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Production of J/ψ Mesons From χ_c Meson Decays in p$\overline{\text{p}}$ Collisions at $\sqrt{s}$ = 1.8 TeV

F. Abe et al.
The CDF Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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F. Abe,[16] H. Akimoto,[35] A. Akopian,[30] M. G. Albrow,[7] S. R. Amendolia,[26] D. Amidei,[19] J. Antos,[32] S. Aota,[35] G. Apollinari,[30] T. Asakawa,[35] W. Ashmanskas,[17] M. Atac,[7] F. Azfar,[25] P. Azzi-Bacchetta,[24] N. Bacchetta,[24] W. Badgett,[19] S. Bagdasarov,[30] M. W. Bailey,[21] J. Bao,[38] P. de Barbaro,[29] A. Barbaro-Galtieri,[17] V. E. Barnes,[28] B. A. Barnett,[15] M. Barone,[9] E. Barzi,[9] G. Bauer,[18] T. Baumann,[11] F. Bedeschi,[26] S. Behrends,[3] S. Belforte,[26] G. Bellettini,[26] J. Bellinger,[37] D. Benjamin,[34] J. Benlloch,[18] J. Bensinger,[3] D. Benton,[25] A. Beretvas,[7] J. P. Berge,[7] J. Berryhill,[5] S. Bertolucci,[9] B. Bevensee,[25] A. Bhatti,[30] K. Biery,[7] M. Binkley,[7] D. Bisello,[24] R. E. Blair,[1] C. Blocker,[3] A. Bodek,[29] W. Bokhari,[18] V. Bolognesi,[2] G. Bolla,[28] D. Bortoletto,[28] J. Boudreau,[27] L. Breccia,[2] C. Bromberg,[20] N. Bruner,[21] E. Buckley-Geer,[7] H. S. Budd,[29] K. Burkett,[19] G. Busetto,[24] A. Byon-Wagner,[7] K. L. Byrum,[1] J. Cammerata,[15] C. Campagnari,[7] M. Campbell,[19] A. Caner,[26] W. Carithers,[17] D. Carlsmith,[37] A. Castro,[24] D. Cauz,[26] Y. Cen,[29] F. Cervelli,[26] P. S. Chang,[32] P. T. Chang,[32] H. Y. Chao,[32] J. Chapman,[19] M. -T. Cheng,[32] G. Chiarelli,[26] T. Chikamatsu,[35] C. N. Chiou,[32] L. Christofek,[13] S. Cihangir,[7] A. G. Clark,[10] M. Cobal,[26] E. Cocca,[26] M. Contreras,[5] J. Conway,[31] J. Cooper,[7] M. Cordelli,[9] C. Couyoumtzelis,[10] D. Crane,[1] D. Cronin-Hennessy,[6] R. Culbertson,[5] T. Daniels,[18] F. DeJongh,[7] S. Delchamps,[7] S. Dell'Agnello,[26] M. Dell'Orso,[26] R. Demina,[7] L. Demortier,[30] M. Deninno,[2] P. F. Derwent,[7] T. Devlin,[31] J. R. Dittmann,[6] S. Donati,[26] J. Done,[33] T. Dorigo,[24] A. Dunn,[19] N. Eddy,[19] K. Einsweiler,[17] J. E. Elias,[7] R. Ely,[17] E. Engels, Jr.,[27] D. Errede,[13] S. Errede,[13]

Q. Fan,[29] G. Feild,[38] C. Ferretti,[26] I. Fiori,[2] B. Flaugher,[7] G. W. Foster,[7]
M. Franklin,[11] M. Frautschi,[34] J. Freeman,[7] J. Friedman,[18] H. Frisch,[5] Y. Fukui,[16]
S. Funaki,[35] S. Galeotti,[26] M. Gallinaro,[25] O. Ganel,[34] M. Garcia-Sciveres,[17]
A. F. Garfinkel,[28] C. Gay,[11] S. Geer,[7] D. W. Gerdes,[15] P. Giannetti,[26] N. Giokaris,[30]
P. Giromini,[9] G. Giusti,[26] L. Gladney,[25] D. Glenzinski,[15] M. Gold,[21] J. Gonzalez,[25]
A. Gordon,[11] A. T. Goshaw,[6] Y. Gotra,[24] K. Goulianos,[30] H. Grassmann,[26]
L. Groer,[31] C. Grosso-Pilcher,[5] G. Guillian,[19] R. S. Guo,[32] C. Haber,[17] E. Hafen,[18]
S. R. Hahn,[7] R. Hamilton,[11] R. Handler,[37] R. M. Hans,[38] F. Happacher,[9] K. Hara,[35]
A. D. Hardman,[28] B. Harral,[25] R. M. Harris,[7] S. A. Hauger,[6] J. Hauser,[4] C. Hawk,[31]
E. Hayashi,[35] J. Heinrich,[25] B. Hinrichsen,[14] K. D. Hoffman,[28] M. Hohlmann,[5]
C. Holck,[25] R. Hollebeek,[25] L. Holloway,[13] A. Hölscher,[14] S. Hong,[19] G. Houk,[25]
P. Hu,[27] B. T. Huffman,[27] R. Hughes,[22] J. Huston,[20] J. Huth,[11] J. Hylen,[7]
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H. Jensen,[7] U. Joshi,[7] R. W. Kadel,[17] E. Kajfasz,[24] H. Kambara,[10] T. Kamon,[33]
T. Kaneko,[35] K. Karr,[36] H. Kasha,[38] Y. Kato,[23] T. A. Keaffaber,[28] L. Keeble,[9]
K. Kelley,[18] R. D. Kennedy,[7] R. Kephart,[7] P. Kesten,[17] D. Kestenbaum,[11]
R. M. Keup,[13] H. Keutelian,[7] F. Keyvan,[4] B. Kharadia,[13] B. J. Kim,[29] D. H. Kim,[7a]
H. S. Kim,[14] S. B. Kim,[19] S. H. Kim,[35] Y. K. Kim,[17] L. Kirsch,[3] P. Koehn,[29]
K. Kondo,[35] J. Konigsberg,[8] S. Kopp,[5] K. Kordas,[14] A. Korytov,[8] W. Koska,[7]
E. Kovacs,[7a] W. Kowald,[6] M. Krasberg,[19] J. Kroll,[7] M. Kruse,[29] T. Kuwabara,[35]
S. E. Kuhlmann,[1] E. Kuns,[31] A. T. Laasanen,[28] S. Lami,[26] S. Lammel,[7]
J. I. Lamoureux,[3] T. LeCompte,[1] S. Leone,[26] J. D. Lewis,[7] P. Limon,[7] M. Lindgren,[4]
T. M. Liss,[Y] . C. Liu,[32] 13 N. Lockyer,[25] O. Long,[25] C. Loomis,[31] M. Loreti,[24]
J. Lu,[33] D. Lucchesi,[26] P. Lukens,[7] S. Lusin,[37] J. Lys,[17] K. Maeshima,[7]
A. Maghakian,[30] P. Maksimovic,[18] M. Mangano,[26] J. Mansour,[20] M. Mariotti,[24]
J. P. Marriner,[7] A. Martin,[38] J. A. J. Matthews,[21] R. Mattingly,[18] P. McIntyre,[33]
P. Melese,[30] A. Menzione,[26] E. Meschi,[26] S. Metzler,[25] C. Miao,[19] T. Miao,[7]

