

Search for particles decaying into a Z boson and a photon in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

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We present the results of the first search for a new particle X produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV and subsequently decaying to $Z\gamma$. The search uses 0.3 fb^{-1} of data collected with the DØ

detector at the Fermilab Tevatron Collider. We set limits on the production cross section times the branching fraction $\sigma(p\bar{p} \rightarrow X) \times B(X \rightarrow Z\gamma)$ that range from 0.4 – 3.5 pb at the 95% C.L. for X with invariant masses between 100 and 1000 GeV/ c^2 over a wide range of X decay widths.

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There is considerable evidence that the standard model (SM) is incomplete [1]. Signs of new physics may appear in the form of a new particle (X). If X is a scalar, pseudo-scalar, or tensor, its decay to lepton pairs might be highly suppressed, but it could have a large decay branching fraction (B) to the di-boson final state $Z\gamma$. A search for X in the $Z\gamma$ final state thus complements searches for production of a new vector boson in the lepton pair decay mode.

Events with pairs of vector bosons have been studied as tests of the SM of electroweak interactions. Specifically, the Z plus photon final state ($Z\gamma$) has been investigated by the DØ [2, 3] and CDF [4] collaborations using $p\bar{p}$ collisions and by the LEP collaborations [5–8] using e^+e^- collisions. In these cases, the measured cross section and photon energy distribution were used to set limits on anomalous Z -photon couplings, but no direct searches for particles decaying to $Z\gamma$ have been performed.

In the SM, the $Z\gamma$ final state is expected to be produced through radiative processes (Figs. 1a and b). In addition, this final state is also expected from Higgs boson production and decay (Fig. 1c). Although the Higgs mass is unknown and the predicted $H \rightarrow Z\gamma$ branching fraction is $\mathcal{O}(10^{-3})$, extensions to the SM can significantly increase this branching fraction [9–12]. Other SM extensions predict new particles that decay into $Z\gamma$. For example, a Z' boson can decay radiatively to a Z boson and a photon [13]. In models with a fourth generation of fermions, a top and anti-top quark bound state (toponium) may exist [14, 15], and this state can decay to $Z\gamma$. In theories with compact extra dimensions, massive Kaluza-Klein spin-2 gravitons can also decay to the $Z\gamma$ final state [16]. The presence of resonance behavior in the $Z\gamma$ final state can thus signal the presence of a wide variety of new physics. In order to make quantitative statements, we will assume that this new physics manifests itself in the form of a spin 0 particle.

A large sample of $Z\gamma$ events has been collected by the DØ experiment and analyzed to measure the $Z\gamma$ cross section and set limits on anomalous couplings [2]. The Fermilab Tevatron Collider provides a higher energy reach than that available to previous experiments, and so this sample deserves further scrutiny. Experimentally, Z bosons are identified through their decay to charged lepton pairs ($\ell\ell = ee$ or $\mu\mu$). Photons are measured with high precision from their electromagnetic showers. The $Z\gamma$ final state has small backgrounds. We select and study the mass distribution of the $\ell\ell\gamma$ events in a sample of 0.3 fb^{-1} of $p\bar{p}$ collision data collected with the DØ Run

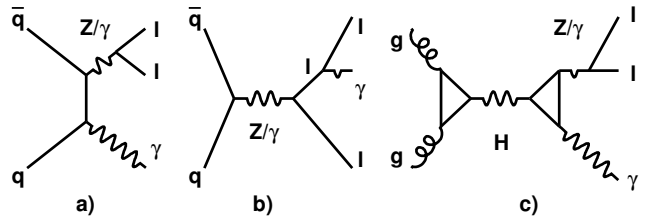


FIG. 1: The Feynman diagrams for leading order $Z\gamma$ processes are shown in a and b. The dominant Higgs production and decay diagram to $Z\gamma$ is shown in c.

II detector from April 2002 to June 2004 at the Fermilab Tevatron Collider at $\sqrt{s} = 1.96 \text{ TeV}$.

The DØ detector [17] includes a central tracking system, composed of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet and optimized for tracking and vertexing capability at pseudorapidities [18] of $|\eta| < 2.5$. Three liquid argon and uranium calorimeters provide coverage out to $|\eta| \approx 4.2$: a central section covering $|\eta|$ up to ≈ 1.1 , and two end calorimeters. A muon system resides beyond the calorimetry, and consists of tracking detectors, scintillation counters, and a 1.8 T toroid with coverage for $|\eta| < 2$. Luminosity is measured using scintillator arrays located in front of the end calorimeter cryostats, covering $2.7 < |\eta| < 4.4$. Trigger and data acquisition systems are designed to accommodate the high luminosities of the Run II Tevatron.

