Search for the rare radiative decay W→πγ in pp[over ¯] collisions at sqrt[s]=1.96 TeV

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Search for the Rare Radiative Decay: $W \to \pi\gamma$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present a search for the rare radiative decay $W^\pm \to \pi^\pm\gamma$ using data corresponding to an integrated luminosity of 4.3 fb^{-1} of proton-antiproton collisions at a center of mass energy of 1.96 TeV collected by the CDF experiment at Fermilab. As no statistically significant signal is observed, we set a 95% confidence level upper limit on the relative branching fraction $\Gamma(W^\pm \to \pi^\pm\gamma)/\Gamma(W^\pm \to e^\pm\nu)$ at 6.4×10^{-5}, a factor of 10 improvement over the previous limit.

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Since their discovery by the UA1 [1] and UA2 [2] experiments, the properties and decays of the massive mediators of the electroweak interaction, the W and Z vector bosons, have been studied extensively. The vector bosons decay predominantly into a pair of a quark and an antiquark, whose hadronization results in final states with two or more jets. Exclusive hadronic decays of the W and Z bosons with all final state particles identified are yet to be observed, and most information about the W and Z properties comes from studies of their leptonic decays, $W^- \to l^-\nu$ and $Z^0 \to l^+l^-$. Radiative decays of the vector bosons $V \to P + \gamma$, where P is a pseudoscalar meson, are sensitive probes of the strong dynamics involved in

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meson formation as well as of the vector boson couplings to the photon. Branching ratios of the radiative decays are suppressed by a factor of $(f_P/M_V)^2$, where f_P is the meson form factor, and M_V is the vector boson mass. As a result, these decays are expected to be rare, with the standard model (SM) predictions for $BR(W^\pm \to \pi^\pm\gamma)$ ranging from $\sim 10^{-6}$ to $\sim 10^{-9}$ [3]. However, the sensitivity of the Tevatron experiments is approaching the upper range of the SM predictions, and observation of the radiative W and Z boson decays could provide important information about these processes.

Previous searches for the $W^\pm \to \pi^\pm\gamma$ decay by the UA1, UA2, and CDF experiments have successively brought the upper limit on $\Gamma(W^\pm \to \pi^\pm\gamma)/\Gamma(W^\pm \to e^\pm\nu)$ down to the level of 7×10^{-4} at 95% confidence level (C.L.)[4, 5].

In this paper we present a search for the $W^\pm \to \pi^\pm\gamma$ decay using data corresponding to $4.3\,\mathrm{fb}^{-1}$ of integrated luminosity recorded by the CDF experiment in $p\bar{p}$ collisions at 1.96 TeV. Compared to the previous CDF search [5], this represents an increase in the size of the data set by a factor of ≈ 50.

The CDF II detector is a general purpose particle detector and is described in detail elsewhere [6]. The z-axis of the detector coordinate system points along the direction of the proton beam. The event geometry and kinematics are described using the azimuthal angle ϕ and the pseudorapidity $\eta = -\ln(\tan\theta/2)$, where θ is the polar angle with respect to the beam axis. The transverse energy and momentum of the reconstructed particles are defined as $E_T = E\sin\theta$, $p_T = p\sin\theta$, where E is the energy and p is the momentum.

The analysis presented below uses electron ($e^\pm$), photon (γ), and charged pion ($\pi^\pm$) candidates, reconstructed and identified using information from the central outer tracker (COT) [7], central electromagnetic (CEM) and hadronic calorimeters (CHA), and the central shower maximum detector (CES) [8, 9].

Candidate $\pi^\pm\gamma$ events are collected using an inclusive photon trigger that has no tracking requirements. As a result, the trigger has similar efficiencies for selecting high-p_T electrons and photons. The kinematic properties of the $W^\pm \to \pi^\pm\gamma$ decay are also in many respects close to the kinematics properties of the $W^\pm \to e^\pm\nu$ decay, which has been extensively studied at the Tevatron [10]. Consequently, many common systematic uncertainties cancel in the ratio $\Gamma(W^\pm \to \pi^\pm\gamma)/\Gamma(W^\pm \to e^\pm\nu)$, and we use sample of $W^\pm \to e^\pm\nu$ events collected with the same trigger to normalize the results of the search.