G. Michail,[11] R. Miller,[20] H. Minato,[35] S. Miscetti,[9] M. Mishina,[16] H. Mitsushio,[35]
T. Miyamoto,[35] S. Miyashita,[35] N. Moggi,[26] Y. Morita,[16] J. Mueller,[27]
A. Mukherjee,[7] T. Muller,[4] P. Murat,[26] H. Nakada,[35] I. Nakano,[35] C. Nelson,[7]
D. Neuberger,[4] C. Newman-Holmes,[7] C-Y. P. Ngan,[18] M. Ninomiya,[35]
L. Nodulman,[1] S. H. Oh,[6] K. E. Ohl,[38] T. Ohmoto,[12] T. Ohsugi,[12] R. Oishi,[35]
M. Okabe,[35] T. Okusawa,[23] R. Oliveira,[25] J. Olsen,[37] C. Pagliarone,[26] R. Paoletti,[26]
V. Papadimitriou,[34] S. P. Pappas,[38] N. Parashar,[26] S. Park,[7] A. Parri,[9] J. Patrick,[7]
G. Pauletta,[26] M. Paulini,[17] A. Perazzo,[26] L. Pescara,[24] M. D. Peters,[17]
T. J. Phillips,[6] G. Piacentino,[26] M. Pillai,[29] K. T. Pitts,[7] R. Plunkett,[7]
L. Pondrom,[37] J. Proudfoot,[1] F. Ptohos,[11] G. Punzi,[26] K. Ragan,[14] D. Reher,[17]
A. Ribon,[24] F. Rimondi,[2] L. Ristori,[26] W. J. Robertson,[6] T. Rodrigo,[26] S. Rolli,[36]
J. Romano,[5] L. Rosenson,[18] R. Roser,[13] T. Saab,[14] W. K. Sakumoto,[29]
D. Saltzberg,[5] A. Sansoni,[9] L. Santi,[26] H. Sato,[35] P. Schlabach,[7] E. E. Schmidt,[7]
M. P. Schmidt,[38] A. Scribano,[26] S. Segler,[7] S. Seidel,[21] Y. Seiya,[35] G. Sganos,[14]
M. D. Shapiro,[17] N. M. Shaw,[28] Q. Shen,[28] P. F. Shepard,[27] M. Shimojima,[35]
M. Shochet,[5] J. Siegrist,[17] A. Sill,[34] P. Sinervo,[14] P. Singh,[27] J. Skarha,[15] K. Sliwa,[36]
F. D. Snider,[15] T. Song,[19] J. Spalding,[7] T. Speer,[10] P. Sphicas,[18] F. Spinella,[26]
M. Spiropulu,[11] L. Spiegel,[7] L. Stanco,[24] J. Steele,[37] A. Stefanini,[26] K. Strahl,[14]
J. Strait,[7] R. Ströhmer,[7a] D. Stuart,[7] G. Sullivan,[5] K. Sumorok,[18] J. Suzuki,[35]
T. Takada,[35] T. Takahashi,[23] T. Takano,[35] K. Takikawa,[35] N. Tamura,[12]
B. Tannenbaum,[21] F. Tartarelli,[26] W. Taylor,[14] P. K. Teng,[32] Y. Teramoto,[23]
S. Tether,[18] D. Theriot,[7] T. L. Thomas,[21] R. Thun,[19] M. Timko,[36] P. Tipton,[29]
A. Titov,[30] S. Tkaczyk,[7] D. Toback,[5] K. Tollefson,[29] A. Tollestrup,[7] H. Toyoda,[23]
W. Trischuk,[14] J. F. de Troconiz,[11] S. Truitt,[19] J. Tseng,[18] N. Turini,[26] T. Uchida,[35]
N. Uemura,[35] F. Ukegawa,[25] G. Unal,[25] J. Valls,[7a] S. C. van den Brink,[27] S. Vejcik,
III,[19] G. Velev,[26] R. Vidal,[7] R. Vilar,[7a] M. Vondracek,[13] D. Vucinic,[18]
R. G. Wagner,[1] R. L. Wagner,[7] J. Wahl,[5] N. B. Wallace,[26] A. M. Walsh,[31]

