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Search for the rare decay $W^{\pm}\to D_s^{\pm}\gamma$ in $p\bar{p}$ collisions at $\sqrt{s}=1.8$ TeV

F. Abe,[17] H. Akimoto,[39] A. Akopian,[31] M. G. Albrow,[7] A. Amadon,[5] S. R. Amendolia,[27] D. Amidei,[20] J. Antos,[33] S. Aota,[37] G. Apollinari,[31] T. Arisawa,[39] T. Asakawa,[37] W. Ashmanskas,[18] M. Atac,[7] P. Azzi-Bacchetta,[25] N. Bacchetta,[25] S. Bagdasarov,[31] M. W. Bailey,[22] P. de Barbaro,[30] A. Barbaro-Galtieri,[18] V. E. Barnes,[29] B. A. Barnett,[15] M. Barone,[9] G. Bauer,[19] T. Baumann,[11] F. Bedeschi,[27] S. Behrends,[3] S. Belforte,[27] G. Bellettini,[27] J. Bellinger,[40] D. Benjamin,[35] J. Bensinger,[3] A. Beretvas,[7] J. P. Berge,[7] J. Berryhill,[5] S. Bertolucci,[9] S. Bettelli,[27] B. Bevensee,[26] A. Bhatti,[31] K. Biery,[7] C. Bigongiari,[27] M. Binkley,[7] D. Bisello,[25] R. E. Blair,[1] C. Blocker,[3] S. Blusk,[30] A. Bodek,[30] W. Bokhari,[26] G. Bolla,[29] Y. Bonushkin,[4] D. Bortoletto,[29] J. Boudreau,[28] L. Breccia,[2] C. Bromberg,[21] N. Bruner,[22] R. Brunetti,[2] E. Buckley-Geer,[7] H. S. Budd,[30] K. Burkett,[20] G. Busetto,[25] A. Byon-Wagner,[7] K. L. Byrum,[1] M. Campbell,[20] A. Caner,[27] W. Carithers,[18] D. Carlsmith,[40] J. Cassada,[30] A. Castro,[25] D. Cauz,[36] A. Cerri,[27] P. S. Chang,[33] P. T. Chang,[33] H. Y. Chao,[33] J. Chapman,[20] M.-T. Cheng,[33] M. Chertok,[34] G. Chiarelli,[27] C. N. Chiou,[33] F. Chlebana,[7] L. Christofek,[13] M. L. Chu,[33] S. Cihangir,[7] A. G. Clark,[10] M. Cobal,[27] E. Cocca,[27] M. Contreras,[5] J. Conway,[32] J. Cooper,[7] M. Cordelli,[9] D. Costanzo,[27] C. Couyoumtzelis,[10] D. Cronin-Hennessy,[6] R. Culbertson,[5] D. Dagenhart,[38] T. Daniels,[19] F. DeJongh,[7] S. Dell'Agnello,[9] M. Dell'Orso,[27] R. Demina,[7] L. Demortier,[31] M. Deninno,[2] P. F. Derwent,[7] T. Devlin,[32] J. R. Dittmann,[6] S. Donati,[27] J. Done,[34] T. Dorigo,[25] N. Eddy,[20] K. Einsweiler,[18] J. E. Elias,[7] R. Ely,[18] E. Engels, Jr.,[28] W. Erdmann,[7] D. Errede,[13] S. Errede,[13] Q. Fan,[30] R. G. Feild,[41] Z. Feng,[15] C. Ferretti,[27] I. Fiori,[2] B. Flaugher,[7] G. W. 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Proudfoot,[1] F. Ptohos,[11] G. Punzi,[27] K. Ragan,[14] D. Reher,[18] M. Reischl,[16] A. Ribon,[25] F. Rimondi,[2] L. Ristori,[27] W. J. Robertson,[6] T. Rodrigo,[27] S. Rolli,[38] L. Rosenson,[19] R. Roser,[13] T. Saab,[14] W. K. Sakumoto,[30] D. Saltzberg,[4] A. Sansoni,[9] L. Santi,[36] H. Sato,[37] P. Schlabach,[7] E. E. Schmidt,[7] M. P. Schmidt,[41] A. Scott,[4] A. Scribano,[27] S. Segler,[7] S. Seidel,[22] Y. Seiya,[37] F. Semeria,[2] T. Shah,[19] M. D. Shapiro,[18] N. M. Shaw,[29] P. F. Shepard,[28] T. Shibayama,[37] M. Shimojima,[37] M. Shochet,[5] J. Siegrist,[18] A. Sill,[35] P. Sinervo,[14] P. Singh,[13] K. Sliwa,[38] C. Smith,[15] F. D. Snider,[15] J. Spalding,[7] T. Speer,[10] P. Sphicas,[19] F. Spinella,[27] M. Spiropulu,[11] L. Spiegel,[7] L. Stanco,[25] J. Steele,[40] A. Stefanini,[27] R. Ströhmer,[7] J. Strologas,[13] F. Strumia,[10] D. Stuart,[7] K. Sumorok,[19] J. Suzuki,[37] T. Suzuki,[37] T. Takahashi,[24] T. Takano,[24] R. Takashima,[12] K. Takikawa,[37] M. Tanaka,[37] B. Tannenbaum,[22] F. Tartarelli,[27] W. Taylor,[14] M. Tecchio,[20] P. K. Teng,[33] Y. Teramoto,[24] K. Terashi,[37] S. Tether,[19] D. Theriot,[7] T. L. Thomas,[22] R. Thurman-Keup,[1] M. Timko,[38] P. Tipton,[30] A. Titov,[31] S. Tkaczyk,[7] D. Toback,[5] K. Tollefson,[19] A. Tollestrup,[7] H. Toyoda,[24] W. Trischuk,[14] J. F. de