The analysis is conducted in two channels, one where the Z boson decays into electrons and the other where it decays into muons. The electron channel requires that electron candidates be isolated in the calorimeter, have longitudinal and transverse energy deposition profiles consistent with those of an electron, have a transverse momentum $p_T > 15 \text{ GeV}/c$, and be contained in either the central calorimeter (CC, $|\eta| < 1.1$) or one of the end calorimeters (EC, $1.5 < |\eta| < 2.5$) and not in the transition region between the central and the end calorimeters. If an electron candidate is in the CC, it is required to have a spatially matched track from the central tracker. One of the electrons must have $p_T > 25 \text{ GeV}/c$. If both electrons have matching tracks, the tracks are not required to be of opposite charge. Electron candidate events are required to satisfy one of a series of single electron triggers. The efficiency for a di-electron candidate to satisfy the trigger and for both electrons to satisfy all quality requirements lead to an event efficiency of 0.69 ± 0.05 if both electrons are in the CC and 0.78

± 0.05 if one electron is in the EC. Events with both electron candidates in the EC are not considered due to small signal acceptance and large backgrounds. These efficiencies are measured with Z boson candidate events.

The muon channel requires two candidate muons with $p_T > 15$ GeV/ c and opposite charge. Both muons must be matched to tracks found in the central tracker. Backgrounds from heavy flavor production are suppressed by isolation requirements on the muons, and backgrounds from cosmic rays are suppressed by a requirement that the muons come from the interaction region and are not exactly back-to-back. Muon candidate events must pass one of a suite of single or di-muon triggers. The efficiency for di-muon event selection and trigger is 0.84 ± 0.05 per event. This efficiency is measured with Z boson candidate events.

Photon candidates must be isolated in the calorimeter and tracker, have longitudinal and transverse shapes in the calorimeter consistent with those of a photon, have $p_T > 25$ GeV/ c , and be contained in the central calorimeter ($|\eta| < 1.1$). For SM $Z\gamma$ production, the average photon identification efficiency is 0.83 ± 0.04 . The inefficiency is mostly found at low p_T , and the efficiency plateaus at 0.90 for $p_T > 35$ GeV/ c .

Both di-electron and di-muon candidate events are further required to have a di-lepton mass greater than 75 GeV/ c^2 , and a photon separated from both leptons by $\Delta\mathcal{R} > 0.7$ [19]. These requirements reduce the contribution from events in which a final state lepton radiates a photon. The acceptance times efficiency, for all requirements described, rises from about 18% to about 20% for masses from 100 to 800 GeV/ c^2 and at higher masses decreases for reasons described later..

To improve the di-lepton-photon mass resolution in the muon channel, the muon transverse momenta are adjusted by employing a one-constraint kinematic fit that forces the di-muon mass to equal the on-shell Z -boson mass. This constraint is only enforced if the $\chi^2/\text{d.o.f.} < 7$ for the fit. Monte Carlo studies show this technique improves the di-muon-photon invariant mass resolution from 6.7% to 3.4%, which is comparable to the expected di-electron-photon mass resolution of 3.9% obtained without a kinematic fit in the electron channel. For the $Z\gamma$ mass range considered, photon energy contributions to the three-body mass resolution dominate those expected from the Z boson natural width; hence, neglecting the finite Z boson natural width in the kinematic fit is justified.

Backgrounds to $Z\gamma$ production from the decay of a new particle include SM $Z\gamma$ and Z +jet processes, where the jet is misidentified as a photon. Backgrounds from processes where the photon is a true photon and one or both of the leptons is a misidentified jet are found to be negligible. Contributions from $Z(\rightarrow \tau\tau)\gamma$ events with leptonic decays of the tau are less than 1% of the sample. Contributions from WZ and ZZ decays, where electrons

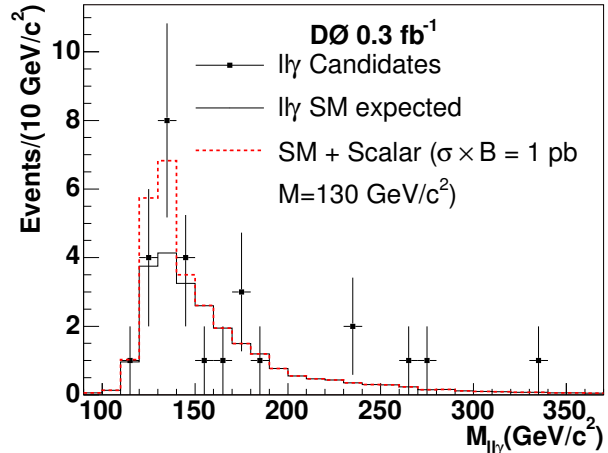


FIG. 2: The $M_{l\gamma}$ distribution for the candidate events is shown with the SM expectation overlaid as well as the sum of the SM expectation and a signal shape for a 130 GeV/ c^2 scalar decaying to $Z\gamma$ with a $\sigma(p\bar{p} \rightarrow X) \times B(X \rightarrow Z\gamma) = 1$ pb.

are misidentified as photons, are also less than 1% of the sample.