C. Wang,[6] C. H. Wang,[32] J. Wang,[5] M. J. Wang,[32] Q. F. Wang,[30] A. Warburton,[14] T. Watts,[31] R. Webb,[33] C. Wei,[6] C. Wendt,[37] H. Wenzel,[17] W. C. Wester, III,[7] A. B. Wicklund,[1] E. Wicklund,[7] R. Wilkinson,[25] H. H. Williams,[25] P. Wilson,[5] B. L. Winer,[22] D. Winn,[19] D. Wolinski,[19] J. Wolinski,[20] S. Worm,[21] X. Wu,[10] J. Wyss,[24] A. Yagil,[7] W. Yao,[17] K. Yasuoka,[35] Y. Ye,[14] G. P. Yeh,[7] P. Yeh,[32] M. Yin,[6] J. Yoh,[7] C. Yosef,[20] T. Yoshida,[23] D. Yovanovitch,[7] I. Yu,[7] L. Yu,[21] J. C. Yun,[7] A. Zanetti,[26] F. Zetti,[26] L. Zhang,[37] W. Zhang,[25] and S. Zucchelli[2]

(CDF Collaboration)

[1] *Argonne National Laboratory, Argonne, Illinois 60439*

[2] *Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*

[3] *Brandeis University, Waltham, Massachusetts 02264*

[4] *University of California at Los Angeles, Los Angeles, California 90024*

[5] *University of Chicago, Chicago, Illinois 60638*

[6] *Duke University, Durham, North Carolina 28708*

[7] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

[8] *University of Florida, Gainesville, FL 33611*

[9] *Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*

[10] *University of Geneva, CH-1211 Geneva 4, Switzerland*

[11] *Harvard University, Cambridge, Massachusetts 02138*

[12] *Hiroshima University, Higashi-Hiroshima 724, Japan*

[13] *University of Illinois, Urbana, Illinois 61801*

[14] *Institute of Particle Physics, McGill University, Montreal H3A 2T8, and University of Toronto, Toronto M5S 1A7, Canada*

[15] *The Johns Hopkins University, Baltimore, Maryland 21218*

[16] *National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 315, Japan*

[17] *Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*

[18] *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

[19] *University of Michigan, Ann Arbor, Michigan 48109*

[20] *Michigan State University, East Lansing, Michigan 48824*

[21] *University of New Mexico, Albuquerque, New Mexico 87132*

[22] *The Ohio State University, Columbus, OH 43320*

[23] *Osaka City University, Osaka 588, Japan*

[24] *Universita di Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-36132 Padova, Italy*

[25] *University of Pennsylvania, Philadelphia, Pennsylvania 19104*

[26] *Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy*

[27] *University of Pittsburgh, Pittsburgh, Pennsylvania 15270*

[28] *Purdue University, West Lafayette, Indiana 47907*

[29] *University of Rochester, Rochester, New York 14628*

[30] *Rockefeller University, New York, New York 10021*

[31] *Rutgers University, Piscataway, New Jersey 08854*

[32] *Academia Sinica, Taipei, Taiwan 11530, Republic of China*

[33] *Texas A&M University, College Station, Texas 77843*

[34] *Texas Tech University, Lubbock, Texas 79409*

[35] *University of Tsukuba, Tsukuba, Ibaraki 315, Japan*

[36] *Tufts University, Medford, Massachusetts 02155*

[37] *University of Wisconsin, Madison, Wisconsin 53806*

[38] *Yale University, New Haven, Connecticut 06511*

We have measured the fraction of J/ψ mesons originating from χ_c meson decays in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The fraction, for $P_T^{J/\psi} >$ 4.0 GeV/c and $|\eta^{J/\psi}| < 0.6$, not including contributions from b flavored hadrons is $(29.7\pm1.7(\mathrm{stat})\pm5.7(\mathrm{syst}))\%$. We have compared the prompt J/ψ cross section with the prediction of the Color Singlet Model and found a large excess of direct production.

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In $p\bar{p}$ collisions charmonium particles come from prompt production and from the decay of b flavored hadrons. Calculations based on the Color Singlet Model (CSM) [1] for prompt production of charmonium, predict that the yield of J/ψ and $\psi(2S)$ mesons not coming from the decay of heavier charmonium states (direct production) is suppressed, and χ_c mesons are expected to be the main source ($> 90\%$) of prompt J/ψ's. Direct production is the only source of prompt $\psi(2S)$ considered in the CSM since higher mass charmonia that can decay to $\psi(2S)$ are not known to exist. The observed yields of prompt J/ψ and $\psi(2S)$ mesons are larger than the theoretical expectation by factors of about 6 and 50 respectively [2]. This discrepancy, especially for the $\psi(2S)$, has suggested that other important mechanisms exist for direct production of charmonium $^3S_1$ states at large P_T, beyond those considered in the CSM [3–5]. It is therefore important to account separately for all charmonium states produced and understand whether the disagreement of the theory with data is confined to the $\psi(2S)$ or an excess of direct production shows up also for the J/ψ.

In this letter we report the results of a study of the reaction $p\bar{p} \rightarrow \chi_c X$, $\chi_c \rightarrow J/\psi\gamma$, $J/\psi \rightarrow \mu^+\mu^-$ at $\sqrt{s} = 1.8$ TeV using the Collider Detector at Fermilab (CDF).

Since the branching fractions for χ_c decays into other modes containing a J/ψ are expected to be small [6] this study yields the fraction of J/ψ from χ_c. This fraction has already been measured by CDF using a smaller data sample [7]. The measurement reported here is based on 18 pb^{-1} of data collected in the 1992-1993 collider run, and is the first where the contribution from b decays to χ_c production is measured. It is therefore possible to disentangle direct J/ψ production from the contribution due to χ_c decays in promptly produced charmonia; this allows to compare the measured prompt J/ψ cross sections with the theoretical predictions, separately for the direct component and the χ_c contribution.