Troconiz,[11] S. Truitt,[20] J. Tseng,[19] N. Turini,[27] T. Uchida,[37] F. Ukegawa,[26] J. Valls,[32] S. C. van den Brink,[28] S. Vejcik III,[20] G. Velev,[27] R. Vidal,[7] R. Vilar,[7] D. Vucinic,[19] R. G. Wagner,[1] R. L. Wagner,[7] J. Wahl,[5] N. B. Wallace,[27] A. M. Walsh,[32] C. Wang,[6] C. H. Wang,[33] M. J. Wang,[33] A. Warburton,[14] T. Watanabe,[37] T. Watts,[32] R. Webb,[34] C. Wei,[6] H. Wenzel,[16] W. C. Wester III,[7] A. B. Wicklund,[1] E. Wicklund,[7] R. Wilkinson,[26] H. H. Williams,[26] P. Wilson,[5] B. L. Winer,[23] D. Winn,[20] D. Wolinski,[20] J. Wolinski,[21] S. Worm,[22] X. Wu,[10] J. Wyss,[27] A. Yagil,[7] W. Yao,[18] K. Yasuoka,[37] G. P. Yeh,[7] P. Yeh,[33] J. Yoh,[7] C. Yosef,[21] T. Yoshida,[24] I. Yu,[7] A. Zanetti,[36] F. Zetti,[27] 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 02254*
[4]*University of California at Los Angeles, Los Angeles, California 90024*
[5]*University of Chicago, Chicago, Illinois 60637*
[6]*Duke University, Durham, North Carolina 27708*
[7]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[8]*University of Florida, Gainesville, Florida 32611*
[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, Canada H3A 2T8*
and University of Toronto, Toronto M5S 1A7, Canada
[15]*The Johns Hopkins University, Baltimore, Maryland 21218*
[16]*Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*
[17]*National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 305, Japan*
[18]*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[19]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[20]*University of Michigan, Ann Arbor, Michigan 48109*
[21]*Michigan State University, East Lansing, Michigan 48824*
[22]*University of New Mexico, Albuquerque, New Mexico 87131*
[23]*The Ohio State University, Columbus, Ohio 43210*
[24]*Osaka City University, Osaka 588, Japan*
[25]*Universita di Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy*
[26]*University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[27]*Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy*
[28]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[29]*Purdue University, West Lafayette, Indiana 47907*
[30]*University of Rochester, Rochester, New York 14627*
[31]*Rockefeller University, New York, New York 10021*
[32]*Rutgers University, Piscataway, New Jersey 08855*
[33]*Academia Sinica, Taipei, Taiwan 11530, Republic of China*
[34]*Texas A&M University, College Station, Texas 77843*
[35]*Texas Tech University, Lubbock, Texas 79409*
[36]*Istituto Nazionale di Fisica Nucleare, University of Trieste/Udine, Italy*
[37]*University of Tsukuba, Tsukuba, Ibaraki 315, Japan*
[38]*Tufts University, Medford, Massachusetts 02155*
[39]*Waseda University, Tokyo 169, Japan*
[40]*University of Wisconsin, Madison, Wisconsin 53706*
[41]*Yale University, New Haven, Connecticut 06520*

