Search for the new physics in the exclusive $\gamma + \not\!\!E_{\rm T}$ final state.

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We present the results of a search for physics beyond the Standard Model in a sample of exclusive $\gamma+\not\!\!E_{\rm T}$ events in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at CDF Run II. Using a sample of 1996 pb^{-1} of collision data we observe 280 events, consistent with the background estimate of 264.8±16.8 events for photon with transverse energy $E_{\rm T} > 50$ GeV. We optimize the search for the best sensitivity to the Large Extra Dimensions model and find 40 event, consistent with the background estimate of 42.4±2.9 events for photons with $E_{\rm T} > 90$ GeV. We combine this search with the updated exclusive jet $+\not\!\!E_{\rm T}$ analysis and set the best Tevatron limits on the Large Extra Dimensions model.

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Since the Standard Model (SM) is known to be incomplete [1], there is a world-wide program to look for hints of new physics. Many popular models such as Large Extra Dimensions (ADD) [2], Gauge Mediated Supersymmetry Breaking (GMSB) [3], Seesaw models [4] and others predict a production of invisible particles in association with a photon. In general, a photon (γ) plus missing transverse energy ($\not\!\!E_{\rm T}$) signature is sensitive to any mechanism that can produce a photon and an exotic particle that escapes the detection. Often these exotic invisible particles are good candidates for the dark matter. In these types of models the exotic signal would appear as an excess over Standard Model (SM) at the tail of the photon transverse energy ($E_{\rm T}$) spectrum. On the other hand, $\gamma+\not\!\!E_{\rm T}$ signature is also sensitive to any heavy resonance that decays to a photon and undetectable particle, or even to two photons because a significant portion of photons is lost in the detector. In such a case the excess would look like peak on top the SM background. For example, 140 GeV heavy particle decaying to two photons would produce via $\gamma+\gamma \rightarrow \gamma+\not\!\!E_{\rm T}$ an excess at photon $E_{\rm T} \sim 70$ GeV.

In this Letter we present an *a priori* model-independent search for new physics in the exclusive $\gamma+\not\!\!E_{\rm T}$ channel using the CDF Run II detector [6] at the Fermilab Tevatron. The data corresponds to 1996±120 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. We optimize the cut on photon transverse energy for the best sensitivity to ADD model. At the end we combine the result with the updated search in the exclusive jet$+\not\!\!E_{\rm T}$ channel, also sensitive to the ADD model. While other experiments have searched in $\gamma+\not\!\!E_{\rm T}$ channel [7], the CDF experiment is in unique position to look into this signature because at high instantaneous luminosities at LHC this signature could be spoiled by a large number of extra-collisions. Reducing cosmic background is crucial for this analysis, and the recently installed photon timing system at CDF [8] allows us to effectively reduce it.

We briefly describe the ADD model we use [2]. In this model the photon is produced via $q\bar{q} \rightarrow \gamma G_{KK}$. Extra spatial dimensions are assumed to be compactified with radius R. The model introduces the fundamental mass scale M_D. The two parameters, M_D and R, are related to the Newton's constant and the number of extra dimensions by $G_N^{-1} = 8\pi R^n M_D^{2+n}$. The SM fields propagate only on the normal 3+1 dimensional plane, while gravitons propagate in the bulk, and would appear to us as massive states of the graviton, or, said differently, as massive minimally-interacting particles. Large values of R result in a large phase space for graviton production, canceling the weakness of the coupling to standard model fields. For a given number of extra dimensions the production cross section scales as $1/M_D^{n+2}$. It turns out that the kinematics are independent of M_D for a given n.

