Fermi National Accelerator Laboratory

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Limit on the Rare Decay $W^{\pm} \rightarrow \gamma\pi^{\pm}$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We search for the rare decay $W^{\pm} \to \gamma\pi^{\pm}$ in 4.2pb^{-1}of p$\bar{\text{p}}$ collisions recorded at the Fermilab Tevatron Collider with the CDF detector. At the 95% confidence level, we find an upper limit on the partial decay width to be $\Gamma(W^{\pm} \to \gamma\pi^{\pm})/\Gamma(W^{\pm} \to e^{\pm}\nu) \leq 7.5 \times 10^{-3}$

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The copious samples of real weak bosons produced at Collider experiments enable searches for unusual processes which may probe the limits of the Standard Model. The rare radiative decay $W^{\pm} \to \gamma\pi^{\pm}$ is experimentally attractive because of its unambiguous final state signature, but highly suppressed by the behaviour of the meson form factor at $\sqrt{s} = M_W$. A detailed treatment predicts $\Gamma(W^{\pm}\to\gamma\pi^{\pm})$ $/\Gamma(W^{\pm}\to e^{\pm}\nu) \sim 3 \times 10^{-8}$, however new physics associated with the W-γ vertex or strong interaction dynamics could enhance this rate.[1] [2] Searches previously performed at the CERN p$\bar{\text{p}}$ Collider set a current limit of Br$(W^{\pm} \to \gamma\pi^{\pm}) \leq 5.4 \times 10^{-4}$ (95% CL).[3] Experiments at LEP have placed similar limits on the analogous neutral mode $Z^0 \to \gamma\pi^0$. [4]

This $W^{\pm} \to \gamma\pi^{\pm}$ search examines 4.2$\pm$0.3 pb^{-1} of p$\bar{\text{p}}$ collisions at $\sqrt{s} = 1.8$ TeV, recorded by the

CDF detector during the 1988-1989 run of the Fermilab Tevatron. The detector incorporates a 1.3 m radius tracking chamber in a 14.1 kG solenoidal magnet, and outside the magnet, projective tower calorimeters in the pseudo-rapidity region $|\eta| \leq 4.0$. In the central region, $|\eta| \leq 1.1$, the calorimeter towers have size $\Delta\eta \times \Delta\phi \approx 0.1 \times 0.26$, ($\phi$ is azimuthal angle), and longitudinal segmentation into electromagnetic (EM) and hadronic (HAD) compartments. The EM compartment of the central calorimeter has proportional chambers at shower maximum to measure transverse shower profiles. This analysis utilizes the precision tracking and electromagnetic calorimetry in the central region to select events where an isolated charged particle and an isolated photon candidate have invariant mass near $M_W \approx 80.0$ GeV/c^2. Further description of the CDF detector can be found in Ref. 5.

This search uses data collected with direct photon triggers. [6] These triggers required a calorimetric energy deposit with total transverse energy $\mathrm{E_T} \equiv \mathrm{E_T^{EM}} + \mathrm{E_T^{HAD}}$ above some threshold, and with electromagnetic fraction $f_{em} \geq 89\%$, where $f_{em} \equiv \mathrm{E_T^{EM}}/\mathrm{E_T}$ is the percentage of $\mathrm{E_T}$ in the EM calorimeter compartment. The $\mathrm{E_T}$ thresholds were set at 23 GeV for 3.3 pb^{-1}, 20 GeV for 0.6 pb^{-1}, and 10 Gev for 0.1 pb^{-1} of the data taking. A photon + jet sample is derived from the direct photon triggers by demanding a single high energy central photon candidate in association with a single central hadronic jet. A subsequent selection identifies those hadronic jets which are consistent with a single charged pion.

The reconstructed photon is required to lie in the region $|\eta| \leq 1.1$, to have $\mathrm{E_T^\gamma} \geq 25$ GeV and $f_{em} \geq 95\%$, to have transverse shower profiles consistent with an electromagnetic deposit [6], and to have no associated charged track with transverse momentum $\mathrm{P_T} \geq 400$ MeV/c. We expect the two-body W decay products to be *isolated.* If the total transverse energy inside a cone of radius $\delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$, centered on the photon, is denoted $\mathrm{E_T^{cone}}$, the isolation is defined as $I \equiv (\mathrm{E_T^{cone}} - \mathrm{E_T^\gamma})/(\mathrm{E_T^{cone}})$ and the photon is required to have $I \leq 0.10$.[7]