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We search for the rare decay $W^{\pm}\rightarrow D_s^{\pm}\gamma$ in 82 pb^{-1} of $p\overline{p}$ collisions recorded with the Collider Detector at Fermilab. At the 95% confidence level, we find an upper limit on the relative branching fraction to be $\Gamma(W^{\pm}\rightarrow D_s^{\pm}\gamma)/\Gamma(W^{\pm}\rightarrow e^{\pm}\nu)<1.2\times10^{-2}$.

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The large samples of weak bosons produced in $p\overline{p}$ collisions enable searches for rare processes which probe the limits of the standard model [1]. While the rare decay modes of the Z boson have been explored in detail, the rare decay modes of the W have just begun to be investigated [2]. Decays of the W into a pseudoscalar meson and a photon are sensitive to physics processes which involve the $WW\gamma$ vertex. The rare radiative decay $W^{\pm}\rightarrow D_s^{\pm}\gamma$ is attractive because of the easily identifiable final state signature, even though it is suppressed by the behavior of the $D_s^{\pm}$ meson form factor at $q^2=M_W^2$. A detailed theoretical treatment predicts the relative branching fraction $\Gamma(W^{\pm}\rightarrow D_s^{\pm}\gamma)/\Gamma(W^{\pm}\rightarrow e^{\pm}\nu)\approx1\times10^{-7}$ [3], which is three times larger than that for the similar decay $W^{\pm}\rightarrow\pi^{\pm}\gamma$ [4]. However, the multitude of $D_s^{\pm}$ decay modes and the choice of particular modes for experimental identification makes the experimental reach smaller in the $W^{\pm}\rightarrow D_s^{\pm}\gamma$ case. The experimental signature consists of an isolated high momentum photon together with