A full description of the CDF Run II detector can be found elsewhere [6]. Here we briefly describe the aspects of the detector relevant to this analysis. The magnetic spectrometer consists of tracking devices inside a 3-m diameter, 5-m long superconducting solenoid magnet that operates at 1.4 T. A 3.1-m long drift chamber (COT) with 96 layers of sense wires is used to determine the momenta of charged particles, the z position of the $p\bar{p}$ interaction, and the time of the interaction. Muons from collisions and cosmic rays are identified with a system of planar drift chambers situated outside the calorimeters in the region with rapidity $|\eta| < 1.0$ [9]. The calorimeter, constructed of projective towers, each with an electromagnetic and hadronic compartment, is divided into a central barrel that surrounds the solenoid coil ($|\eta| < 1.1$) and a pair of plug barrels that cover the region $1.1 < |\eta| < 3.6$. Both are used to identify and measure photons, electrons, jets and $\not\!\!E_{\rm T}$. The electromagnetic compartments of the central and plug calorimeters were recently instrumented with a new system, EMTiming, to provide a measurement of the arrival time of the energy in each tower [8]. The timing system is used to fight background induced by cosmic rays.

The analysis selection cuts and cut efficiencies, all estimated from data, are summarized in Table I. The selection begins with events passing online the CDF three-level trigger by virtue of having a high energy EM cluster in the region $|\eta| <1.1$ with $E_{\rm T}> 25$ GeV (presumably from the photon) and $\not\!\!E_{\rm T}>25$ GeV. The trigger is 100% efficient for the final γ and $\not\!\!E_{\rm T}$ energy requirements. Offline, the highest $E_{\rm T}$ photon candidate in the fiducial region of the calorimeter is required to pass the standard photon identification (ID) cuts [10, 16]. We require at least one central photon with $|\eta| < 1.1$ and $E_{\rm T} > 50$ GeV.

Quality Cuts	ϵ(%)
Photon ID ($E_{\mathrm{T}}^{\gamma} > 50$ GeV)	
$\not\!\!E_{\mathrm{T}} > 50$ GeV	68
Non-collision Rejection	
Cosmics Rejection	
Timing	99
RVM	92
at least 3 COT tracks	79
Beam Halo Rejection	99
High E_{T} objects from extra collisions	98
No jets with $E_{\mathrm{T}} > 15$ GeV	
No tracks with $P_{\mathrm{T}} > 10$ GeV	

TABLE I: The data selection criteria and the efficiency for central photons with rapidity $|\eta|$ <1.1. All efficiency are estimated from data and should be model-independent. The lower set of cuts are model-dependent. The overall efficiency for photons with $|\eta| < 1.1$ is $45.5 \pm 4.7\%$.

Channel	$E_{\mathrm{T}}^{\gamma} > 50$ GeV	$E_{\mathrm{T}}^{\gamma} > 90$ GeV
$W \to e \to \gamma$	47.3 ± 5.1	2.6 ±0.4
$W \to \mu/\tau \to \gamma$	19.1 ± 4.2	1.0 ± 0.2
$W\gamma \to \mu\gamma \to \gamma$	33.1 ± 10.2	1.7 ±1.2
$W\gamma \to e\gamma \to \gamma$	8.0 ± 3.0	0.8 ±0.7
$W\gamma \to \tau\gamma \to \gamma$	17.6 ± 1.6	2.5 ±0.2
$\gamma\gamma \to \gamma$	18.9 ± 2.3	2.3 ±0.6
cosmics	36.4 ± 2.5	9.8 ± 1.3
$Z\gamma \to \nu\nu\gamma$	84.4 ± 8.0	20.9± 2.0
Total	264.8 ± 14.8	42.4 ± 2.9
Data	280	40

TABLE II: The table shows the background estimates for photons with $E_{\mathrm{T}} > 50$ GeV and $E_{\mathrm{T}} > 90$ GeV.

We also ask that the missing transverse energy is greater than 50 GeV. We veto events with jets above 15 GeV or tracks above 10 GeV. To reduce non-collision backgrounds we ask for at least 3 COT tracks, the photon timing has to be consistent with coming from a collision and to pass the discriminant that separates collision photons from look-alike cosmic ray candidates. For the discriminant we use Relevance Vector Machine [11] (RVM) that is trained on data to distinguish between collision and cosmic photon candidates.

