

Analysis of the CDF II Data in Search of the Higgs Boson Decaying to Two Photons

Callie DeMay

Office of Science, PST Program

University of Illinois

Fermi National Accelerator Laboratory

Batavia, Illinois

August 3, 2007

Prepared in partial fulfillment of the requirements of the Office of Science, Department of Energy's Pre-Service Teachers (PST) Program under the direction of Craig Group in the CDF Experiment of the Particle Physics Division at Fermi National Accelerator Laboratory.

Participant:

Signature

Research Advisor:

Signature

Table of Contents

Abstract	iii
Introduction	1
Experimental Apparatus	2
Analysis Methods	4
Results	8
Discussion and Conclusions	9
Acknowledgements	9
References	10
Tables	12
Figures	12

ABSTRACT

Analysis of the CDF II Data in Search of the Higgs Boson Decaying to Two Photons.

CALLIE DEMAY (University of Illinois, Urbana-Champaign, IL, 61820) CRAIG

GROUP (Fermi National Accelerator Laboratory, Batavia, IL 60510)

Although the Standard Model is unbelievably accurate, the one fundamental aspect needed to complete the model, a massive particle called the Higgs Boson, has not yet been discovered. In this investigation, we searched for a non-Standard Model, fermiophobic Higgs, which would decay to two photons. This decay mode is predicted to have a very small branching fraction according to the Standard Model; however, some models predict a higher branching fraction. We initially optimized selection criteria in order to become as sensitive as possible to the signal region. Using the 2fb^{-1} of data provided by Fermilab's Tevatron and collected by the CDF experiment, we were unable to see a signal for the Higgs; therefore, the focus of our research shifted to placing a limit on the cross section for the Higgs in the fermiophobic model. We were able to place a lower limit of 99 GeV on the mass of the fermiophobic Higgs. This limit is currently the best in the world for a hadron collider. The previous limits at Fermilab included one by CDF at 82 GeV, and one by DZero at about 90 GeV. However, the world's best limit of 109.7 GeV was placed by LEP in Switzerland. Although we were not able to find a Higgs signal, the techniques used to improve sensitivity to photon events will be useful in the next generation of collider experiments, which will be more sensitive to the small branching fraction of diphoton events.

INTRODUCTION

The Standard Model of particle physics is the theory that attempts to explain the properties of all particles and forces that exist throughout our universe. This compact model is comprised of three families of quarks and leptons along with four fundamental force carriers. The observable matter in our current universe is comprised of the up and down quarks and the force carriers. The other quarks have not been abundant since the beginning of the universe, and current research in particle physics has the goal of finding and explaining these fundamental particles and their interactions. Although the Standard Model has been confirmed with many experimental observations, theorists believe that it is not complete. Countless extensions have been proposed, which include massive particles. One unobserved prediction of the Standard Model is a particle called the Higgs boson, which could potentially allow the observed particle masses to fit into the Standard Model. Many of the proposed extensions are centered around possible creation and decay mechanisms of the Higgs boson [1].

Because there are only two quarks that are abundant in nature today, researchers have discovered ways to create the other fundamental particles in the lab in order to study their properties. Particles can be accelerated to very high energies and velocities near the speed of light using either synchrotron (circular) or linear (straight) accelerators. High energy is required by particle physics in order to have a chance to produce new, massive particles ($E = mc^2$). Similarly, at higher energies, the properties of particles can be observed on smaller distance scales ($\lambda = hc/E$). Once these particles have enough energy, they are either smashed into a metal target, which is called a fixed target experiment, or into another energetic particle, which is called a collider experiment. After the collision,

newly created particles spray away from the collision site. These resulting particles are captured with detectors. Accelerators and detectors vary depending on what the experimental group is hopeful of finding.

The accelerator chain at Fermi National Accelerator Laboratory (FNAL) accelerates protons and antiprotons to 1.96 TeV. This is approximately 2000 times the rest mass of one proton! These collisions are currently the highest proton collisions in the world. In order to accelerate the particles up to this speed and energy, the protons and antiprotons go through five different accelerator stages. The final stage of the accelerator chain is the four-mile synchrotron called the Tevatron. The particles are forced to collide at two points along the ring. At each collision site there is an experimental group and a detector to analyze the resulting particles [2].