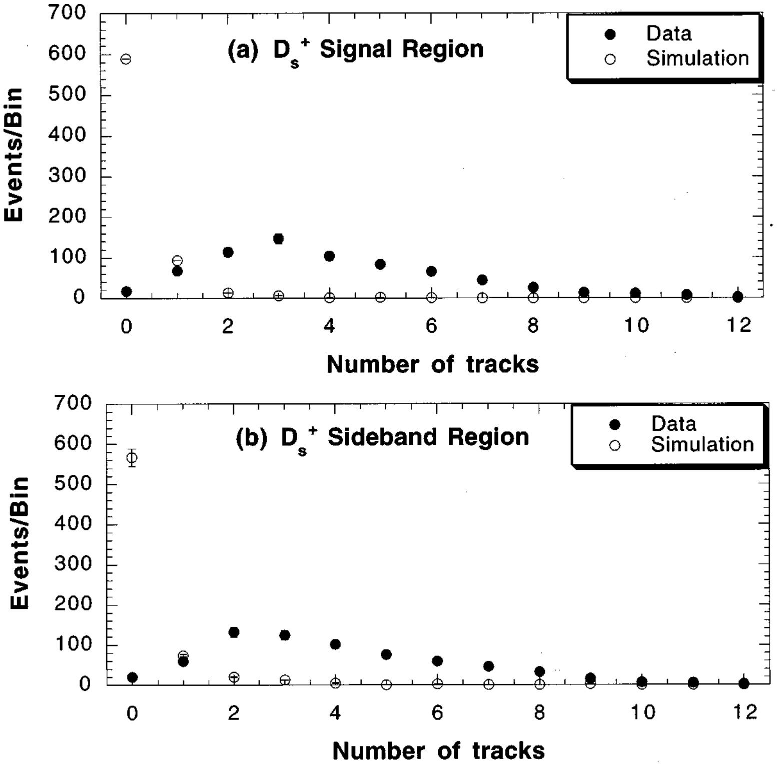

FIG. 1. A comparison of the number of tracks in a cone of radius 0.7 around the D_s^+ direction for data (filled circles) and Monte Carlo simulation of $W^{\pm}\rightarrow D_s^{\pm}\gamma$ (open circles), (a) for the D_s^+ signal sample and (b) for the D_s^+ sideband sample. The Monte Carlo samples have been normalized to the data samples. There are 708 events in the D_s signal sample, 18 having no tracks in the cone. There are 684 events in the sideband sample, 20 having no tracks in the cone.

$D_s^{\pm}$ mesons identified via the decay modes $D_s^+\rightarrow\phi\pi^+$ and $D_s^+\rightarrow\overline{K^{*0}}K^+$ [5]. This search is complementary to a similar search in the $\pi\gamma$ channel [4]. We expect the search to be dominated by background from QCD processes, with the most significant being direct photon production and combinatoric background from particles in the jet recoiling against the photon. Though expected to be smaller, an additional background is production of $\gamma+c$, where the charm quark fragments into a leading D_s^+ meson.

The $W^{\pm}\rightarrow D_s^{\pm}\gamma$ search examines 81.8 ± 6.5 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}=1.8$ TeV, recorded by the Collider Detector at Fermilab (CDF) during the 1994–1995 Tevatron run. The CDF detector has been described in detail elsewhere [6]. We use a coordinate system where ϕ is the azimuthal angle around the beam line and θ is the polar angle with respect to the z (proton beam) direction. Pseudorapidity, η, is defined by $\eta=-\ln(\tan(\theta/2))$; $p_T=p\,\sin(\theta)$ and $E_T=E\,\sin(\theta)$ are the momentum and energy flow measured transverse to the beam line, respectively. The key detector components used in the analysis are the central electromagnetic calorimeter, covering $|\eta|<1.1$ and 2π in azimuth in a projective tower geometry, proportional chambers located at shower maximum within the electromagnetic calorimeter, and the central tracking chamber, a 1.3 m radius wire drift chamber immersed in a 1.4 T solenoidal field.

The data sample was collected with a three level trigger, with both energy thresholds and isolation criteria applied [7]. The first level trigger required a total transverse energy greater than 8 GeV in a contiguous pair of electromagnetic towers with $|\eta|<1.1$. The second level trigger raised the transverse energy threshold to 23 GeV and required that there be less than 4 GeV additional transverse energy in surrounding towers (corresponding approximately to a cone in η-ϕ space of $\Delta R=\sqrt{\Delta\eta^2+\Delta\phi^2}\approx0.4$). The third level trigger required that the photon candidate be in a good fiducial region [8] of the calorimeter. The E_T dependence of the trigger efficiency has been measured by comparison to photons from a prescaled trigger with an E_T threshold of 10 GeV. The efficiency rises from 0 near threshold to a plateau value of 0.970 ± 0.005 for transverse energies greater than 30 GeV. The photon trigger efficiency, when convoluted with the expected E_T spectrum from $W^{\pm}\rightarrow D_s^{\pm}\gamma$ decays, is estimated to be 0.844 ± 0.032, including the hardware efficiency, threshold dependence, and isolation requirements.

