion among the theoretical models investigated), the acceptance could be as large as 65%. Changes of one unit in the exponents in the assumed x_F and p_t distribution, $E\,d^3\sigma/dp^3 \approx p_t \exp[-(p_t/p_0)^2](1-|x_F-x_0|^c)$, an extremely large variation, could decrease the acceptance to 57%.

The reconstruction and pattern recognition efficiency for the photons in the acceptance of the EM detector was $0.27 \pm 0.01 \pm 0.03$. The first error is due to the statistics of the Monte Carlo χ events used in the determination of the efficiencies and the second to the systematics of using e^+e^- pairs to estimate the efficiency of the χ photon pattern recognition and reconstruction. The widths of the reconstructed χ peaks are greater than our resolution of $\sigma \approx 30 \pm 3$ MeV/c^2 for a single χ state (based on electromagnetic calorimeter resolution fixed by the experimentally observed E/p distributions for electrons and the observed width of the π^0), indicating the production of both χ_1 and χ_2.

The fractions of total J/ψ production due to radiative χ_1 and χ_2 decay, determined from the total number of background-subtracted χ's corrected for acceptance and reconstruction efficiencies, are 0.40 ± 0.04, 0.37 ± 0.03, and 0.30 ± 0.04 for the π^+, π^-, and proton data, respectively. These data are compared in Fig. 3 with data from other experiments [1] at different $\sqrt{\tau} = M\chi/\sqrt{s}$. As can be observed from Fig. 3(b), the π^+ and π^- fractions measured in this experiment are consistent with each other and with previous π^- measurements at approximately the same $\sqrt{\tau} = M\chi/\sqrt{s}$. Our proton datum as shown in Fig. 3(a) has a somewhat smaller value than those obtained in other proton experiments at different $\sqrt{\tau}$.

In addition to radiative χ decay, another contribution to J/ψ production, for which there have been no previous estimates, is ψ' production followed by decay into final states containing J/ψ's. Combining our measurement [8] of J/ψ and ψ' production, determined using the branching ratio [10] for $\psi' \to \mu\mu$ (0.0077 ± 0.0017), the newly determined branching ratio [11] for $\psi \to \mu\mu$ ($0.0591 \pm 0.0011 \pm 0.0020$), and our observation of the $J/\psi \to \mu\mu$ and $\psi' \to \mu\mu$ channel, with the inclusive branching ratio [12], 0.535 ± 0.04, for $\psi' \to J/\psi$+anything, excluding double radiative transitions through the χ states, we find that (6.4 ± 2.2)% and (7.5 ± 1.7)% of the J/ψ signal in 300 GeV/c π^+N and π^-N interactions respectively comes from ψ' production followed by decay into J/ψ other than through ψ' radiative decays involving χ states. In the same manner, the fraction of J/ψ from ψ' is found to be (7.5 ± 1.7)% for the pN interactions at 300 GeV/c.

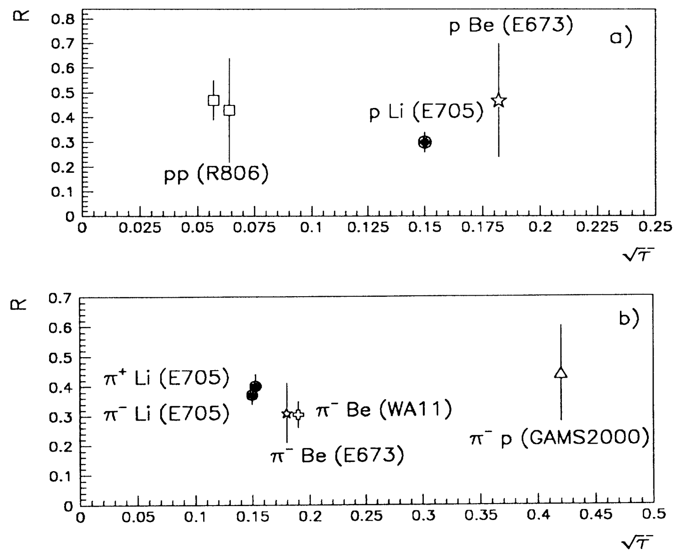

FIG. 3. Fraction of J/ψ produced via radiative χ in 300 GeV/c (a) proton and (b) $\pi^{\pm}$ ^{7}Li interactions.

