Search for the Rare Decay $W^{\pm} \rightarrow \pi^{\pm} + \gamma$

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We have searched for the rare decay $W^{\pm} \to \pi^{\pm} + \gamma$ in 16.7 pb^{-1} of data taken in proton-antiproton collisions at $\sqrt{s} = 1.8$ TeV with the CDF detector at Fermilab. We find one event consistent with the expected signal, and estimate the background to be 2.6 ± 1.0(stat) $\pm$ 1.3(syst) events. Without background subtraction, we find the ratio of partial widths to be $\Gamma(W^{\pm} \to \pi^{\pm} + \gamma)/\Gamma(W^{\pm} \to e^{\pm} + \nu) \leq 2.0 \times 10^{-3}$ at the 95% confidence level.

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Rare decays of the W boson provide precision tests of the standard model of electroweak interactions. The ratio of the partial widths of the decays $W^{\pm} \to \pi^{\pm} + \gamma$ to $W^{\pm} \to e^{\pm} + \nu$ is estimated [1] to be $\Gamma(W^{\pm} \to \pi^{\pm} + \gamma)/\Gamma(W^{\pm} \to e^{\pm} + \nu) \simeq 3 \times 10^{-8}$. Observation of this decay in excess of the theoretical prediction could be an indicator of new physics beyond the standard model. Data taken during our 1988–89 run with the Collider Detector at Fermilab (CDF) have set an upper limit [2] on this ratio of 7.5×10^{-3} (95% CL) on the basis of 4.2 pb^{-1} of data. The UA2 collaboration at CERN has placed a limit of 4.9×10^{-3} (95% CL) on the basis of 13.7 pb^{-1} of data [3]. The major backgrounds to the signal are expected to arise from QCD processes, including direct photon production, in which a photon candidate is identified in the detector, and an additional jet fragments into a single, leading charged particle. In principle, additional backgrounds can arise from allowed weak decays $W \to q\bar{q}$, in which the quark jets fragment into a leading π^0 and $\pi^\pm$. For example, with the nominal probability [4] for a jet to fragment into a single pion of order $\lesssim 10^{-3}$, we can estimate the branching ratio for $W^\pm \to \pi^0 + \pi^\pm$ to be $\lesssim 10^{-6}$, substantially larger than the $W^\pm \to \pi^\pm + \gamma$ signal in the standard model, but too small to be detectable in our experiment.

Data for this analysis were collected during our 1992–93 run with proton-antiproton collisions at a center-of-mass energy of 1.8 TeV. The CDF detector has been described elsewhere [5]. 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.

We have used PAPAGENO [6] to study the physical observables of the $W \to \pi + \gamma$ decay, and we model the detector response and event selection efficiency with a fast detector simulation. We find the W mass peak reconstructed in this channel to be well described by a Gaussian distribution with an rms width of 2.7 GeV$/c^2$, where this result includes the natural linewidth of the W. We have verified the energy and momentum resolution of the simulation using $Z \to ee$ and $Z \to \mu\mu$ events. Therefore, we define the W mass window for the final event selection by the requirement $|M(\pi\gamma) - M(W)| < 8.1$ GeV$/c^2$.

Where possible, we have checked the event selection efficiency directly from the data sample, using, for example, $W^\pm \to e^\pm + \nu$ events collected from the same photon trigger. The Monte Carlo efficiencies agree quite well with the direct determinations, and we apply small corrections to the Monte Carlo prediction to obtain the final result. Anticipating the results of the discussion below, the overall correction to the Monte Carlo efficiency is given by an upward factor of $1.065 \pm 0.022(\text{stat}) \pm 0.083(\text{syst})$.

The data sample consists of a total of 1.21×10^6 events accumulated with a three level trigger. The first level trigger requires total energy greater than 6 GeV in a contiguous pair of central ($|\eta| < 1.1$) electromagnetic (EM) calorimeter towers. At the second level, the trigger imposes a photon energy threshold of 16 GeV and requires that the photon be isolated, with less than 5.0 GeV of additional energy in a 5×10 grid of calorimeter towers centered on the photon direction. Photon candidates which pass the third level trigger must be in the good fiducial region of the calorimeter [7], and there must be less than 4 GeV of additional energy in a cone of radius $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$ around the photon direction.