The reconstructed photon is required to have $E_T>22$ GeV, $|\eta|<1.0$, to be in a good fiducial region of the calorimeter, and to have no track pointing at the calorimeter cells containing the electromagnetic shower. The transverse shower profile in both the longitudinal and azimuthal views is required to be consistent with an electromagnetic shower [7]. As we expect the W decay products to be isolated [9], we require that the additional total transverse energy in a cone of $\Delta R=0.4$ centered on the photon candidate be less than 4.0 GeV. Further details on photon identification can be found in Ref. [4]. Finally, we require that the identified $|z|$ vertex position be less than 60 cm from the nominal interaction point.

In events with an identified photon candidate, we look for the presence of a D_s^+ meson by identifying the decay modes $\phi\pi^+$ and $\overline{K^{*0}}K^+$, followed by the decays $\phi\rightarrow K^+K^-$ and $\overline{K^{*0}}\rightarrow K^-\pi^+$. With current measured branching fractions [10], we are sensitive to $(4.03\pm0.75)\%$ of D_s^+ decays. For mass reconstruction, we use reconstructed tracks with $p_T>1.0$ GeV/c and $|\eta|<1.1$ and require that the constrained

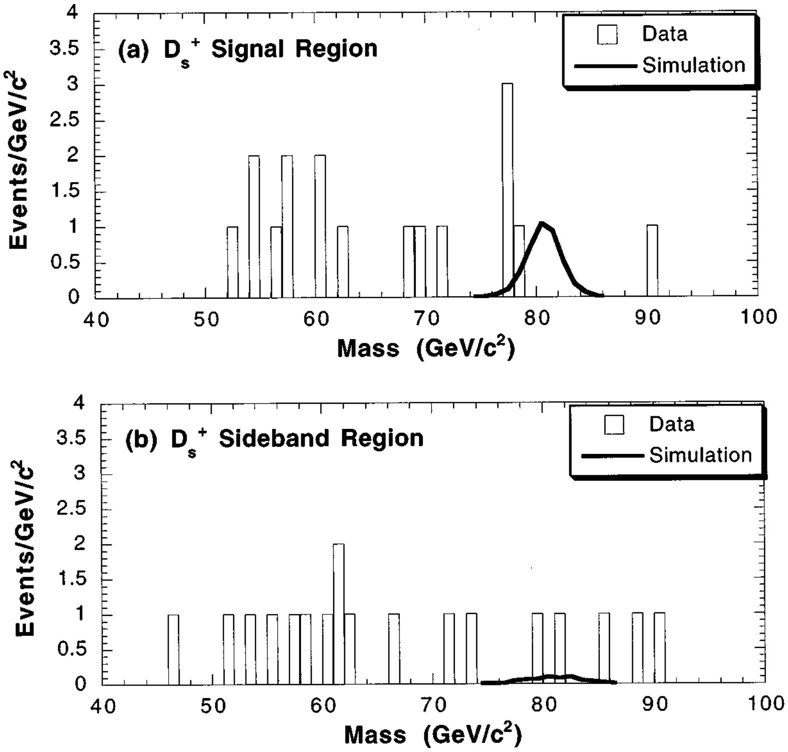

FIG. 2. A comparison of data (open histogram) and Monte Carlo simulation of $W^{\pm}\rightarrow D_s^{\pm}\gamma$ (curve) for the final selection. (a) is for the D_s^+ signal region, (b) for the sideband region. The Monte Carlo simulation sample has been normalized to four events in the W signal region (72.5–88.3) GeV/c^2. With this normalization, there is an expected contribution of 0.1 events in the sideband region.