The reconstructed jet is a localized cluster of calorimeter energy with centroid in the region

$|\eta| \leq 1.1$, and $E_T \geq 25$ GeV. To suppress backgrounds from QCD processes, we demand that the photon and the jet be back-to-back in azimuth such that $\cos(\Delta\phi) \leq -0.95$, and that there be no other jet anywhere in the region $|\eta| \leq 4.0$ with $E_T \geq 15$ GeV. Finally, to eliminate electron backgrounds, the jet must have $f_{em} \leq 0.90$. Acceptance uncertainties in this selection are discussed below. Further details on jet reconstruction and energy calibration can be found in Ref. 8. The combined photon + jet selection at this point yields 3149 events.

To select the final $W^{\pm} \rightarrow \gamma\pi^{\pm}$ candidate sample, we require that the hadronic jet is consistent with the signal of a single isolated charged pion. We use a fragmentation-like variable, $\mathcal{Z} = P_{track}/E_{jet}$, to select jets where the leading charged particle momentum P_{track} is consistent with the jet energy E_{jet}, within the limits of calorimeter resolution. The jet is required to have $\mathcal{Z} \geq 0.7$. To ensure that $\mathcal{Z}$ is well measured, a fiducial requirement eliminates 5% of events where the jet centroid is aligned with azimuthal cracks between calorimeter towers. We make an isolation requirement on the pion candidate by demanding that there be one and only one track with $P_T \geq 1.0$ GeV in a cone of $\delta R = 0.7$ around the jet centroid. The final sample contains 11 events.

The efficiency of this selection for $W^{\pm} \rightarrow \gamma\pi^{\pm}$ depends on the geometric and kinematic acceptances for $\pi^{\pm}$ and γ, the trigger efficiency, and the pion and photon identification cuts. Acceptances are calculated using a version of the ISAJET Monte Carlo program [9] modified to produce the decay $W^{\pm} \rightarrow \gamma\pi^{\pm}$ with the proper angular distribution. A full detector simulation incorporates a calorimeter model tuned to the measured test beam response.[10] We find the kinematic and fiducial requirements to have an acceptance $A_W = .131 \pm 0.013$. The error is the sum in quadrature of the statistical uncertainty in the Monte Carlo model and estimated systematic effects. The largest systematic contribution to the uncertainty, $\delta A_W^{f(x)} = 0.007$, reflects the theoretical uncertainty in the proton structure functions. A smaller contribution results from the effect of higher order QCD corrections on the jet selection requirements. Based on large variations in the W production model in ISAJET, we estimate a conservative bound on this uncertainty to be $\delta A_W^{QCD} = 0.002$.

The efficiency curve for a particular photon trigger E_T threshold is measured using prescaled samples triggered at lower thresholds. We estimate our efficiency at each of the 3 thresholds used by folding the efficiency curve with the expected shape of the E_T^γ spectrum from the $W^\pm \to \gamma\pi^\pm$ Monte Carlo. We find a trigger efficiency $\epsilon_T = 0.995 \pm 0.005$.

The efficiencies of the γ and $\pi^\pm$ selection cuts are measured in a variety of ways. The calorimetric photon variables are studied with electrons from W decay, and found to have combined efficiency of $\epsilon_\gamma = 0.90 \pm 0.01$. [11] The f_{em} and $\mathcal{Z}$ cuts are studied with ISAJET and the test beam tuned detector simulation. The $\mathcal{Z}$ distribution for the complete photon + jet sample is compared with a hypothetical signal of arbitrary normalization in Fig. 1. The efficiency of the $\mathcal{Z}$ cut is $0.96^{+0.01}_{-0.07}$. The track isolation cut is studied using the tracking data from $W \to e\nu$ events. The overall efficiency of the pion selection is $\epsilon_\pi = 0.83^{+0.03}_{-0.08}$.

Finally, we consider the distribution of invariant mass $M(\pi\gamma)$ in the candidate sample. The expected distribution for $W^\pm \to \gamma\pi^\pm$, using charged particle tracking and EM calorimetry, is modeled with ISAJET and the detector simulation; a Gaussian fit to this distribution has mean $M(\pi\gamma) =$ 80.2 GeV/c^2 and width $\sigma = 3.08$ GeV/c^2. We define a signal region $71.0 \leq M(\pi\gamma) \leq 89.0$ GeV/c^2. The distribution of $M(\pi\gamma)$ for the 11 data events is shown in Fig. 2 along with the shape of the expected signal of arbitrary normalization. We find 3 candidate events in the signal region. The combined acceptance and efficiency of this complete selection for $W^\pm \to \gamma\pi^\pm$ is $\epsilon_{total} = 0.097^{+0.012}_{-0.015}$.