Since we have measured J/ψ, ψ', and χ production in a single experiment, it is possible to obtain a cross section for direct production of J/ψ. If we assume that the only sources of J/ψ other than direct production are the decays of the χ_1, χ_2, and ψ', then the fractions of directly produced J/ψ are (56 ± 3)%, (54 ± 5)%, and (62 ± 4)% in π^-N, π^+N, and pN interactions, respectively, at 300 GeV/c. While other indirect sources of J/ψ such as χ_0 or B meson decay can contribute, a small branching ratio (0.0066 ± 0.0018 for $\chi_0 \to J/\psi\gamma$ from Ref. [13]) and the combination of an expected small cross section for B production at 300 GeV/c (in the range of 10–20 nb/nucleon [14]) and small branching ratios (0.0112 ± 0.0018 for $B \to J/\psi$ inclusive decays [15]) make these sources negligible compared to production via χ_1, χ_2, and ψ' decay. Combining the above fractions of direct J/ψ production with our measurement [8] of the inclusive J/ψ production, we obtain direct J/ψ production cross sections of 97 ± 14, 102 ± 14, and 89 ± 12 nb/nucleon for the π^+N, π^-N, and pN interactions, respectively, where the error includes systematic and statistical components as well as the errors in the various branching ratios used in extracting these cross sections. We have assumed an $A^{0.92}$ atomic number dependence to extract the cross section per nucleon. The large percentage of directly produced

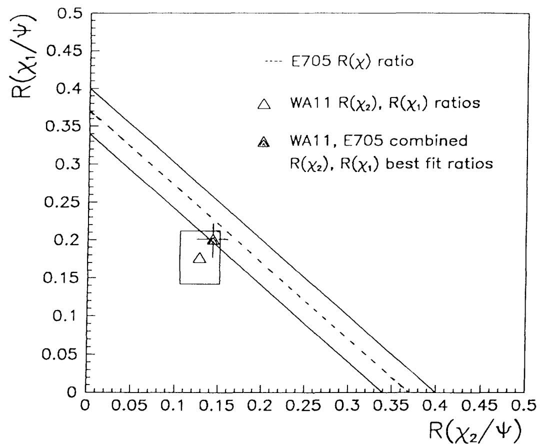

FIG. 4. Composite WA11 and E705 results for ratio of χ_1/ψ and χ_2/ψ in π^-N interactions.

J/ψ, unexpected in the color singlet model, indicates that processes other than simple quark and/or two gluon fusion must be involved in hadroproduction of hidden charm at these energies.

The CERN WA11 experiment [4] has measured the ratios χ_1/ψ and χ_2/ψ in 185 GeV/c π^-Be interactions by reconstructing the charmonium states in the subset of the $\chi \to \gamma\psi$ decays in which the radiated photons converted. They obtain $(17.7 \pm 3.5)\%$ and $(12.8 \pm 2.3)\%$ for the χ_1/ψ and χ_2/ψ ratios, respectively. These measurements together with our measurement of 0.37 ± 0.03 for the ratio of the combined χ_1 and χ_2 to J/ψ production at 300 GeV/c are shown in Fig. 4. Ignoring the possibility of an energy dependence of the ratio of χ states to J/ψ production [none is required by the data of Fig. 3(b)], the new best values for the ratios χ_1/ψ, χ_2/ψ, and $\chi_1+\chi_2/\psi$ in 300 GeV/c π^-N interactions from a fit to the combined WA11 and E705 data are 0.201 ± 0.024, 0.143 ± 0.020, and 0.344 ± 0.031, respectively.

Combining the ratios of χ_1/ψ and χ_2/ψ determined in this manner together with the absolute cross section for J/ψ production in 300 GeV/c π^- nucleon interactions ($178 \pm 6 \pm 20$ nb/nucleon), as measured in our experiment [8], and using branching ratios of 0.273 ± 0.016 and 0.135 ± 0.11 for $\chi_1 \to \gamma\psi$ and $\chi_2 \to \gamma\psi$, respectively [16], we obtain the following cross sections for χ_1 and χ_2 production in π^- nucleon interactions at 300 GeV/c: $\sigma(\pi^-N \to \chi_1 + x) = 131 \pm 18 \pm 14$ nb/nucleon and $\sigma(\pi^-N \to \chi_2 + x) = 188 \pm 30 \pm 21$ nb/nucleon, where the first error is statistical and the second systematic, and the cross sections are for $x_F > 0$.