The CDF detector has been described in detail elsewhere [8]. The events used in this analysis were collected with the dimuon trigger described in [2]. A J/ψ is identified by requiring two oppositely charged muon candidates both with $P_T > 2.0$ GeV/c and at least one with $P_T > 2.8$ GeV/c (P_T is the momentum component perpendicular to the beam axis). The muon pair is required to have $P_T(\mu^+\mu^-) > 4.0$ GeV/c and $|\eta(\mu^+\mu^-)| < 0.6$ (η=-ln[tan(θ/2)] is the pseudorapidity, where θ is the polar angle). The muon pair is considered a J/ψ candidate if its invariant mass is in the region 3057 MeV/c^2 $< M(\mu^+\mu^-) <$ 3137 MeV/c^2. This selection yields a sample of 34367 J/ψ candidates, where the estimated number of real J/ψ mesons is 32642 ± 185. In the J/ψ sample we select photon candidates by demanding an energy deposition of at least 1 GeV in a cell of the central electromagnetic calorimeter ($|\eta| < 1.1$) and a signal in the fiducial volume of the strip chambers (CES), embedded in the calorimeter at a depth of six radiation lengths. We also require that no charged particles point to the cell corresponding to the photon candidate (the no-track cut). The location of the signal in the CES chambers and the event interaction point determine the direction of the photon momentum; its magnitude is the energy deposited in the calorimeter cell. The J/ψ candidate is combined with all photon candidates in the event and the invariant mass difference, $\Delta M = M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$, is calculated. The ΔM distribution is shown in Fig. 1. A clear signal is present near $\Delta M = 400$ MeV/c^2 as expected from χ_c decays, but the individual χ_{c1} and χ_{c2} states are not resolved. The mass resolution of 50 (55) MeV/c^2, predicted by a detector simulation for the χ_{c1} (χ_{c2}), is insufficient to resolve the two states which are separated by 45.6 MeV/c^2.

The shape of the background resulting from combinations of the J/ψ with photons of the underlying event is obtained with a Monte Carlo method that uses J/ψ candidate events as input. Photons come primarily from the decay of π^0, η and K^0_S. These sources are simulated replacing each charged particle in the event, other than the two muons, by a π^0, η or K^0_S with probabilities proportional to 4:2:1. These proportions follow from isospin symmetry and the ratios $K^\pm/\pi^\pm = 0.25$, $\eta/\pi^0 = 0.5$ [9]. Uncertainties in these ratios, and the effect of physics processes resulting in a J/ψ associated with photons in the final state, are considered as sources of systematic uncertainty. The response of the detector to the photons resulting from the decay of these embedded neutral particles is calculated using a Monte Carlo simulation. Applying the χ_c reconstruction to these events results in a mass distribution that models the shape of the background. This model was tested by comparing the Monte Carlo distribution with that directly obtained from the data for dimuon pairs in the mass sidebands of the J/ψ peak where there should be no χ_c signal. The two distributions agree well as shown in the inset of Fig. 1. The number of χ_c signal events is determined by fitting the data ΔM distribution to the sum of the background distribution, with an unconstrained normalization, and a Gaussian function associated with the signal. This results in 1230 ± 72 χ_c signal events for the distribution shown in Fig. 1.

We measure the fraction of J/ψ mesons from χ_c decays, as function of $P_T^{J/\psi}$, determining the rate of J/ψ and χ_c mesons in four bins defined by: $4 < P_T^{J/\psi} < 6$, $6 < P_T^{J/\psi} < 8$, $8 < P_T^{J/\psi} < 10$ and $P_T^{J/\psi} > 10$ GeV/c. The fraction is calculated according to the equation:

$$F_{\chi}^{J/\psi} = \frac{N^{\chi_c}}{N^{J/\psi} \cdot A^{\gamma}_{J/\psi} \cdot \epsilon^{\gamma}_{no-track} \cdot \epsilon^{\gamma}_{envir}}$$

where N^{χ_c} and $N^{J/\psi}$ are the numbers of reconstructed χ_c and J/ψ mesons respectively, $A^{\gamma}_{J/\psi}$ is the probability to reconstruct the photon once the J/ψ is found, $\epsilon^{\gamma}_{no-track}$ is the efficiency of the no-track cut and $\epsilon^{\gamma}_{envir}$ is the efficiency to reconstruct the photon in the presence of additional energy deposited in the calorimeter.

The photon acceptance, $A^{\gamma}_{J/\psi}$, is the product of the probability that the photon is within the fiducial volume and the efficiency for reconstruction of the fiducial photon. The geometric acceptance is determined by using a Monte Carlo simulation. The χ_c's are generated uniformly in η, and with a P_T distribution tuned to reproduce the observed rate of χ_c's as function of $P_T^{J/\psi}$. The $\chi_c \rightarrow J/\psi\,\gamma$ decay is generated with a uniform angular distribution in the χ_c rest frame. The $J/\psi \rightarrow \mu^+\mu^-$ decay is also generated uniformly in the J/ψ rest frame and the trigger simulation is applied to the decay muons. The unknown χ_c polarization is considered as a source of systematic uncertainty. The photon reconstruction efficiency is obtained from real data by applying the photon requirements, except for the no-track cut, to a sample of electrons from photon conversions selected using only tracking information. This efficiency is then corrected for the differences in detector response between photons and electrons. For $P_T^{J/\psi} > 4.0$ GeV/c, the photon acceptance is 0.146 ± 0.002(stat).

To study the effect of the no-track cut, and the effect of additional energy deposited in the calorimeter, we use a sample of $\chi_c \rightarrow J/\psi\,\gamma$ reconstructed by requiring the decay photon to convert into an electron-positron pair. The resulting sample of 26 ± 5 χ_c's is unbiased with respect to the no-track cut and calorimetric requirements. The effect of these can be determined by measuring the track multiplicity and energy distribution associated with the calorimeter cell which would have been hit by the photon, had it not converted. The mean multiplicity of non-muon tracks pointing to this cell has a value of 0.08 ± 0.06, and the efficiency of the no-track cut is measured to be $\epsilon^{\gamma}_{no-track} = (97.9^{+2}_{-5})\%$. The electromagnetic energy distribution in the same cell, when there are no tracks pointing to it, has a mean value of (0.15 ± 0.08) GeV. The effect of this energy deposition on our photon reconstruction is accounted for by an "environmental" efficiency of $\epsilon^{\gamma}_{envir} = (96.5^{+3.5}_{-4.5})\%$.