The three level calorimeter-based trigger selects events with at least one central calorimeter cluster with $E_T >$ 25 GeV and a large fraction of energy deposited in the CEM: $E_{CHA}/E_{CEM} < 0.0055 + 0.00045 \times E$. A cluster is required to be isolated such that the additional energy in a cone of $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4$ is less than 10% of the cluster energy. To reduce background from the multi-photon decays of neutral mesons, most importantly π^0 mesons, the lateral profile of the CES shower is required to be consistent with that produced by a single photon. Offline $\pi^\pm\gamma$ selection requires each event passing the trigger to have a photon candidate with $E_T > 25$ GeV and a charged pion candidate with $p_T > 25$ GeV/c and with significant azimuthal separation ($\Delta\phi > 2$ radians) between them.

Photon candidates are reconstructed from CEM energy clusters with $|\eta| \leq 1.1$ and within the CES fiducial. To distinguish photons from electrons, no high-p_T track should point into the cluster, $N_{tracks} <= 1$ with track $p_T < 1GeV/c + 0.005 \times E_T^\gamma/c$. Most of "fake" photons come from decays of the neutral mesons, π^0 and η^0, produced in jets. Background from the neutral meson decays is suppressed by vetoing photon candidates which have additional CES clusters with $E_T > 2.4\,\mathrm{GeV} + 0.01 \times E_T^\gamma$ in the same CES chamber. To suppress the jet background further, the reconstructed photon candidates are required to be isolated. The total additional, or isolation, energy reconstructed in the calorimeter within a cone of $\Delta R = 0.4$ around the photon candidate should be less than $1.6\,\mathrm{GeV} + 0.02 \times E_T^\gamma$, and the sum of transverse momenta of the COT tracks within the same cone - less than $2.0\,\mathrm{GeV/c} + 0.005 \times E_T^\gamma/c$. More details on the photon reconstruction can be found in [11].

Charged pion candidates are reconstructed as COT tracks with impact parameter ≤ 0.2 cm with respect to the beam axis. The track must be consistent with originating from the primary event vertex, which is required to be within 60 cm of the center of the detector along the beam line. The track must point to a narrow calorimeter cluster and extrapolate to a fiducial region of the CES detector. As with photons, pions from $W^\pm \to \pi^\pm\gamma$ decays are expected to be isolated, and the pion candidates are required to satisfy a number of tracking and calorimeter isolation criteria. A pion candidate is rejected if there is another track originating from the same vertex having $p_T > 1$ GeV/c within a cone of 10° around the pion track. The total additional calorimeter energy within the cone of $\Delta R = 0.4$ around the cluster is required to be less than 10% of the track p_T and the sum of transverse momenta of all tracks within $\Delta R = 0.4$ of the pion track is required to be less than 5% of its p_T. To reject background from QCD jets, which often contain neutral particles, no CES clusters with energy greater than 500 MeV may be found within 30° of the track. Finally, pion candidates passing electron identification criteria are excluded from the analysis. This selection yields a total of 1398 $\pi^\pm\gamma$ candidate events.

The acceptance for the $W^\pm \to \pi^\pm\gamma$ decay is determined using a sample of Monte Carlo (MC) events generated with the PYTHIA event generator [12] and the CTEQ5L parton distribution functions [13]. The angular distribution of pions in the W boson rest frame is described by the formula $dN/d\cos\theta = 1 + \cos^2\theta$, where θ is the angle of the pion with respect to the W boson line of flight axis. This distribution describes the decay of a spin-one particle (W) into a photon and a pseudoscalar pion averaged over W boson polarizations and summed over photon polarizations. The detector response is simulated with a GEANT3 based simulation program [14].

The photon identification efficiency is determined using MC simulated events and corrected using $Z^0 \to e^+e^-$ data events, where only probe electrons with suppressed bremsstrahlung, $|E/p - 1| < 0.1$, are selected. The method assumes that the detector response to photons is the same as that to non-radiating electrons. Comparing simulations of electron and photon showers in the CEM, we verified that the accuracy of this assumption is better than 1%.