In conclusion, we have determined the fraction of J/ψ production due to the radiative decays of the χ_1 and χ_2 charmonium states in $\pi^\pm$ and proton interactions with ^{7}Li at 300 GeV/c. Using our measurement of J/ψ from the decay of the ψ', we have also determined the cross section for direct J/ψ production. Combining our measurement of the ratio of $\chi_1+\chi_2$ to J/ψ production with previous measurements of the χ_1/ψ and χ_2/ψ ratios and using our measurement of the total cross section for J/ψ at 300 GeV/c, we have obtained values for the cross section for χ_1 and χ_2 production in π^--nucleon interactions. Both the large fraction of direct J/ψ production and the approximately equal cross sections for χ_1 and χ_2 production indicate that processes in addition to the color singlet processes are necessary to explain the data.

We wish to thank the U.S. Department of Energy, the Natural Sciences and Engineering Research Council of Canada, the Quebec Department of Education, and the Scientific Affairs Division of the North Atlantic Treaty Organization for their support of this experiment. In particular, we wish to acknowledge the administration and staff of the Fermi National Accelerator Laboratory for their help.

[1] R806 Collaboration, J. H. Cobb *et al.*, Phys. Lett. **72B**, 497 (1978); R806 Collaboration, C. Kourkoumelis *et al.*, Phys. Lett. **81B**, 405 (1979); WA11 Collaboration, Y. Lemoigne *et al.*, Phys. Lett. **113B**, 509 (1982); GAMS2000 Collaboration, F. Binon *et al.*, Nucl. Phys. **B239**, 311 (1984); E673 Collaboration, S. R. Hahn *et al.*, Phys. Rev. D **30**, 671 (1984); E673 Collaboration, D. A. Bauer *et al.*, Phys. Rev. Lett. **54**, 753 (1985).

[2] C. E. Carlson and R. Suaya, Phys. Rev. D **18**, 760 (1978); C. H. Chang, Nucl. Phys. **B172**, 425 (1980); R. Baier and R. Ruckl, Z. Phys. C **19**, 251 (1983); J. H. Kuhn, Phys. Lett. **89B**, 385 (1979).

[3] H. Fritzsch, Phys. Lett. **67B**, 217 (1977); M. Gluck *et al.*, Phys. Rev. D **17**, 2324 (1978).

[4] Y. Lemoigne *et al.*, Phys. Lett. **113B**, 509 (1982).

[5] L. Antoniazzi *et al.*, "The Experiment 705 Spectrometer: A Large Aperture Spectrometer at Fermilab to Study High Mass Dimuons and High Transverse Momentum Photons" (to be published).

[6] B. Cox *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **219**, 487 (1984); B. Cox *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **219**, 491 (1984); D. Wagoner *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **238**, 315 (1985); B. Cox *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **238**, 321 (1985); L. Antoniazzi *et al.*, "The Experiment 705 Electromagnetic Calorimeter" (to be published).

[7] H. Areti *et al.*, Nucl. Instrum. Methods Phys. Res. **212**, 135 (1983).

[8] L. Antoniazzi *et al.*, Phys. Rev. D **45**, 4828 (1992).

[9] B. L. Ioffe, Phys. Rev. Lett. **39**, 1589 (1977).

[10] Particle Data Group, Phys. Rev. D **45**, VII.178 (1992).

[11] MARK III Collaboration, D. Coffman *et al.*, Report No. SLAC-PUB-5592, 1992 (to be published).

[12] Particle Data Group, Phys. Rev. D **45**, VII.174–178 (1992).

[13] Particle Data Group, Phys. Rev. D **45**, VII.174 (1992).

[14] P. Nason, S. Dawson, and R. K. Ellis, Nucl. Phys. **B327**, 49 (1989).

[15] Particle Data Group, Phys. Rev. D **45**, VII.145 (1992).

[16] Particle Data Group, Phys. Rev. D **45**, VII.175, 176 (1992).