The systematic uncertainty on $F_{\chi}^{J/\psi}$ associated with the reconstruction efficiency of the low energy photon is $\pm 10\%$. This is due to uncertainties in the estimation of the detector response difference between photons and electrons. A $\pm 11\%$ uncertainty is associated with the χ_c production and decay model used for the acceptance calculation. This is estimated upon variations of the shape of the P_T spectrum as well as the decay angular distribution to account for fully polarized χ_c. The uncertainty in the determination of N^{χ_c} associated with the model of the background shape is $\pm 10\%$. This includes the effect of varying the fitted normalization of the background contribution by $\pm 1\sigma$; varying the π^0, η and K_S^0 composition in our background model from 4:2:1 to equal amount of π^0 and K_S^0, and to all π^0; and includes the effect of physics processes resulting in a J/ψ associated with photons in the final state. The process that could possibly have the largest effect is $h_c \rightarrow J/\psi\, \pi^0$ where h_c is the $^1P_1$ state of charmonium. Decays of the $\psi(2S)$ can also produce a J/ψ and photons but have a negligible effect on the determination of N^{χ_c}. An additional $\pm 6\%$ uncertainty arises from the statistical and systematic uncertainties associated with the determination of the photon efficiencies $\epsilon^{\gamma}_{no-track}$ and $\epsilon^{\gamma}_{envir}$. We combine these uncertainties, assuming they are independent, in a total systematic uncertainty of $\pm 18.9\%$ correlated in the four bins. The fraction of J/ψ mesons coming from χ_c decays is $F_{\chi}^{J/\psi} = (27.4 \pm 1.6(\mathrm{stat}) \pm 5.2(\mathrm{syst}))\ \%$ for $P_T^{J/\psi} > 4$ GeV/c and $|\eta^{J/\psi}| < 0.6$.

This fraction includes a contribution from b decays in the numerator and denominator. The fraction of J/ψ mesons from χ_c decays not including contributions from b decays is calculated according to the equation:

$$F(\not b)_{\chi}^{J/\psi} = \frac{N^{\chi_c} - N_b^{\chi_c}}{(N^{J/\psi} - N_b^{J/\psi}) \cdot A^{\gamma}_{J/\psi} \cdot \epsilon^{\gamma}_{no-track} \cdot \epsilon^{\gamma}_{envir}} = F_{\chi}^{J/\psi} \cdot \frac{1 - F_b^{\chi}}{1 - F_b^{J/\psi}}$$

where $N_b^{\chi_c}$ and $N_b^{J/\psi}$ are the numbers of reconstructed χ_c and J/ψ mesons from b's, F_b^{χ} and $F_b^{J/\psi}$ are the fractions of reconstructed χ_c and J/ψ mesons from b's.

To measure F_b^{χ} we use a sample of 555 ± 47 reconstructed χ_c where both muon tracks have information in the silicon vertex detector (SVX). We constrain the two muons to come from a common decay vertex and we calculate L_{xy}, the projection of the decay length onto the transverse momentum vector of the J/ψ. To account for the difference between the Lorentz boost $\beta\gamma$ of the parent b hadron and that of the observed J/ψ, we convert L_{xy} into a proper lifetime using $\beta\gamma$ of the J/ψ, and a correction factor F_{corr} determined from Monte Carlo: $c\tau = L_{xy} \cdot (M^{J/\psi}/P_T^{J/\psi})/F_{corr}$ [10]. We fit the $c\tau$ distribution to the sum of two functions, one associated with the χ_c signal and one associated with its background. Each function is the sum of a zero lifetime component, described by a Gaussian plus symmetric exponential tails, and a long lived component, described by a positive exponential smeared with a Gaussian resolution function. The background component is derived from the Monte Carlo described previously and normalized to the estimated background under the χ_c signal. In the fit we fix the lifetime of the long lived component to the average b lifetime of 438μm [10]. The $c\tau$ distribution and the result of this fit are shown in Fig. 2. This yields $F_b^{\chi} = (10.8\pm3.1)\%$, which is the fraction of χ_c mesons from b decays in the sample of reconstructed χ_c, and is not corrected for the acceptance of the photon cuts. Using the method described in [2] we find $F_b^{J/\psi} = (17.8 \pm 0.45)\%$ for $P_T^{J/\psi} > 4.0$ GeV/c and $|\eta^{J/\psi}| < 0.6$. The resulting correction factor is $(1-F_b^{\chi})/(1-F_b^{J/\psi}) = 1.085\pm0.037$. A Monte Carlo calculation shows that this correction factor is independent of $P_T^{J/\psi}$. Therefore we use this correction factor for all P_T bins. The uncertainties in $F_b^{J/\psi}$ and F_b^{χ} increase the total systematic uncertainty in the measurement of $F(\not{b})_{\chi}^{J/\psi}$ to 19.2%. The resulting fraction of J/ψ mesons from χ_c decays, not including contributions from b's, is $F(\not{b})_{\chi}^{J/\psi} = (29.7 \pm 1.7(\text{stat}) \pm 5.7(\text{syst}))$ %. Figure 3 shows this fraction as a function of $P_T^{J/\psi}$.