The trigger does not reject photon candidates with associated charged tracks; therefore, isolated electrons can satisfy the photon trigger requirements. The hardware and threshold dependence of the 16 GeV photon trigger has been measured by comparison with electrons from a trigger with a nominal threshold of 9 GeV. The photon trigger efficiency, when convoluted with the expected p_T spectrum of photons from $W^\pm \to \pi^\pm + \gamma$, is estimated to be $0.86 \pm 0.03(\text{syst})$, including the hardware efficiency, threshold dependence, and combined hardware and software isolation cuts.

All events (data or Monte Carlo) were passed through two analysis paths: one designed to select photons and one to select jets with isolated, high p_T tracks. Each path produced an output stream of events surviving its respective cuts, and events from each path were used to produce efficiency and background estimates. Information for events surviving both analysis paths was assembled, and overall event topology cuts were applied. All events were required to pass the photon trigger and to have an event vertex (z_{vertex}) within ± 60 cm of the nominal interaction point. We first discuss the photon identification strategy and detection efficiencies, and then describe the analysis designed to find isolated pions.

In the photon analysis, we first correct the photon energies in order to optimize the energy resolution using corrections derived from the electron trigger samples [8]. We require that photon candidates have no reconstructed track pointing at the calorimeter cells containing the EM shower. We also require the photon transverse shower shape, as measured with strip chambers located 6 radiation lengths deep in the EM calorimeter, to be consistent with test beam results on the basis of an approximate $\tilde{\chi}^2$ test [7] ($\tilde{\chi}^2 < 20$). The direction of the photon is computed from the event vertex and the location of the shower in the strip chambers. A measure of the sharing of energy between neighboring towers, L_{shr}, defined as the energy in a tower minus the expected value (from test beam results) divided by the square root of the EM cluster energy (all in GeV), must be consistent with a single EM shower ($L_{\text{shr}} < 0.2$). From $W^\pm \to e^\pm + \nu$ events (see below), we measure the combined efficiency of the L_{shr}, z_{vertex}, and $\tilde{\chi}^2$ cuts to be $0.942 \pm 0.013(\text{stat}) \pm 0.018(\text{syst})$. In addition, we require that there be no other strip chamber cluster with energy greater than 1 GeV associated with the EM calorimeter cluster, with efficiency $0.87 \pm 0.03(\text{syst})$ [7]. Of the 1.21×10^6 events analyzed, 231×10^3 events (19%) contain at least one candidate EM shower that passes the photon requirements.

In the isolated pion analysis we search the full data sample for jets with $E_T > 15$ GeV that are consistent with a single pion. We require a central jet ($|\eta| < 1.1$) with exactly one track with $p_T > 15$ GeV$/c$, and no other charged tracks with p_T greater than 1 GeV$/c$ in a cone of radius $\Delta R = 0.7$ around the high p_T track. This high p_T track must pass within 5 cm of the event vertex. To improve the momentum resolution, the track trajectory is constrained to come from the beam line. The energy in the calorimeter must be consistent with coming from a single track. In particular, the charged fraction (CHFR), defined as the ratio of the track p_T to the total calorimeter jet E_T, must be greater than 0.7.

At this point, we have made no requirement on the fraction of EM energy in the single track jet, and the sample is dominated by electrons (these come mainly from the photon candidate jets, which are included in our search). Of the 1.21×10^6 events, 10.1×10^3 survive the jet cuts, without any EM fraction cut. Requiring that the EM fraction (EMFR) of the jet energy be less than 80% of the total calorimeter energy removes all but 320 events (see Fig. 1 and discussion below).

We use $W^\pm \to e^\pm + \nu$ events to measure the efficiencies of the cuts on the single pion jet where appropriate by substituting the ν with a single, simulated pion as follows: We begin by selecting events from the single-track jet sample consistent with an electron from $W^\pm \to e^\pm + \nu$ decay. We require exactly one jet with E_T greater than 15 GeV and containing at least 15 GeV of electromagnetic energy. From the imbalance in transverse energy measured in each event (missing E_T, or $\not{E}_T$) we try to reconstruct the possible directions of a neutrino in $W^\pm \to e^\pm + \nu$ decay. We pick a W mass from a distribution obtained from PAPAGENO and the fast detector simulation. This parent mass distribution includes the effect of both the W line shape and the detector resolution. Given the W mass, the electron momentum, and the two components of the missing transverse energy, there are two possible results for the neutrino direction. If the results yield physical solutions for the ν momentum, we choose those events where the ν longitudinal momentum is consistent with $|\eta_\nu| < 1.1$. If both solutions satisfy this requirement, we choose randomly between them (i.e., at most one solution per event is used and events with nonphysical solutions are discarded).