EXPERIMENTAL APPARATUS

Both of the experimental detectors track the resulting particles after the proton-antiproton collision. The two beams, each containing roughly 10^{16} particles, collide once every 120 nanoseconds (10^{-9} seconds). Most of the events from the collisions are not particularly interesting or unique; therefore, computers sort out the exciting events from the ordinary ones. This process of selecting good events is called triggering. The events that produce highly energetic particles are called hard collisions. After each collision, the resulting particles can be studied through their interactions with a detector.

The detector at the Collider Detector at Fermilab (CDF) is comprised of six layers, each used to detect different particles. The first two layers, the Silicon Vertex Tracker and the Central Tracker, measure the locations of where charged particles pass through the detector layers. By tracing out the paths of these particles, “tracks” are

reconstructed. The curvature of these tracks, which occurs when a charged particle is placed in the magnetic field, is used to obtain the momentum of the charged particles ($r = mv/qB$). The next two layers, the Electromagnetic (EM) and Hadronic (HAD) calorimeters, are comprised of lead (iron) sheets sandwiched with scintillator. All particles, charged or uncharged, interact with the lead (iron). After an interaction occurs with the lead (iron), the resulting charged particles emit a flash of light when they pass through the scintillator. The amount of light in the calorimeter is proportional to the total amount of energy of the particles. While electromagnetic particles, such as photons and electrons, leave most of the energy in the EM calorimeter, hadrons, such as pions and protons, leave most of their energy in the HAD calorimeter. The fifth layer of the detector, the iron absorber, is used to absorb all of the leftover hadronic showers. The final layers of the detector are the muon chambers. If a charged particle is able to make it out to this layer, it most likely is not a hadron, and is therefore, a good muon candidate.

All of the above layers are part of the central detector. This area of the detector ranges from 30° - 150° above the z-axis and is the most precise part of the detector, because the majority of the important event particles spray in that direction. From about 10° - 30° above the z-axis on each side is the plug detector. The plug part of the detector has EM and HAD calorimeters, but has poor tracking capabilities [3].

After all of the resulting particles are detected, the characteristics of the event can be used to classify the physics process that occurred. Once the events are categorized, they can be compared with the theoretical predictions of the Standard Model and beyond.

ANALYSIS METHODS

The Higgs boson has been sought after for over 40 years; yet, some believe we may be on the brink of detecting the particle. However, there are several prominent theories predicting its properties and behaviors.

There are three main production mechanisms in the Standard Model in which a low mass Higgs ($M_H < 150$ GeV) could be produced by the Tevatron collisions. The first mechanism, gluon fusion, as seen in Figure 1, requires two gluons to come together, and through a top quark loop, the Higgs would be produced. The second production mode, associated production, as seen in Figure 2, occurs when two quarks collide and produce a W or a Z boson along with the Higgs. The last mode, vector boson fusion, as seen in Figure 3, requires two quarks to each radiate a W or a Z, and those two bosons collide to produce the Higgs and two quarks.

There are also many decay modes of the Higgs in the Standard Model. Each of these decay modes depends on the mass of the Higgs. The dominant decay mode for a low mass Higgs is the Higgs to a b anti-b quark pair (b b-bar), as seen in Figure 4. The other decay mode, as seen in Figure 5, which will be focused on in this analysis, is when the Higgs decays to two photons through a W loop, which is predicted to have a tiny branching fraction (for $M_H = 100 \sim 10^3$) [4].

Although the Standard Model predicts a small branching fraction for the Higgs decay to two photons, there are many other theories, all of which should be considered until proven otherwise, that predict how often these modes occur. In the theory investigated here, it is thought that the Higgs may be “fermiophobic,” meaning that it would not couple to fermions, namely quarks or leptons. In this model, the gluon fusion

production mode and the $b\bar{b}$ decay mode would not occur. Thus, the Higgs decay to two photons can become the dominant decay mode [5]. There are many reasons why it may be beneficial to search for the Higgs in this manner. Two photons have a very clean and clear signature in the detector compared to the jet signature from the $b\bar{b}$. Also, the research being conducted in the next generation of particle colliders will be sensitive to this very small branching fraction. Therefore, any techniques we develop may be used by future experiments that have greater sensitivity to small branching fractions.