To obtain the direct J/ψ cross section, we subtract from the prompt J/ψ cross section [2] the contribution from χ_c decays, and the contribution from $\psi(2S)$ decays. The first is obtained by multiplying the prompt J/ψ cross section with a parametrization of

$F(\not{b})^{J/\psi}_{\chi}$ as a function of $P_T^{J/\psi}$. The second is calculated from the prompt $\psi(2S)$ cross section measured in [2] and a Monte Carlo simulation of the decays $\psi(2S) \to J/\psi\, X$, where $X = \pi\pi, \eta, \pi^0$. With this calculation we find that the fraction of prompt J/ψ's from $\psi(2S)$'s rises from $(7\pm2)\%$ at $P_T^{J/\psi} = 5$ GeV/c to $(15\pm5)\%$ at $P_T^{J/\psi} = 18$ GeV/c. The fraction of directly produced J/ψ's is $(64 \pm 6)\%$ and is approximately independent of $P_T^{J/\psi}$ between 5 and 18 GeV/c. Direct production is therefore the largest source of prompt J/ψ mesons. The resulting cross sections are shown in Fig. 4. The curves correspond to the theoretical predictions [11]. The calculation of the direct J/ψ cross section (dashed line) is below the experimental measurement by a factor of 80 at $P_T^{J/\psi} = 5$ GeV/c, and by a factor of 30 at $P_T^{J/\psi} = 18$ GeV/c. This indicates that the CSM underestimates direct production of the J/ψ by about the same factor found for the $\psi(2S)$. The solid curve in Fig. 4 includes contributions from the CSM and Color Octet Model (COM), where the Color Octet contribution is based on early extractions [12] of the relevant non-perturbative parameters from the branching ratios of $b \to \chi_c X$ decays. The extension of the COM to the $^3S_1$ states has been proposed in [4]; the corresponding calculations have been compared in [5] with our preliminary data showing that agreement between theory and data can be obtained by adjusting the non-perturbative parameters introduced in the COM.

In conclusion, we have measured the fraction of J/ψ's originating from χ_c's and found that the majority of prompt J/ψ's do not come from χ_c's but are directly produced. We conclude that the CSM fails to describe direct production of both the J/ψ and the $\psi(2S)$ by the same large factor.

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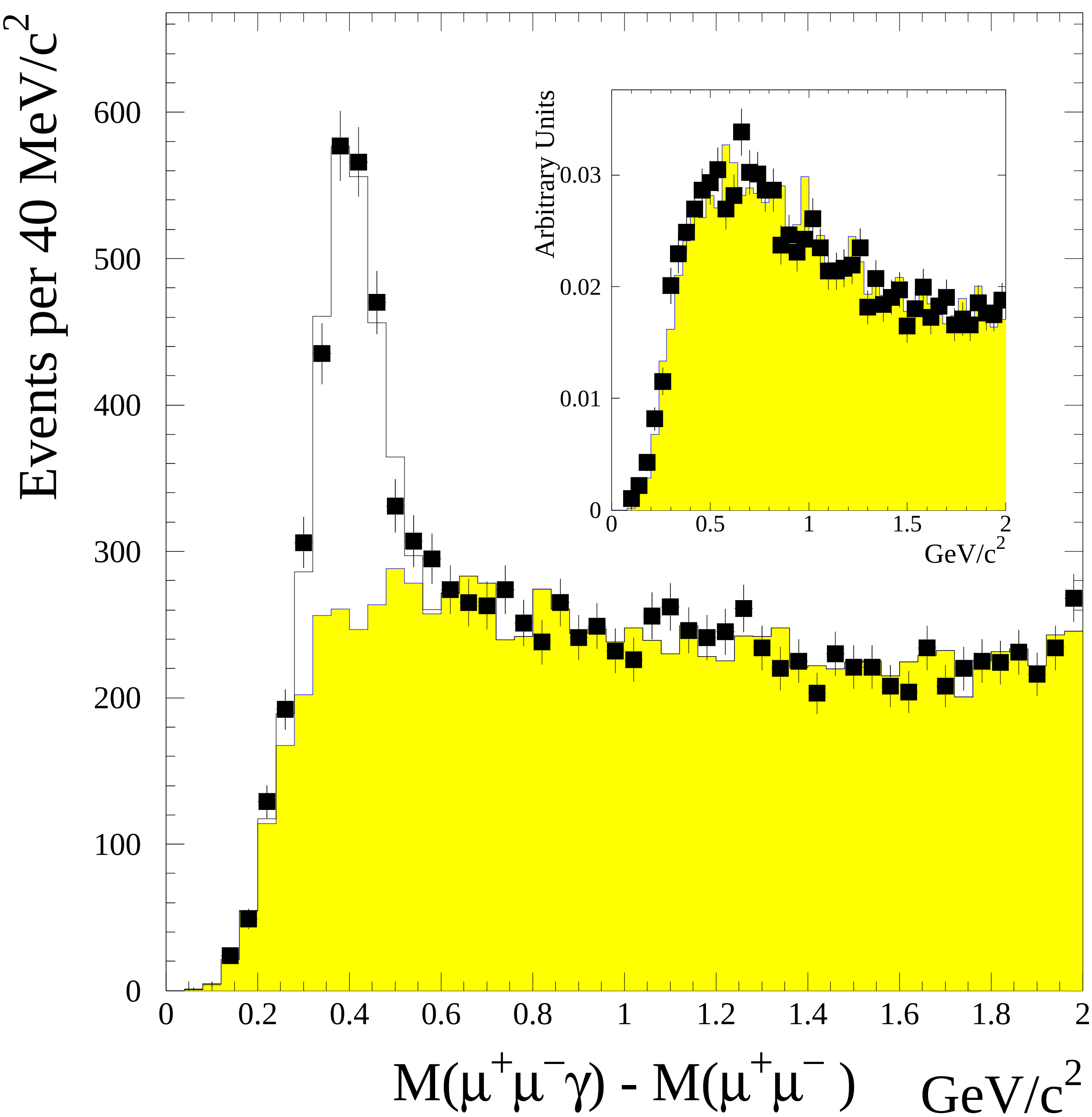
Figure Captions

FIG. 1. The distribution of the mass difference after the selection described in the text. The points represent the data. The shaded histogram is the background shape predicted by the Monte Carlo calculation. The solid line is the fit of the data to a Gaussian function plus the background histogram. The inset shows the comparison between the ΔM distribution for dimuons in the J/ψ sidebands, and the corresponding one predicted by the Monte Carlo calculation; the two distributions are normalized to equal area and the vertical scale is arbitrary.