vertex fit have a χ^2 probability greater than 0.01. The mass windows for the various decay modes are based on Monte Carlo simulation samples, described below. We select two track combinations consistent with the ϕ ($\overline{K^{*0}}$) hypothesis, assuming the $K^{\pm}$ or π^+ mass appropriately. The combination is considered a ϕ candidate if the reconstructed mass is in the range (0.98–1.05) GeV/c^2 and $p_T > 10$ GeV/c. It is considered a $\overline{K^{*0}}$ candidate if the reconstructed mass is in the range (0.84–0.96) GeV/c^2 and $p_T > 10$ GeV/c. For events passing these requirements, a third track is added to the vertex fit, again assuming the K^+ or π^+ mass appropriately. The D_s^+ signal region is the mass range (1.90–2.02) GeV/c^2 and $p_T > 22$ GeV/c. We also select a D_s^+ sideband region, used for background calculations, with three track combinations in the mass ranges (1.83–1.89) GeV/c^2 or (2.03–2.09) GeV/c^2 and $p_T > 22$ GeV/c. At this stage of the analysis, there are 708 events with three track combinations in the D_s^+ signal region and 684 events with three tracks in the D_s^+ sideband regions.

In Fig. 1, we show the distribution of tracks in a cone of $\Delta R = 0.7$ around the reconstructed-candidate direction for both the signal and sideband regions, overlaid with the results from a Monte Carlo simulation for the decay $W^{\pm}\rightarrow D_s^{\pm}\gamma$ (discussed below). The data sample still shows a large contribution from the combinatoric backgrounds in direct photon events. We therefore require that there be no tracks with $p_T > 1$ GeV/c in the cone, resulting in 18 events in the D_s^+ signal region and 20 in the sideband regions. This last requirement is a track analogue of the calorimeter isolation applied to the photon candidate.

We select W candidate events by requiring that the $D_s^+\gamma$ mass lie in the range (72.5–88.3) GeV/c^2. This mass range spans the expected 3σ width of the W candidates, including both the effects of the W width (assumed to be 2.1 GeV/c^2) and the simulated mass resolution, centered on a W mass of 80.4 GeV/c^2. There are four events, one in the $\phi\pi^+$ decay mode and three in the $\overline{K^{*0}}K^+$ mode, in this mass range from the D_s^+ signal region and four events, one in the $\phi\pi$ and three in the $\overline{K^{*0}}K^+$ mode, from the sideband regions. Figure 2 shows the two samples, overlaid with the Monte Carlo simulation normalized to four events in the signal histogram. We use the method of the Particle Data Group to set a 95% confidence level limit on the signal size in the presence of an estimated background [11]. With four signal events and an estimate of four background events, the upper limit is 5.9 events at the 95% confidence level.

A Monte Carlo simulated sample of $W^{\pm}\rightarrow D_s^{\pm}\gamma$ decays has been created with a combination of event generators and a full detector simulation. The PYTHIA Monte Carlo program [12] is used to generate W bosons and the associated event characteristics. The CLEO Monte Carlo program [13], with adjustments to the list of allowed decays, is used to force the decay $W^{\pm}\rightarrow D_s^{\pm}\gamma$, and to simulate the decays of the D_s^+ mesons. Events satisfying the following requirements are accepted: (1) the photon has $E_T > 22$ GeV and $|\eta| < 1$; (2) be in the good fiducial region of the calorimeter; (3) all three tracks from the D_s^+ decay to have $p_T > 1.0$ GeV/c and $|\eta| < 1.1$; (4) the ϕ or $\overline{K^{*0}}$ has $p_T > 10$ GeV/c; and (5) the D_s^+ has $p_T > 22$ GeV/c. Using the Martin-Roberts-Stirling set A (MRSA) [14] parton distribution functions and the results of the full detector simulation, we find that $(15.4\pm 0.4)\%$ of $W^{\pm}\rightarrow D_s^{\pm}\gamma$ decays pass these criteria. Results with other parton distribution function sets are consistent with this value.