The number of observed events (N) in the detector can be calculated by:

$$N = \sigma\epsilon L$$

In this equation, the L stands for the integrated luminosity, which is the amount of data the detector records; the σ represents the cross section multiplied by the branching fraction and is proportional to the probability that the process will occur; and the ϵ stands for the efficiency of the process to be observed in the detector. Using the values for $M_H = 100$ GeV ($L = 2\text{fb}^{-1}$, $\sigma = 450\text{fb}$, $\epsilon = 0.15$), and assuming a very high branching fraction, the predicted number of events is calculated to be about 135 events. However, the branching fraction is often quite less than one; therefore, the 135 events calculated above is the maximum number events possible. Using the branching fraction for the Standard Model Higgs for 100 GeV, 10^{-3} , the number of events is decreased to 0.135.

In order to study the low mass Higgs to two photons, it is important to understand that photons are uncharged, and therefore, do not leave tracks in the first two layers of the detector. Photons are detected in the EM calorimeter, where, on average, most of their energy is absorbed. The leftover energy is absorbed in the Hadronic calorimeter; however, this energy fraction is small. In the fermiophobic models, associated production

is the dominant production mode; therefore, we made requirements based on the properties of this signature. For example, the transverse momentum (p_T), which is defined to be the momentum orthogonal to the z -axis, of the photon pair is significant because it recoils against the vector bosons (W 's or Z 's). The energy of the system is known before the collision, and due to conservation of energy, all of the energy after the collision should remain constant. If for some reason it does not, that missing energy is referred to as missing transverse energy (MET). Isolated tracks, which are the paths of charged particles which are spatially separated from other particles in the event, come from leptons passing through the detector. Jets occur when a quark passes through the detector and decays repeatedly, causing a group of tracks to be formed. These three generic identification requirements are defined to select decays of the W 's and Z 's.

Background events are defined to be any events that are not the Higgs decaying to two photons. The two types of background events are real diphoton events (Standard Model background events) and fake photon background events. The fake photons are produced when a jet mostly composed of a neutral pion decays into two photons. The angle between these two photons is so small that it looks like a single photon. Although this is a rare occurrence, because the cross section for jets is so large, the number of times it occurs is still significant. We used a sideband study to estimate the background events from fake photons. The sidebands are the events that almost pass the photon cuts, but are not clear photons. Therefore, they are mostly composed of events with similar characteristics to the fake background and can be used as a good model for the fake photon background events. Fake background events are 75 percent of the total background and 25 percent are real Standard Model diphoton events.

Because the expected number of signal events is calculated to be quite small, one vital process in the analysis is to make cuts on the data set in order to remove these background events. We first had to optimize selection criteria in order to keep as many signal events and to remove as many background events as possible. There were several variables we studied in order to find the optimum cut.

Because of the small width of Higgs invariant mass distribution, as seen in Figure 6, we set a mass window around the Higgs of $\pm 10\text{GeV}$. We then studied the effects of making cuts on the transverse momentum of the diphoton pair (p_T), the missing transverse energy (MET), the p_T of the second jet, and the p_T of the isolated tracks. We made a grid of all of these parameters in order to find the optimal cut. The study consisted of taking various p_T cuts with an “or” between an additional MET, p_T of the second jet, and p_T of the isolated track cut. After looking through all of the various cut options, we decided that a p_T cut of 75 GeV and no other cuts was best for our study. This cut reduces the backgrounds by over 99 percent, while keeping at least 50 percent of the signal.

In order to observe the Higgs, we would need to see a significant bump in mass spectrum graph. Since no significant excess of events were observed in the graph, see Figure 7, the goal of the analysis shifted to placing a limit on the Higgs production cross section for the fermiophobic models.

In addition to signal and background expectations, the acceptance of the Higgs signal in the CDF detector must be understood in order to quantify the sensitivity to the Higgs. PYTHIA Monte Carlo and CDF detector simulation was used to study the acceptances of the diphoton signal with all cuts for each mass point and for systematic

variations. The acceptance is calculated by dividing the number of events that passed all of our cuts by the total number of events. We calculated the acceptances for mass points ranging from 70-120 GeV. The values for the points can be seen in Table 1.

After obtaining the acceptances, we used our data to place a limit on the cross section of the fermiophobic Higgs. In this process, the number of observed events in the data and the number of expected background events are compared. Including systematic and statistical fluctuations, we were able to place a limit on the number of signal events we would be sensitive to within a 95 percent confidence level. A Bayesian bin method was used to calculate the limits on the cross sections for mass points ranging from 70-120 GeV [6].