The identification efficiency for pions from the $W^\pm \to \pi^\pm\gamma$ decay is also calculated using MC simulation. The correction factor to this efficiency, which takes into account the effects of calorimeter shower mismodeling and instantaneous luminosity, is determined by comparing properties of the reconstructed jets in photon+jet data to those in photon+jet MC.

The total corrected acceptance times efficiency for $\pi^\pm\gamma$ selection is $A \times \epsilon = 0.0503 \pm 0.0006(stat) \pm 0.0011(sys)$. The uncertainty is dominated by the systematic uncertainty on the pion identification efficiency.

The dominant backgrounds to this search come from photon+jet events, where the jet fragments into a single charged particle, and from multi-jet events, where one of the jets fragments into a single charged particle and another is misidentified as a photon. Drell-Yan pair production and W/Z decays, especially to τ leptons, also contribute to the background at a level of $\approx 10\%$. The signal from the $W^\pm \to \pi^\pm\gamma$ decay would appear as a peak in the $\pi^\pm\gamma$ invariant mass spectrum centered at the W boson mass with a resolution of 2.5 GeV/c^2, which includes the experimental resolution and the full width of the W boson, 2.1 GeV/c^2 [15]. We therefore define the signal region as $75 < M_{\pi^\pm\gamma} < 85$ GeV/c^2, which includes 90% of $W^\pm \to \pi^\pm\gamma$ decays. The background within the signal region is estimated by fitting the sidebands, $67.5 < M_{\pi^\pm\gamma} < 75$ GeV/c^2 and $85 < M_{\pi^\pm\gamma} < 120$ GeV/c^2, with an exponential function using a χ^2 minimization.

Figure 1 shows the $M_{\pi^\pm\gamma}$ distribution as well as the sideband fit for all events passing selection. The fit residuals, plotted in Figure 2, show that the exponential fit is an adequate model of the background shape with the present level of statistics. The statistical uncertainty on the fit results in a $\approx 5\%$ uncertainty on the background expectation.

From the sideband fit, a total of 219 $\pm$ 10 events are expected in the signal region from the fit and 206 are observed. Since the data in the signal region are consistent with the expected background, we set a 95% C.L. upper limit on the $\sigma(p\bar{p} \to W) \times BR(W^\pm \to \pi^\pm\gamma)$. We divide the signal region into four 2.5 GeV bins. The limits calculated for each bin are then combined assuming that uncertainties across the bins are 100% correlated. This provides a gain in sensitivity by using information about the shape of the expected $W^\pm \to \pi^\pm\gamma$ mass peak.

For the normalization measurement in the $W^\pm \to e^\pm\nu$ channel we select events which have a central ($|\eta| < 1.2$) electron with $E_T > 25\,\text{GeV}$ and missing transverse energy $\not\!\!E_T > 25\,\text{GeV}$ [16]. The electron reconstruction and identification algorithms used in this analysis are discussed in [10]. In addition, a standalone measurement of electron energy in the CES helps to identify electron candidates that radiate a significant fraction of their energy (due to bremsstrahlung) and improves overall electron identification efficiency. This selection results in a sample with $\leq$ 5% background, the dominant sources of which are $W^\pm \to \tau^\pm\nu$, $Z^0 \to e^+e^-$ decays and multijet events with one of the jets misidentified as an electron. The backgrounds are subtracted using MC simulation and the resulting $\sigma \times \mathrm{BR}(W^\pm \to e^\pm\nu) = (2.67 \pm 0.06(\text{stat.} + \text{syst.}) \pm 0.16(\text{lumi.}))$ nb, is consistent with the previous Tevatron measurements [10]. The dominant source of uncertainty on the cross section is the uncertainty on the integrated luminosity [17], which cancels in the ratio $\Gamma(W^\pm \to \pi^\pm\gamma)/\Gamma(W^\pm \to e^\pm\nu)$.