Efficiencies, acceptances, and background contributions are calculated using independent data samples and Monte Carlo simulations. Scalar particle decays to $Z\gamma$ are modeled using PYTHIA [20] SM Higgs boson production in which the Higgs is forced to decay to $Z\gamma$, and the Z boson is forced to decay to leptonically. For the SM $Z\gamma$ events, we use an event generator employing leading order QCD calculations and first order EW radiation [21]. These events are processed through a parameterized detector simulation that is tuned on Z boson candidate events. The background due to jets misidentified as photons is estimated by scaling the measured Z +jet event rate by the measured probability for a jet to mimic a photon [2].

The final sample used in the analysis consists of 13 candidates in the electron channel and 15 candidates in the muon channel. We expect from SM sources 11.2 ± 0.8 events in the electron channel and 12.9 ± 0.9 events in the muon channel. Uncertainties in the SM contributions are due to uncertainties in the luminosity, higher order QCD contributions, parton distribution functions, and the rate at which a jet mimics a photon. The luminosity uncertainty is the largest, contributing 0.5 events to the electron channel uncertainty and 0.7 events to the muon channel uncertainty. The di-lepton-photon invariant mass, $M_{l\gamma}$, of the candidate events is shown in Fig. 2 for the combined dataset with overlays of the SM expectation and a Higgs-like signal with a mass of 130 GeV/ c^2 and a $\sigma \times B$ of 1 pb. This figure is just for illustration purposes and is not used further in the analysis.

None of the 28 photon plus di-lepton events satisfying

the selection criteria has more than one photon or more than two leptons. Among all the events we only find three jets with $p_T > 15$ GeV/ c . Two of these jets are in a single event. The missing transverse momentum in all candidate events is less than 20 GeV/ c .

We use two methods in our search to ensure sensitivity to scalar states over a broad range of natural decay widths. The first looks for an excess in a sliding narrow mass search window, and the second sets a sliding lower mass threshold and counts events above this threshold. The window technique gives very good separation of signal from background; however it is sensitive to the natural width (Γ) of the new particle. The separation of signal from background of the window method is highest when Γ is small compared to the mass resolution. The size of the search window was chosen to be 4.4% of the mass by optimization of the signal MC acceptance for a 130 GeV/ c^2 $Z\gamma$ resonance over the square-root of the SM background expectation.

The low mass threshold technique also generally requires knowledge of Γ . To reduce this dependence, we place the threshold at the median value of the mass distribution (M'), which introduces an acceptance factor of 0.5. The value of M' is the same as the nominal mass of the particle if its width is fairly narrow ($\lesssim 4$ GeV/ c^2), or if its mass is fairly low ($\lesssim 250$ GeV/ c^2). If neither condition is met, the available parton luminosity begins to affect the generated mass distribution. The SM Higgs boson provides a good example of this effect. A Higgs with a nominal mass of 250 GeV/ c^2 has a width of 4 GeV/ c^2 and the median mass is 249.7 GeV/ c^2 . As the nominal mass increases, the width grows and the median mass begins to deviate from the nominal value. At 350 (450) GeV/ c^2 , the width is 15 (42) GeV/ c^2 and the median is 346.4 (401.0) GeV/ c^2 .

Using these techniques, we can determine how well the data and SM expectation agree (Fig. 2), assuming Poisson statistics and taking into account systematic uncertainties. Using the threshold technique, we find that the smallest probability of agreement between data and SM expectations is 7%, which occurs at the median mass $M' = 230$ GeV/ c^2 . Applying the narrow mass window method to search for objects with $\Gamma \rightarrow 0$ (i.e. generated within the mass bin), we find that for a mass of 140 GeV/ c^2 , the probability of agreement between the data and SM expectation is 0.8%. The window at 140 GeV/ c^2 has the lowest probability of agreement in the mass range considered. To further assess the statistical significance of this effect, we generate an ensemble of 100,000 simulated experiments in which only SM sources for $Z\gamma$ were included and possible systematic effects are neglected. Eleven percent of the experiments contain a search window with a probability of agreement with the SM expectation of 0.5% or less. The disagreement of 140 GeV/ c^2 mass window has a significance of less than 2.5 standard deviations and lies at the mass where the SM

background is largest and, therefore, where the ensemble tests indicate fluctuations would also be largest.