After obtaining the cross section limits for the mass points, we plotted them along with the expected cross section limits, the bosonic Higgs model limits, and the Standard Model limits as a function of the Higgs mass. The cross section limit line rules out any models which predict a cross section value above that curve. For our benchmark fermiophobic model (red line in Figure 9), we were able to set a lower limit on the mass of the Higgs based on the model intersection with our limit. See Figures 8 and 9.

RESULTS

Although we did not find the fermiophobic Higgs decaying to two photons, we were able to place a limit of 99 GeV on its mass for the fermiophobic models. With respect to previous CDF results, we extended and lowered the line of the cross section limit, as seen in Figures 8 and 9.

DISCUSSION AND CONCLUSIONS

We were able to place a limit on the mass of the fermiophobic Higgs to 99 GeV, because if it had been any lower, we would have seen it. This limit is currently the best limit for the bosonic Higgs in the world from a hadron collider measurement. Previous hadron collider limits include 82 GeV by CDF Run1 and about 90 GeV by DZero [7][8]. The two main factors that helped us increase our sensitivity were the increase in luminosity to 2 fb^{-1} and the large p_T cut we made on the diphoton pair. The only factors that would help us further increase our sensitivity would be a higher luminosity and higher energies; however, here at Fermilab, we cannot increase the energy, and more luminosity will only be obtained with time. However, the world's best limit of 109.7 GeV was placed by LEP in Switzerland [9]. The skills gained by focusing on diphotons will be useful in the next generation of collider experiments in Switzerland, which will be sensitive to the small branching fraction.

ACKNOWLEDGMENTS

This research was conducted at Fermi National Accelerator Laboratory in Batavia, Illinois. I would like to thank the Department of Energy, Office of Science for this opportunity. I would like to thank Spencer Pasero for introducing me to Fermilab and providing ongoing support throughout the summer. I would like to thank Raymond Culbertson for all of his hard work and help in this research process. I would also like to thank Anna Zuccarini for her help in introducing me to education concepts and LaMargo Gill for revising and editing my paper.

REFERENCES

- [1] B.R. Martin and G. Shaw. *Particle Physics*, 2nd ed. England: John Wiley & Sons Ltd, 1997, pp. 1-78.
- [2] Brent Evanger. (2002). “Accelerator Rookie Book Version #3.” Fermi National Accelerator Laboratory. Batavia, IL. [Online]. Available: http://www-bdnew.fnal.gov/operations/rookie_books/Concepts_v3.1.pdf
- [3] John Yoh. (2007, Jan.) “Introduction to the CDF detector and the Particles We Observe.” Fermi National Accelerator Laboratory. Batavia, IL. [Online]. Available: <http://www-cdf.fnal.gov/events/detintro.html>
- [4] Craig Group and Raymond Culbertson (2007, March). *Update on the Higgs to gamma gamma*. Fermi National Accelerator Laboratory. Batavia, IL. [presentation].
- [5] Greg Landsberg and Konstantin T. Matchev. “Discovering a Light Higgs Boson with Light”. *Phys.Rev.D62*. Fermi National Accelerator Laboratory, Batavia, IL. FERMILAB-PUB-00/003-T. Jan. 20, 2000.
- [6] J. Goldstein, S. Harper, P. Renton. “The Search For New Physics in Di-Electron Events.” Fermi National Accelerator Laboratory. Batavia, IL. CDF Note 7784. Aug. 16, 2005.
- [7] The D0 Collaboration. “Search for non-SM Light Higgs Boson in the $h \rightarrow \gamma\gamma$ Channel at D0 in Run II.” Fermi National Accelerator Laboratory. Batavia, IL. D0 Note 4374-CONF. March 18, 2004.

- [8] CDF Collaboration. “Search for Narrow Diphoton Resonances and for $\gamma\gamma + W/Z$ Signatures in $p\bar{p}$ Collisions at 1.8 TeV.” Phys.Rev.D64. Fermi National Accelerator Laboratory. Batavia, IL. Oct. 30, 2006.
- [9] LEP Collaboration. “Searches for Higgs Bosons Decaying into Photons: Combined Results from the LEP Experiments.” European Organization for Nuclear Research. LHWG Note 2002-02. July, 2002.
- [10] P.J Wilson and H.J Frisch. “Search for a Higgs Decaying to Two Photons.” Fermi National Accelerator Laboratory, Batavia, IL. CDF Note 4523. March 26, 1998.
- [11] S-M Wynne ,T. Berry, and R. Culbertson. “Search for Randall-Sundrum Gravitons in 1155pb^{-1} Run II High Mass Diphoton Data.” Fermi National Accelerator Laboratory, Batavia, IL. CDF Note 8359. Jan. 10, 2007.