Table II shows the breakdown of various backgrounds. There are two major sources: collision and non-collision photon candidates. Collision photons are presumed to be from the SM interactions such as irreducible $Z\gamma \to \gamma\nu\bar{\nu}$ electroweak process, $W \to l\nu$ production where lepton fakes the photon, $W\gamma$ and $\gamma\gamma$ events when the second lepton or photon is lost. All of the above backgrounds, except for irreducible $Z\gamma$ and cosmics, are important at low energies, but die out fast as photon energy increases. $Z\gamma$ and $W \to \mu/\tau \to \gamma$ are estimated from Monte Carlo, for the rest the data is used.

At low energies the dominant background is $W \to l \to \gamma$. To understand this background we rely on Monte Carlo to find the E_{T} dependence of the fake rate. The data sample of $e\gamma$ events is used to normalize the fake rate. The sample is selected to have no $\not\!\!E_{\mathrm{T}}$ and mass of the electron-photon pair to be consistent with Z peak. For the electroweak $W\gamma$ and QCD $\gamma\gamma$ backgrounds we use similar approach. The rate at which only a single photon would be left in the detector is determined from Monte Carlo, but the data is used for the absolute normalisation. For example, to estimate $\gamma\gamma$ the ratio of the events with single photon to events with 2 photons is found from Monte Carlo, and multiplied by the number of events with 2 photon in the data. In this way the additional contribution from $\gamma + \pi$ QCD process, where a photon is lost and jet fakes a photon, production is naturally accounted for.

As we look at photons with higher energies, the $Z\gamma \to \nu\nu\gamma$ background becomes dominant. To estimate this background we use Monte Carlo with only Leading Order contributions to the cross-section which adequately describes the production cross-section in the presence of jet veto cut [17].

Non-collision backgrounds come from cosmic rays and beam effects which produce fake photons and $\not\!\!E_{\mathrm{T}}$. Beam halo photon candidates are produced by muons that originate upstream of the detector and fly parallel to the beam line. Those muons produce fake photon candidates as they interact with the calorimeter. Beam halo muons normally leave a trail of the calorimeter towers with some energy deposited in the same wedge with the photon. We use this fact to develop highly efficient rejection cuts that completely eliminates this background.

We rely heavily on the recently installed calorimeter timing system to fight the cosmics ray background. Photon candidates from cosmic rays are not correlated in time with collisions, and therefore their timing shape is roughly flat in time. The timing for the collision photons has Gaussian shape with the mean at zero and RMS of 1.6 ns [8]. We select photon candidates with timing above 20 ns to predict the level of the background in the prompt window. We also use photon candidates to select a sample of pure cosmic photons to train the discriminant to separate collision photons from cosmic ones. At the end we are able to reduce the cosmic background by ~ 600 times. Still, it remains to be the dominant background at hight E_T region where we are most sensitive to the new physics.

Figure 1 and Table II show the comparison between data and background prediction. We note that the data is in a good agreement at low and high regions of the photon E_{T} spectrum. There is an excess in the data around photon $E_{\mathrm{T}} \sim 70$ GeV. The probability for the background fluctuation is 0.68% which is eqvivalent to the less than 3σ significance. It would be interesting to see if the excess fades away as more data is analyzed in the future.