Since we find no evidence of a statistically significant excess in the data compared to the SM expectation, we extract limits on $\sigma(p\bar{p} \rightarrow X) \times B(X \rightarrow Z\gamma)$ for new scalar states. The limits are set using a Bayesian technique [22] with a flat prior for the signal and with systematic uncertainties on the signal and background taken into account. At lower $Z\gamma$ masses, the three largest contributions to the systematic uncertainty arise from uncertainties in luminosity, particle identification efficiency, and jet-photon mis-identification probability. These all contribute approximately half an event to the uncertainty on the total number of events expected in the SM. For $Z\gamma$ masses greater than 800 GeV/ c^2 , inefficiencies due to one lepton overlapping the isolation region of the other lepton and to charge mis-identification in the di-muon channel become significant. The systematic uncertainty on the two high mass inefficiencies become the dominant uncertainties. Given that no SM events are expected at these masses, these effects only contribute to the signal efficiency, and at 800 GeV/ c^2 the uncertainty is about 10%, but by 1000 GeV/ c^2 it has reached 40%.

We extract the sensitivity and limits for two cases; they are shown in Fig. 3. In the first case, we use the narrow window technique and assume the width is negligible compared to the detector resolution of 3.9% (labeled “Narrow scalar”). In the second case, we use the threshold technique where the width is not relevant (labeled “Arbitrary width”). We can see that the expected limit for the window technique is highest where SM sources provide the largest number of events, is lowest between 300 and 800 GeV/ c^2 where no events are expected, and then rises again as the high mass inefficiencies become important. We see qualitatively similar structures from the threshold technique limit. Recall that M' is less than the nominal mass of the particle. In Fig. 4, curves representing the expected cross section times branching fraction for three Higgs models are compared to the limits. These models are the SM Higgs boson [9], a fermiophobic Higgs boson [11], and a model with four generations of quarks [12].

In summary, we have performed the first search for $Z\gamma$ resonant states with an invariant mass greater than 100 GeV/ c^2 . We find no statistically significant evidence for the existence of these objects. Narrowing our search to scalar and pseudo-scalar resonances, we limit the production cross section times branching fraction to ≈ 1 pb for both narrow and arbitrary width states with invariant masses up to 1 TeV/ c^2 .

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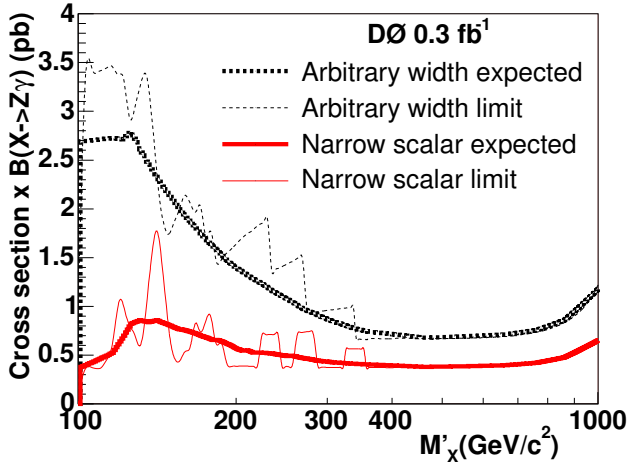


FIG. 3: The expected and observed cross section times branching fraction 95% C.L. limit for a scalar X decaying into $Z\gamma$ as a function of M' for both a narrow scalar and a scalar of arbitrary width. M' is the median of the true mass distribution for a generic object using the arbitrary width technique and is the mass of the particle in the narrow scalar technique.

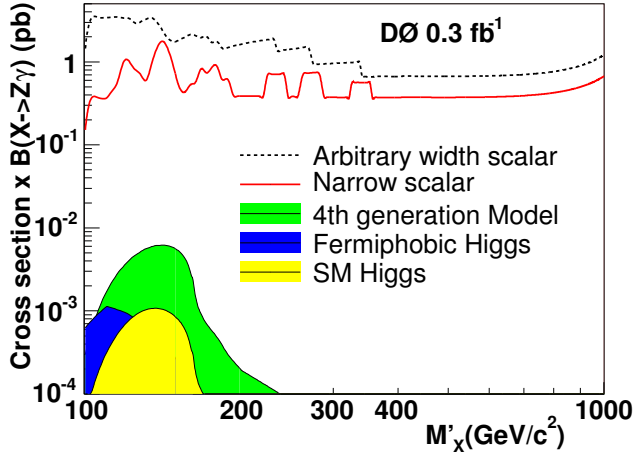


FIG. 4: The cross section times branching fraction 95% C.L. limits for a scalar X decaying into $Z\gamma$ as a function of M' . M' is the median of the true mass distribution for a generic object using the threshold width technique, and is the mass of the particle in the narrow window technique.

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