Mode	Higgs Mass	Acceptance CC	Acceptance CP
WH,ZH	70	0.02927	0.01819
WH,ZH	80	0.03799	0.02371
WH,ZH	90	0.04369	0.03183
WH,ZH	100	0.04934	0.03748
WH,ZH	110	0.05440	0.04481
WH,ZH	120	0.06006	0.05157

Table 1: Acceptances for Associated Production (WH,ZH), Vector Boson Fusion (VBF), and Gluon Fusion (ggH)

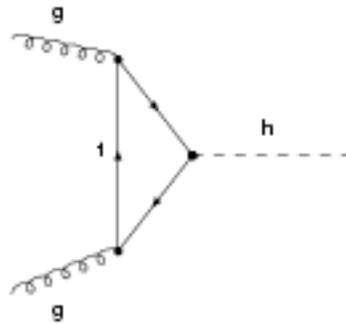


Figure 1: Gluon Fusion

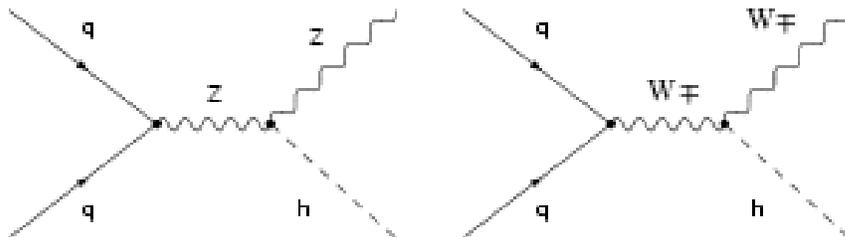


Figure 2: Associated Production

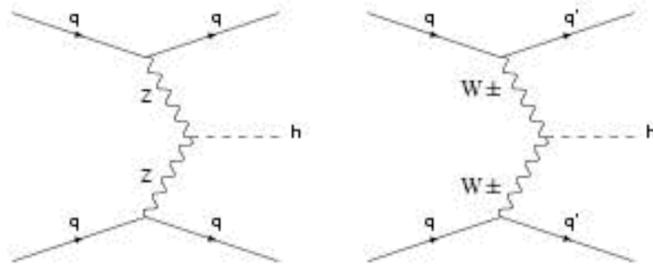


Figure 3: Vector Boson Fusion

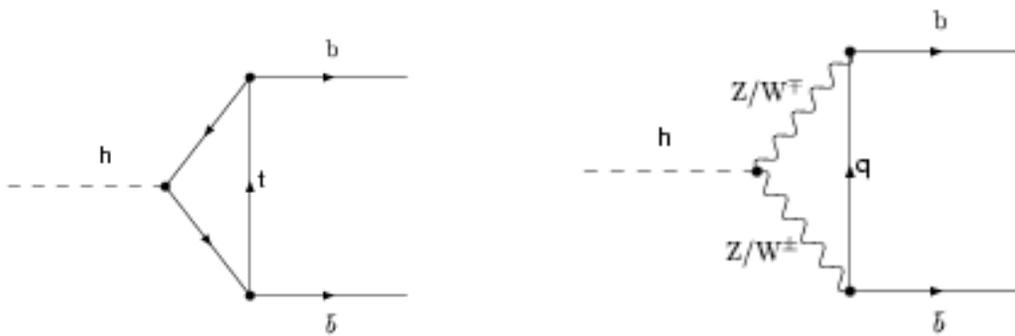


Figure 4: Higgs to b b-bar decay mode.