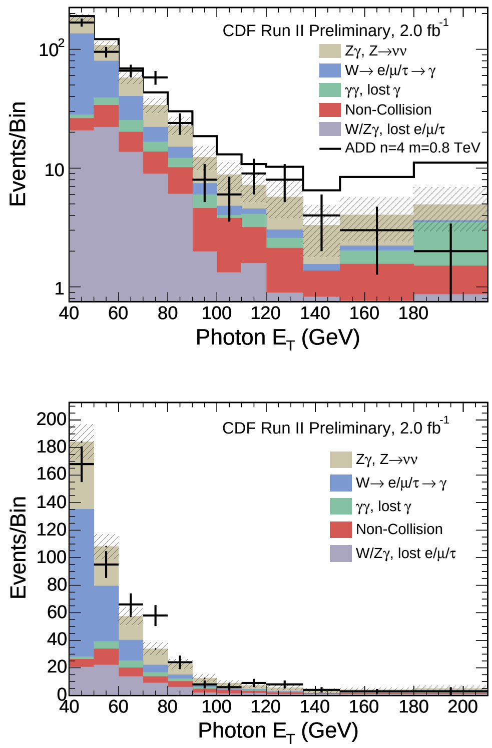

FIG. 1: The figure shows photon $E_{\rm T}$ distrribution on the log and linear scales. The backgrounds are stacked on top of each other. The top plot also shows the signal from ADD model stacked on top of SM backgrounds.

To estimate our sensitivity to ADD model we simulate the signal with the PYTHIA Monte Carlo [12] along with the standard GEANT [13] based detector simulation. For each extra-dimension we simulate the the samples for M_D in the range between 0.7 and 2 TeV. The final kinematic selection requirements defining the final data sample are determined by optimizing the expected cross section limit without looking at the data. To compute the expected 95% confidence level (C.L.) cross section upper limit we combine the predicted ADD signal and background estimates with the systematic uncertainties using a Bayesian method with a flat prior [14]. The expected limits are computed as a function of photon $E_{\rm T}$. The acceptance, the ratio of simulated events that pass all the requirements in Table I to all events produced, is found to be almost independent within 2% of the mass M_D. The total sysematic uncertainity on the signal is 5.7%. The major contributions to the systematic error are from initial/final state radiation convoluted with jet veto cut (4.8%), uncertainty on the Q^2 scale (2%), and uncertainty in parton distribution functions (1%).

The optimization shows that the maximum sensitivity is reached at photon $E_{\rm T}>$ 90 GeV independent of the number of extra dimensions. The data yields 40 events above 90 GeV, in good agreement with the predicted background of 42.3 events. Figure 1 shows the total number of events including the estimated signal from ADD.

	$\gamma + \not{E}_{\rm T}$			$Jet + \not{E}_{\rm T}$		
N LED	α	σ^{95}_{obs}	M^{obs}_D	α	M^{obs}_D	M^{comb}_D
2	7.1	99.2	1040	9.9	1310	1400
3	7.1	99.0	970	11.1	1080	1150
4	7.4	93.9	940	12.6	980	1040
5	7.2	96.8	900	12.1	910	980
6	7.1	98.6	880	12.3	880	940

TABLE III: The table shows the limits on the ADD model for different numbers of extra-dimensions.

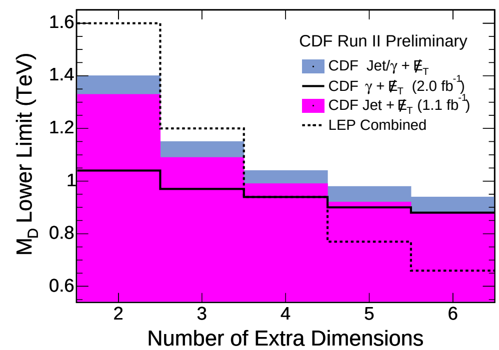

FIG. 2: The figure shows exclusion limits for the ADD model.

In conclusion, the CDF experiment has recently completed a search for new physics in the exclusive $\gamma + \not{E}_{\rm T}$ channel that decay to photons using 1996 pb^{-1}of data. While the current data is consistent with the background expectations, limits on the ADD model are among the worlds most sensitive for these types of new particle production. As the experiment collects more and more data, this search becomes more sensitive for the potential discovery. The next couple of years are equally exciting as the analysis is expected to triple the dataset and to further improve the sensitivity for discovery.

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