The primary backgrounds to the $W^\pm \to \gamma\pi^\pm$ signature are QCD events where a jet which fragments into a single charged particle recoils against a direct photon, or against an isolated π^0 or η which decays into photons. An isolated π^0 or η occurs as another rare fragmentation, and for $E_T \geq 25$ GeV is indistinguishable, in this analysis, from an isolated photon. The measured fragmentation probability for an isolated π^0 or η, approximately 5×10^{-4}, is such that their effective cross section is roughly equal to that for direct photons.[6] We can estimate the size of this combined $\gamma + \pi^0 + \eta$ background by scaling the size of the inclusive photon + jet parent population by the probability $P_1^{\pm}$ that the jet undergoes a single charged fragmentation, as defined by our cuts.

We estimate $P_1^{\pm}$ with an inclusive jet sample consisting of 151,000 events collected by requiring a single jet with $E_T \geq 20.0$ GeV. Imposing the fiducial and kinematic requirements of the $W^{\pm} \rightarrow \gamma\pi^{\pm}$ sample, as well as the f_{em} requirement, leaves 31,489 jets which model those of the photon + jet sample. Of these, 49 jets satisfy the $\mathcal{Z}$ and track isolation cuts. The single track probability is found to be independent of jet E_T in the signal region, and we calculate a simple mean probability for a jet in this sample to fragment into one charged track to be $P_1^{\pm} = 1.6 \pm 0.6 \times 10^{-3}$. The main part of the stated uncertainty is the average variation from changes in $\mathcal{Z}$ due to 1σ fluctuations in calorimeter response.

If we assume that jet fragmentation in the photon + jet sample is similar to that in the inclusive jet sample, we can use $P_1^{\pm}$ above to predict 5.0 ± 1.9 events at all $M(\pi\gamma)$ in the final $W^{\pm} \rightarrow \gamma\pi^{\pm}$ selection. This prediction is significant, but low compared to the 11 events seen in the data. We conclude that we can model at least one plausible background source for the observed events, and we use the result from this model as a lower limit on the total background. The amount of background in the signal region, $71.0 \leq M(\pi\gamma) \leq 89.0$ GeV/c^2, is estimated by scaling the photon + jet sample in that region, $28 \pm 3\%$ of the total, by $P_1^{\pm}$. The error on the signal fraction is dominated by the resolution in $M(\pi\gamma)$, which is calculated in this sample using calorimetric information for both photon and jet. We predict a background of *at least* 1.4 events in the signal mass region from QCD processes.

Backgrounds from electroweak processes are very small. For example, the decay $Z \rightarrow e^+e^-$, where one electron fakes a photon because of lost track, and the other fakes a pion because of a calorimeter fluctuation, is estimated to contribute 0.02 events to the sample. We take the background from this and similar electroweak contributions to be zero.

To set a limit on $W \to \pi\gamma$, we use a standard treatment for the case of a Poisson process with background [12] augmented by a Monte Carlo treatment which folds in a Gaussian smearing of signal by the uncertainty on the efficiency. For 3 observed events with 1.4 QCD background events, the upper limit is 6.3 events at 95% confidence. Since we believe our background is underestimated, this limit is conservative. For comparison, we note that a background of 3 events would have given an upper limit of 5.4 events.

Using our measurement of $\sigma \cdot Br(W^\pm \to e^\pm \nu) = 2.19 \pm 0.04(\text{stat}) \pm 0.21(\text{syst})$ nb [11] and integral luminosity we find an upper limit on the decay width for the process $W^\pm \to \gamma\pi^\pm$ to be

$$\Gamma(W^\pm \to \gamma\pi^\pm)/\Gamma(W^\pm \to e^\pm\nu) \leq 7.5 \times 10^{-3} \text{ (95\%CL)}$$

The systematic uncertainty on $\sigma \cdot Br(W^\pm \to e^\pm\nu)$ is mainly the correlated luminosity error, which cancels in the ratio, and the effect of remaining uncertainties is negligible.