FIG. 2. The proper lifetime distribution, for $J/\psi\gamma$ combinations in the χ_c signal region, when both muons have SVX information. The points represent the data. The shaded area shows the contribution from the background.

FIG. 3. The fraction of J/ψ mesons from χ_c decays as a function of $P_T^{J/\psi}$ with the contribution from b's removed. The error bars correspond to the statistical uncertainty. The solid line is the parametrization of the fraction. The dashed lines show the upper and lower bounds corresponding to the statistical and systematic uncertainties combined.

FIG. 4. The differential cross sections of prompt $J/\psi \rightarrow \mu^+\mu^-$ as a function of $P_T^{J/\psi}$. The dashed curve is the Color Singlet calculation for J/ψ production. The solid curve is the calculation of $\chi_c \rightarrow J/\psi\,\gamma$ production and includes both Color Singlet and Color Octet contributions. The error bars correspond to the statistical and systematic uncertainties combined.



Events per 40 MeV/c^2
600
500
400
300
200
100
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
M($\mu^+\mu^-\gamma$) - M($\mu^+\mu^-$) GeV/c^2
Arbitrary Units
0.03
0.02
0.01
0
0
0.5
1
1.5
2
GeV/c^2

FIG. 1.

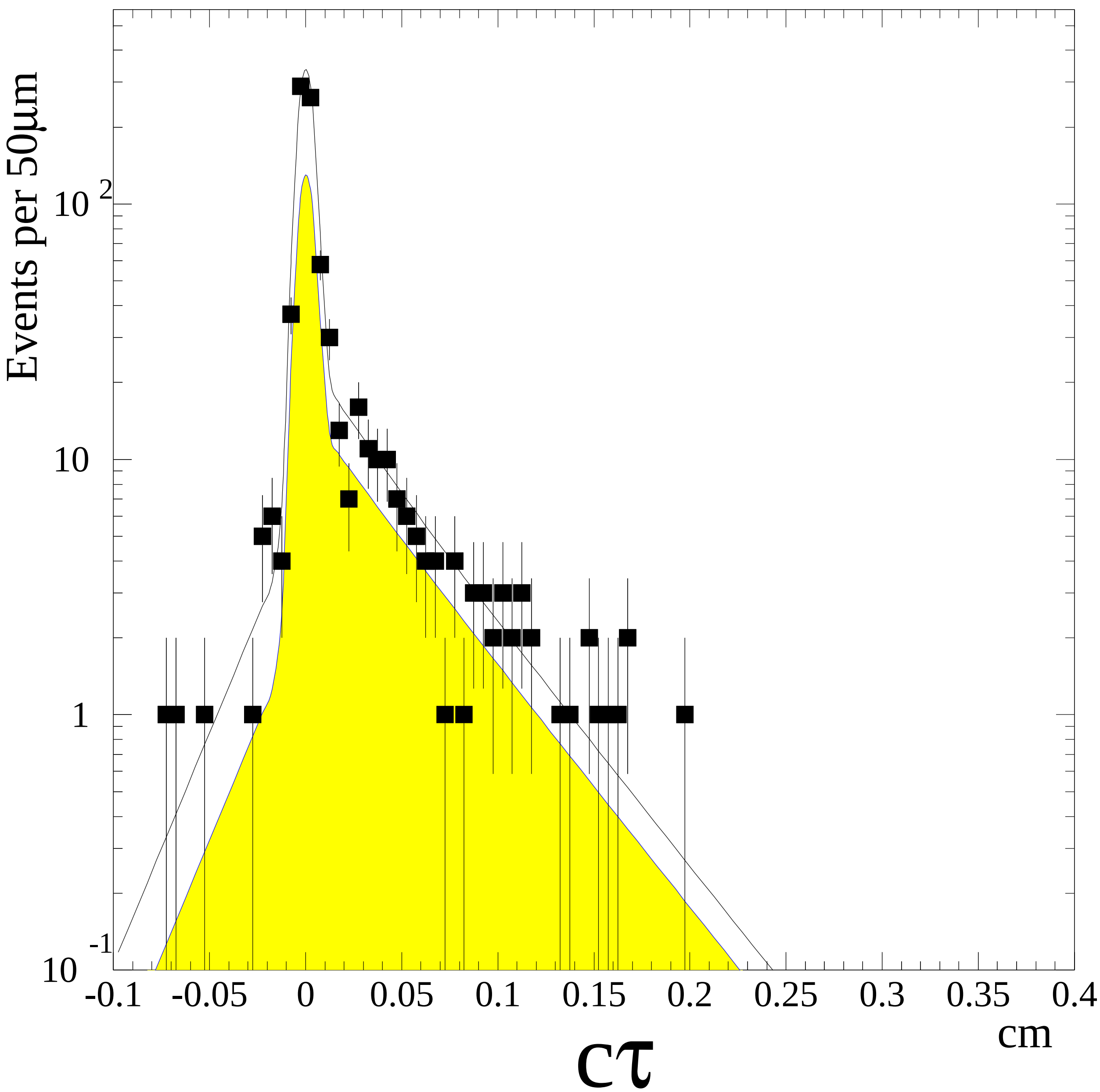
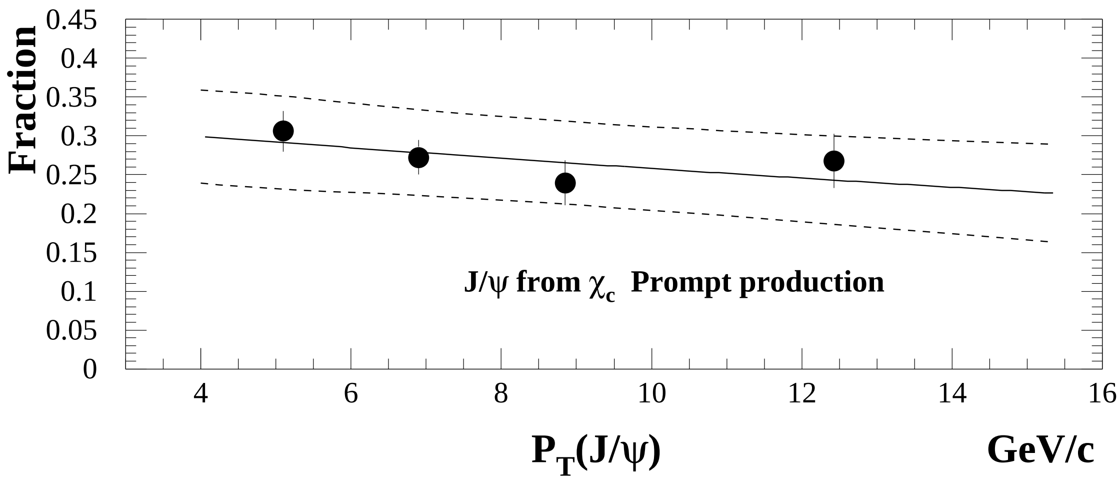