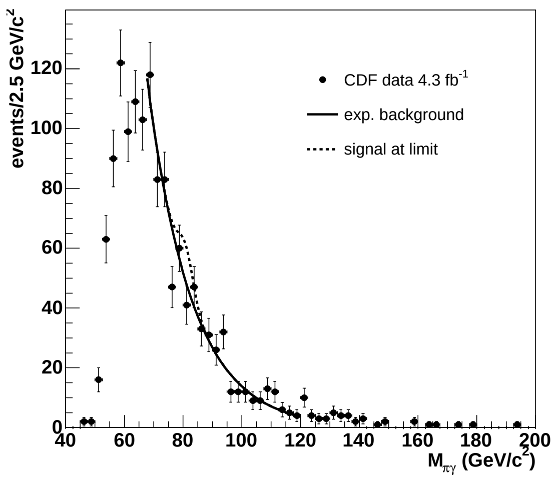

FIG. 1: The invariant mass, $M_{\pi^\pm\gamma}$, distribution for 1398 events passing full selection. The background expectation is shown with the solid curve and determined from the exponential fit to the sidebands, $67.5 < M_{\pi^\pm\gamma} < 75$ GeV/c^2 and $85 < M_{\pi^\pm\gamma} < 120$ GeV/c^2. The expected W boson (80.4 GeV/c^2) signal at the 95% C.L. upper limit is shown with the dashed curve. The error bars represent statistical uncertainties only.

Other sources of the systematic uncertainties

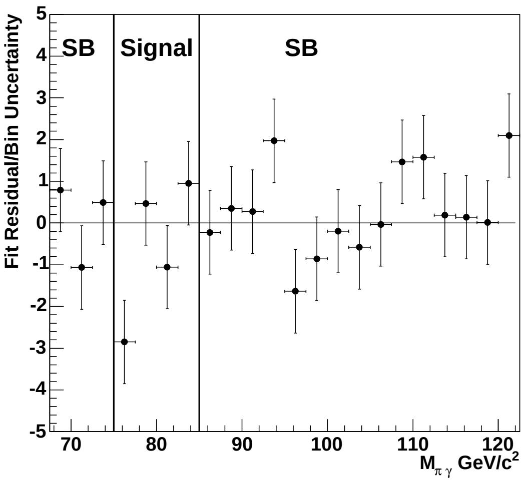

FIG. 2: The fit residual divided by bin uncertainty for Figure1. The signal and sideband (SB) regions are noted with the vertical lines.

that cancel almost entirely in the measurement of $\Gamma(W^\pm \to \pi^\pm\gamma)/\Gamma(W^\pm \to e^\pm\nu)$ include the uncertainties on the trigger efficiency as well as the uncertainties on parton distribution functions [18] and on the W transverse momentum, which affect the experimental acceptance. The uncertainties on the electron and photon identification efficiences cancel partially but result in a negligible uncertainty on the measurement of $\Gamma(W^\pm \to \pi^\pm\gamma)/\Gamma(W^\pm \to e^\pm\nu)$. The dominant remaining sources of uncertainties are the statistical and systematic uncertainties on $A \times \epsilon$ ($\sim$ 2%) and the statistical uncertainty on the $\pi^\pm\gamma$ background fit ($\sim 5\%$).

The 95% C.L. upper limit on the ratio of partial widths $\Gamma(W^\pm \to \pi^\pm\gamma)/\Gamma(W^\pm \to e^\pm\nu)$, calculated using a Bayesian approach that takes into account the effect of systematic uncertainties [19], is 6.4×10^{-5}. This improves the previous world's best limit [5] by more than a factor of 10. The corresponding 95% C.L. upper limit on the branching ratio $BR(W^\pm \to \pi^\pm\gamma)$, calculated using the world average $BR(W^\pm \to e^\pm\nu) = 0.1075 \pm 0.0013$ [15], is 7.0×10^{-6}. While no $W^\pm \to \pi^\pm\gamma$ signal was observed, the sensitivity of the CDF experiment to this decay channel has reached a level comparable to theoretical predictions. With increases in the dataset size, we expect the sensitivity to improve as $1/\sqrt{L}$, where L is the integrated luminosity. We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; the Academy of Finland; and the Australian Research Council (ARC).

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