Using the Standard Model value $Br(W \to e\nu) = 0.109$ for $M_{top} \geq M_W$, we find

$$Br(W^\pm \to \gamma\pi^\pm) \leq 8.2 \times 10^{-4}.$$

This is consistent with other measured results for both W and Z decays [3,4]. At the present level of sensitivity there is no evidence for deviations from the Standard Model prediction for two body radiative decays of the weak vector bosons.

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Figures

Fig.1 The ratio $Z = P/E$ for jets in the photon + jet sample (points) and pions in the $W^{\pm} \rightarrow \gamma\pi^{\pm}$ Monte Carlo (solid).

Fig.2 Invariant mass of the $\pi\gamma$ combination in the final sample. One event with $M(\pi\gamma) \geq 140$ GeV/c^2 is not shown. Solid curve is the expected mass resolution from $W^{\pm} \rightarrow \gamma\pi^{\pm}$ Monte Carlo with arbitrary normalization.

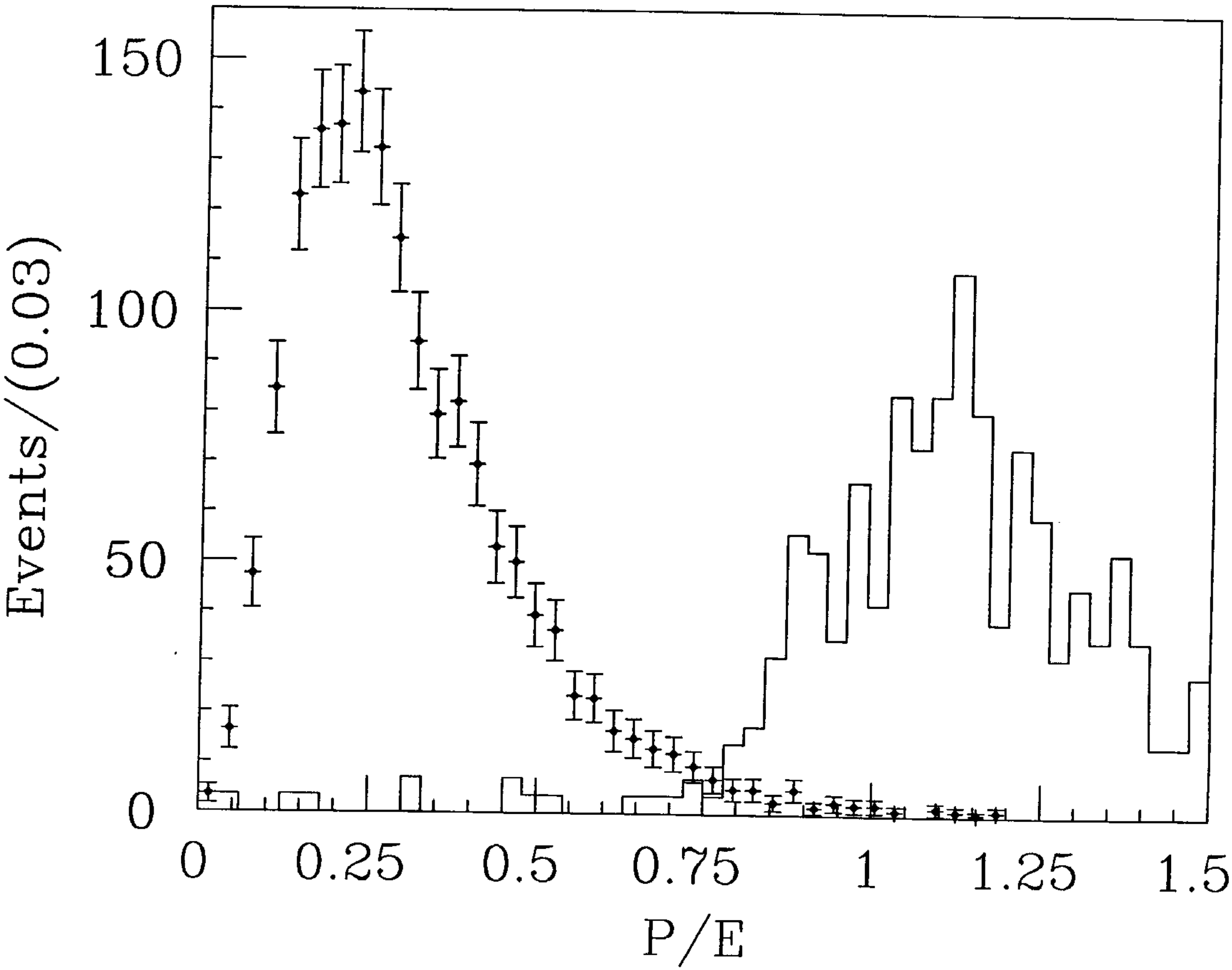

Fig. 1

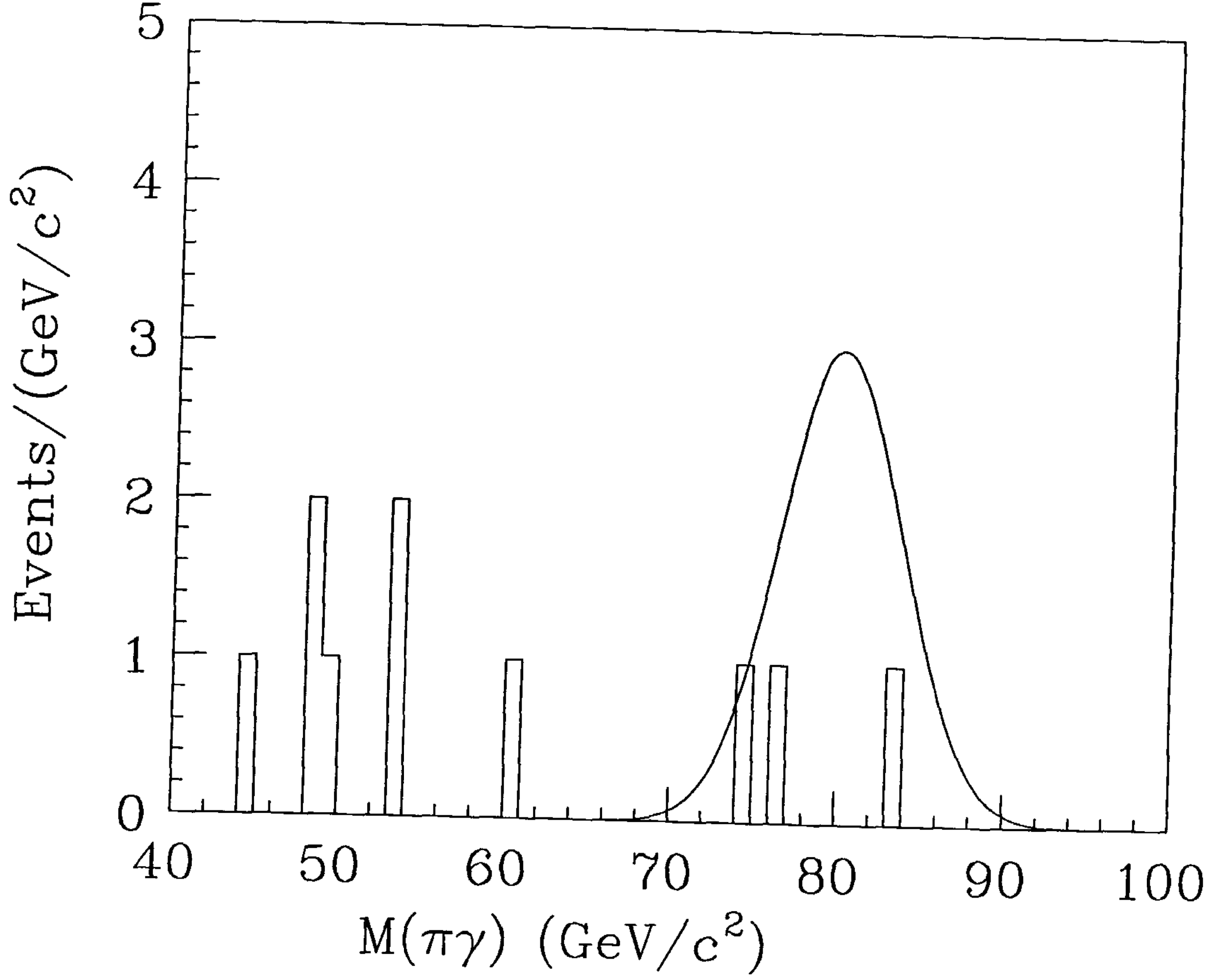

Fig. 2