Events per 50μm
10^2
10
1
10^{-1}
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
cm
cτ

FIG. 2.



Fraction
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
J/ψ from χ_c Prompt production
4
6
8
10
12
14
16
$P_T(J/\psi)$
GeV/c

FIG. 3.

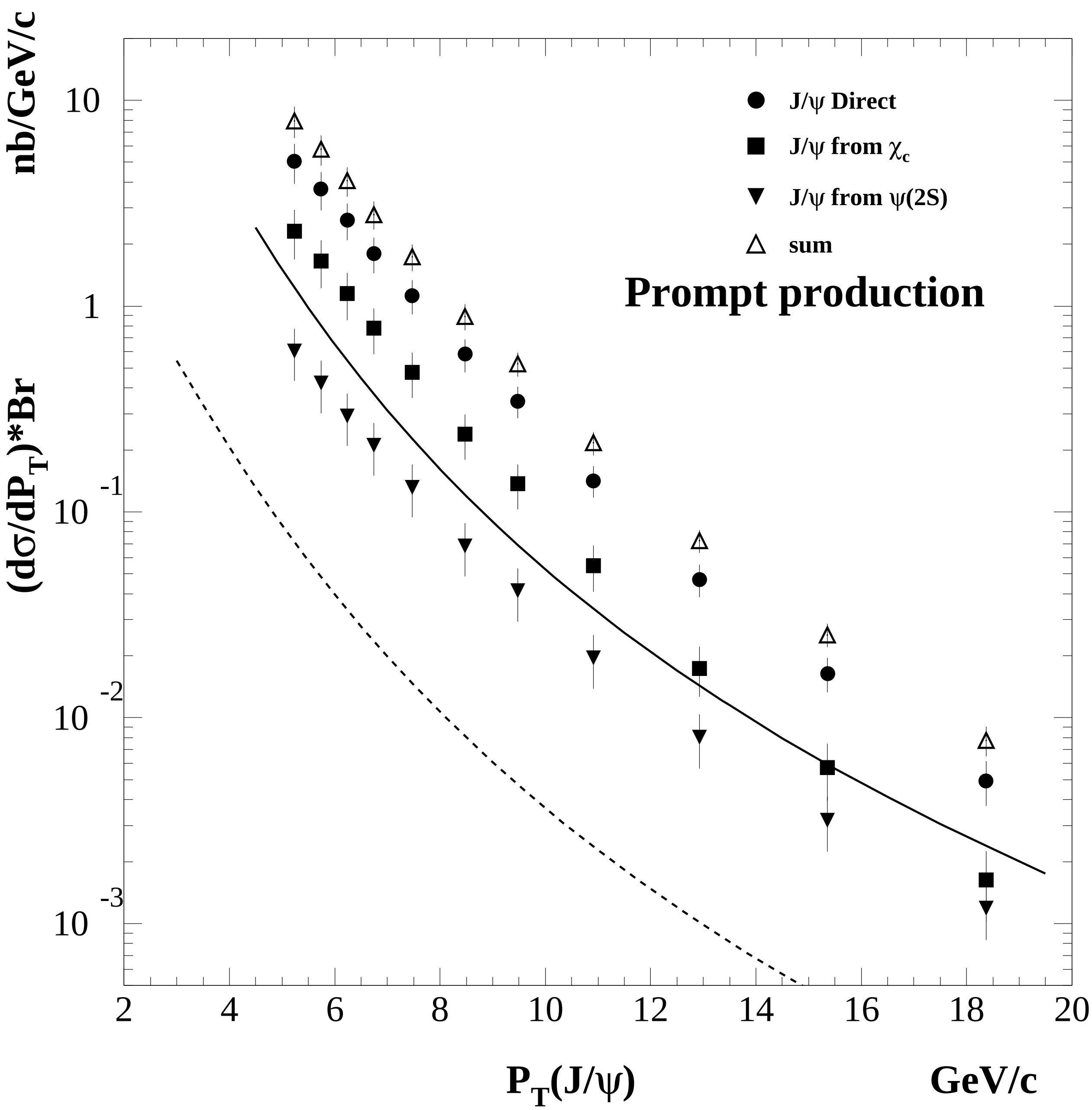

nb/GeV/c
(dσ/dP_T)*Br
10
1
10^-1
10^-2
10^-3
J/ψ Direct
J/ψ from χ_c
J/ψ from ψ(2S)
sum
Prompt production
2
4
6
8
10
12
14
16
18
20
P_T(J/ψ)
GeV/c

FIG. 4.