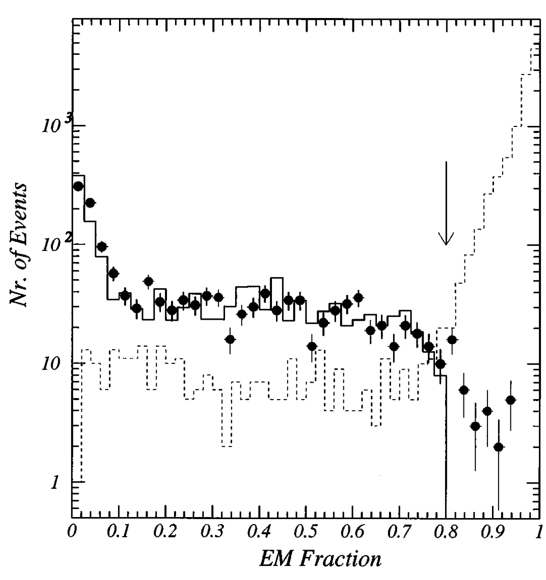

FIG. 1. EM fraction of pions from pure Monte Carlo events (solid line) and a simulation based on $W^\pm \to e^\pm + \nu$ events (points), where the ν is replaced by a pion as described in the text (normalized to the same number of events). The Monte Carlo data have been cut at 0.8. The broken line shows the EM fraction in 10.1×10^3 events passing the single track jet filter. The arrow shows the location of the cut: Events are accepted with EMFR < 0.8.

We simulate the effect of a pion with the momentum of the ν in the calorimeter to calculate the efficiency of the jet EM fraction and charged fraction cuts. To accomplish this we replace the neutrino with a single, simulated pion in the $W^\pm \to e^\pm + \nu$ events selected above, and recompute the EMFR and the CHFR of the resulting jet in the neutrino direction. As an example, we show in Fig. 1 the distribution of the jet EM fraction for the pure Monte Carlo and the simulation based on $W^\pm \to e^\pm + \nu$ events just described. The efficiencies for the EMFR and CHFR cuts measured in this way are $0.976 \pm 0.004(\text{stat}) \pm 0.007(\text{syst})$ and $0.995 \pm 0.002(\text{stat}) \pm 0.002(\text{syst})$, respectively. We also calculate the fraction of $W^\pm \to e^\pm + \nu$ events that have no other charged tracks with $p_T > 1$ GeV/c in a cone of $\Delta R = 0.7$ around the simulated pion direction; we find the efficiency of this cut to be $0.736 \pm 0.014(\text{stat}) \pm 0.064(\text{syst})$.

Finally, to select $W^\pm \to \pi^\pm + \gamma$ candidates, we pick events from the data sample with one photon candidate, one jet consistent with a single charged pion, the track and the photon separated by at least $\Delta\phi > 1.5$ rad, and no other jets with $E_T > 15$ GeV. After these cuts 79 events remain, with only one event in the W mass window. We will refer to these 79 events as the "signal sample," even though at most one event is consistent with the $W^\pm \to \pi^\pm + \gamma$ decay hypothesis.

We measure the "random" coincidence rate between the photon and single-track jet candidates by considering the class of events from the photon trigger described above with two central jets ($|\eta| < 1.1$), both with $E_T > 15$ GeV, separated by $\Delta\phi > 1.5$, and no other jets with $E_T > 15$ GeV in the event. Of these two jet events, $26.1\% \pm 1.2\%(\text{stat})$ have one jet satisfying all photon requirements. Of the 320 events in the full data sample with a single-track jet, 294 have exactly two jets as described above. Hence, we expect $76.7 \pm 4.5(\text{stat})$ events in the signal sample, in good agreement with the number of events in the signal sample.