The simulated sample was passed through all the analysis requirements, except that the mass ranges for meson and W selection were relaxed. The final values for the mass selections were set to be $\pm 3\sigma$. The combined efficiency of the 3 mass cuts (ϕ or $\overline{K^{*0}}$, D_s^+, and W), including the two vertex probability requirements, is 0.96 ± 0.01.

Photon identification efficiencies for the transverse shower profiles and isolation requirements are measured in a sample of $W^{\pm}\rightarrow e^{\pm}\nu$ events, selected independently of the identification variables used in the photon selection [4]. Including the trigger efficiency measurement described earlier, the total efficiency for the photon identification is 0.752 ± 0.029.

Track finding efficiencies for the D_s^+ selection are found by embedding simulated pion tracks in $J/\psi\rightarrow\mu^+\mu^-$ data events and measuring the fraction of times the simulated track is found [15]. We convolute the expected p_T distribution from the Monte Carlo sample with the measured efficiency curves. We assume that the efficiency for finding three tracks is the product of individual track finding efficiencies. The total efficiency for finding all three tracks from the D_s^+ decay is $0.898^{+0.033}_{-0.045}$. The track isolation requirement around the D_s^+ candidate is studied in the $W^{\pm}\rightarrow e^{\pm}\nu$ sample. The ν direction is calculated based on the W mass, the electron momentum, and the transverse energy imbalance (summed over calorimeter towers) [9]. If the results yield physical solutions for the ν momentum, we choose the solution for which $|\eta_\nu|<1.1$. The fraction of events with no tracks in a cone around the calculated ν direction is 0.718 ± 0.007 [4]. The efficiency of the z vertex requirement is estimated to be 0.956 ± 0.002, using the same techniques described in [16].

We include systematic uncertainties in acceptance, efficiency, and luminosity measurements according to the procedure outlined in Ref. [17], which provides a prescription for including systematic uncertainties into an upper limit determined from Poisson statistics. The 95% confidence level upper limit, including systematic uncertainties, is 6.7 events.

TABLE I. Summary of the cross section results.

Observed Events	4 events
Estimated Background Events	4 events
Signal Events	<6.7 at 95% C.L.
Acceptance	0.154 ± 0.004
Photon Identification	0.752 ± 0.029
Vertex Reconstruction	0.96 ± 0.01
Track Finding	$0.898^{+0.033}_{-0.045}$
D_s^+ Track Isolation	0.718 ± 0.007
z Vertex	0.956 ± 0.002
Total Efficiency	0.445 ± 0.029
$\int L\ dt$	81.8 ± 6.5 pb^{-1}
Branching Fraction	0.0403 ± 0.0075
$\sigma(\overline{p}p\rightarrow W^{\pm}\rightarrow D_s^{\pm}\gamma)$	<29.7 pb at 95% C.L.

Combining the number of signal events, acceptance, identification efficiency, integrated luminosity, and branching fraction (as summarized in Table I), we find that $\sigma(\overline{p}p\rightarrow W^{\pm}\rightarrow D_s^{\pm}\gamma)<29.7$ pb. With a measured cross section $\sigma(\overline{p}p\rightarrow W^{\pm}\rightarrow e^{\pm}\nu)=2.49\pm0.12$ nb [16], we find the relative branching fraction $\Gamma(W^{\pm}\rightarrow D_s^{\pm}\gamma)/\Gamma(W^{\pm}\rightarrow e^{\pm}\nu)<1.2\times10^{-2}$ at 95% confidence level. This result is the first measurement of this quantity. At the present level of sensitivity there is no evidence for deviations from the standard model prediction for two-body radiative decays of weak vector bosons.

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