The primary background to $W^\pm \to \pi^\pm + \gamma$ comes from QCD production in which the jet opposite the photon candidate fragments into a single charged track. To estimate the background and avoid trigger biases, we have used a subset of events which satisfy the photon requirements and general event topology cuts, but fail the single-track jet cuts. We estimate the background by combining the momentum vectors of all the charged tracks (at least two are required) with $p_T > 1$ GeV/c in the jet opposite the photon to form a single charged "pseudotrack." This jet is then required to meet all of our standard jet criteria (except the number of charged tracks/jet). In addition, we require the total charge of all tracks making up the pseudotrack to be ± 1. There are several ways to combine the charged track momenta to form the pseudotrack, and all give similar results [9]; their rms difference is included in the systematic error. We compute the photon-pseudotrack mass, and normalize the distribution to the 79 signal events (Fig. 2). Within errors ($\chi^2/N_{\mathrm{DOF}} = 1.2$), the estimated number of background events inside the W mass window is linear in the number of tracks used to form a pseudotrack, and extrapolating to 1 track/jet we estimate $2.6 \pm 1.0(\mathrm{stat}) \pm 1.3(\mathrm{syst})$ background events in the W mass window. Hence, we conclude that the single event we see is consistent with background. Figure 3 shows the distribution of π-γ masses from the data near the W mass. We observe one event in the signal region. From the above studies, we find the corrected, net efficiency $\times$ acceptance ($A\epsilon$) for the decay $W^{\pm} \to \pi^{\pm} + \gamma$ is $0.060 \pm 0.002(\mathrm{stat}) \pm 0.007(\mathrm{syst}) \pm 0.002$ (luminosity), including the trigger efficiency, all event topology cuts, and a 7% relative error due to structure function variation [2]. From Poisson statistics [10], we compute a limit of 4.7 events at the 95% confidence level limit, without background subtraction. To translate this value into a cross section limit, we follow the method of Ref. [11], which provides a prescription for including systematic errors into an upper limit determined from Poisson statistics. Using $\sigma B = N_{\mathrm{evt}}/A\epsilon\mathcal{L}$, where $\mathcal{L}$ is the integrated luminosity (16.7 pb^{-1}), we conclude that $\sigma B(W \to \pi + \gamma) \leq 4.9$ pb at the 95% confidence level. We note that the limit is totally dominated by the Poisson statistics of the upper limit. Dividing this result by our value of $\sigma B(W \to e + \nu) = 2.49 \pm 0.02(\mathrm{stat}) \pm 0.08(\mathrm{syst}) \pm 0.09$ (luminosity) nb [12] we find $\Gamma(W^{\pm} \to \pi^{\pm} + \gamma)/\Gamma(W^{\pm} \to e^{\pm} + \nu) \leq 2.0 \times 10^{-3}$ at the 95% confidence level, ignoring the common luminosity and z_{vertex} errors. This limit is about a factor of 3.7 better than our previous result from our data collected in 1989, and 2.4 times lower than the result reported by UA2, but still 6×10^4 away from the standard model estimate.

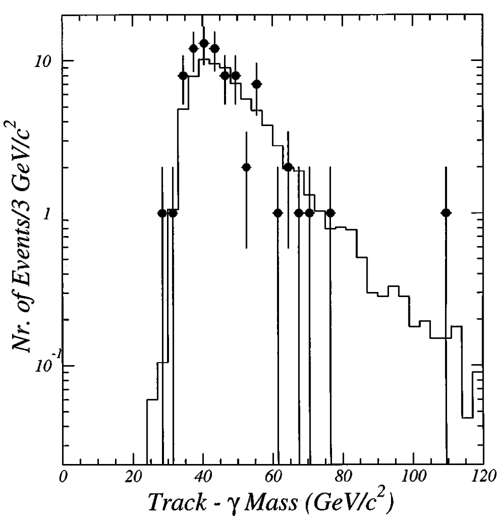

FIG. 2. Comparison of the π-γ mass distribution between the signal sample of 79 events and background estimate as described in the text. Data points are the signal sample, and the solid line is the background estimate normalized to 79 events.

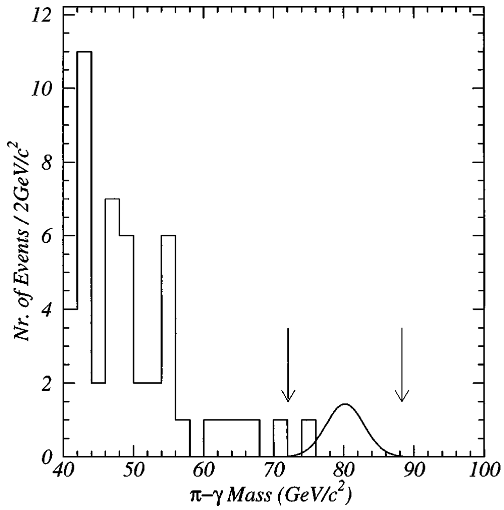

FIG. 3. The distribution of π-γ masses in the region of the W mass. The smooth curve in a Gaussian distribution centered at $M(W)$, with $\sigma = 2.7\ \mathrm{GeV}/c^2$ and normalized to an area of 4.9 events, our 95% confidence level limit. The region between the two arrows is our W mass window, and the event near 70 GeV/c^2 mass is about 1σ below the minimum allowed mass.

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