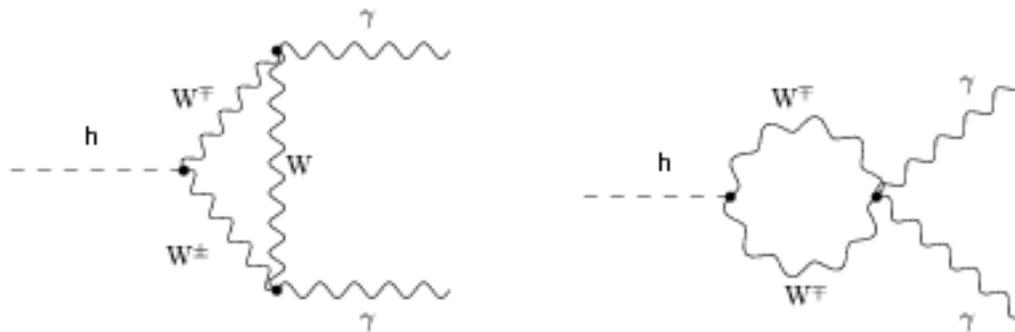


Figure 5: Higgs to gamma gamma decay mode.

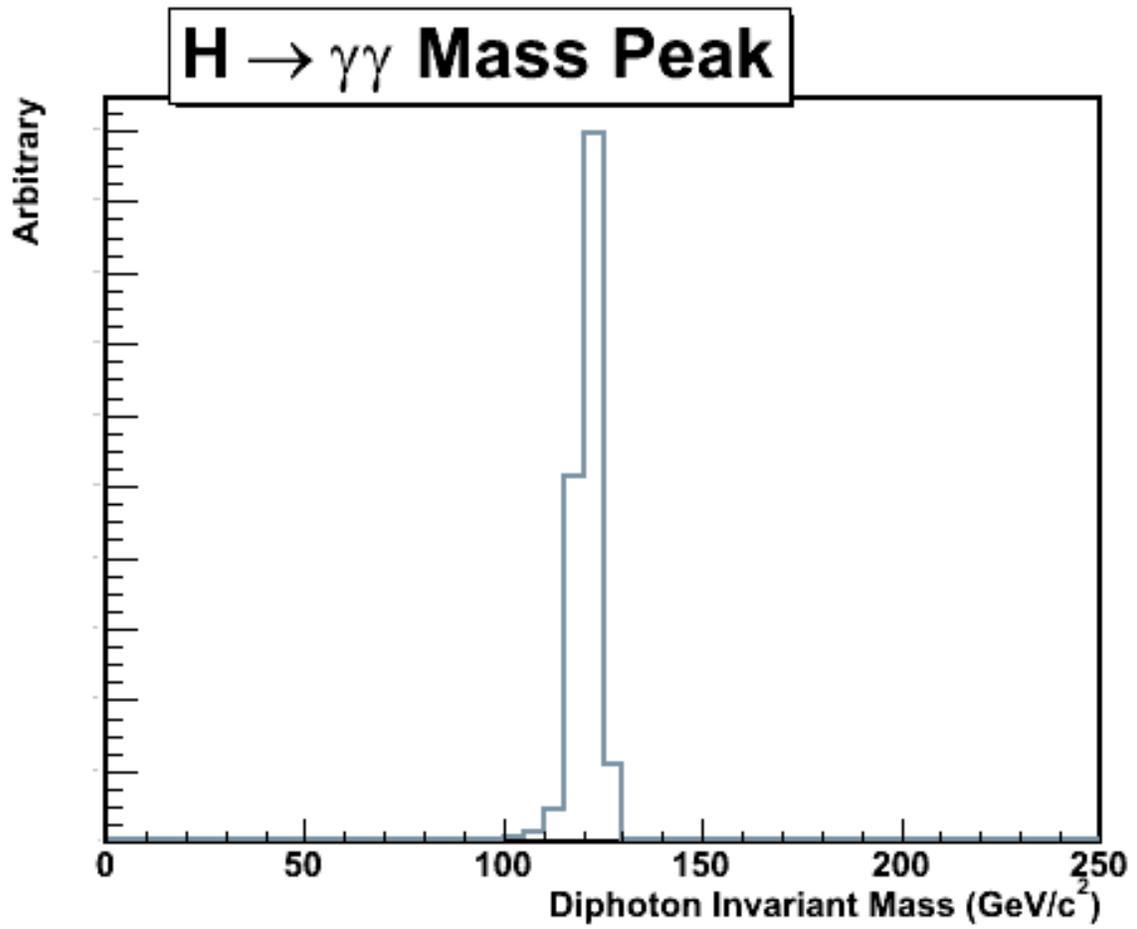


Figure 6: Diphoton mass peak from 120 GeV Higgs decaying to two photons as predicted by PYTHIA plus CDF detector simulation.

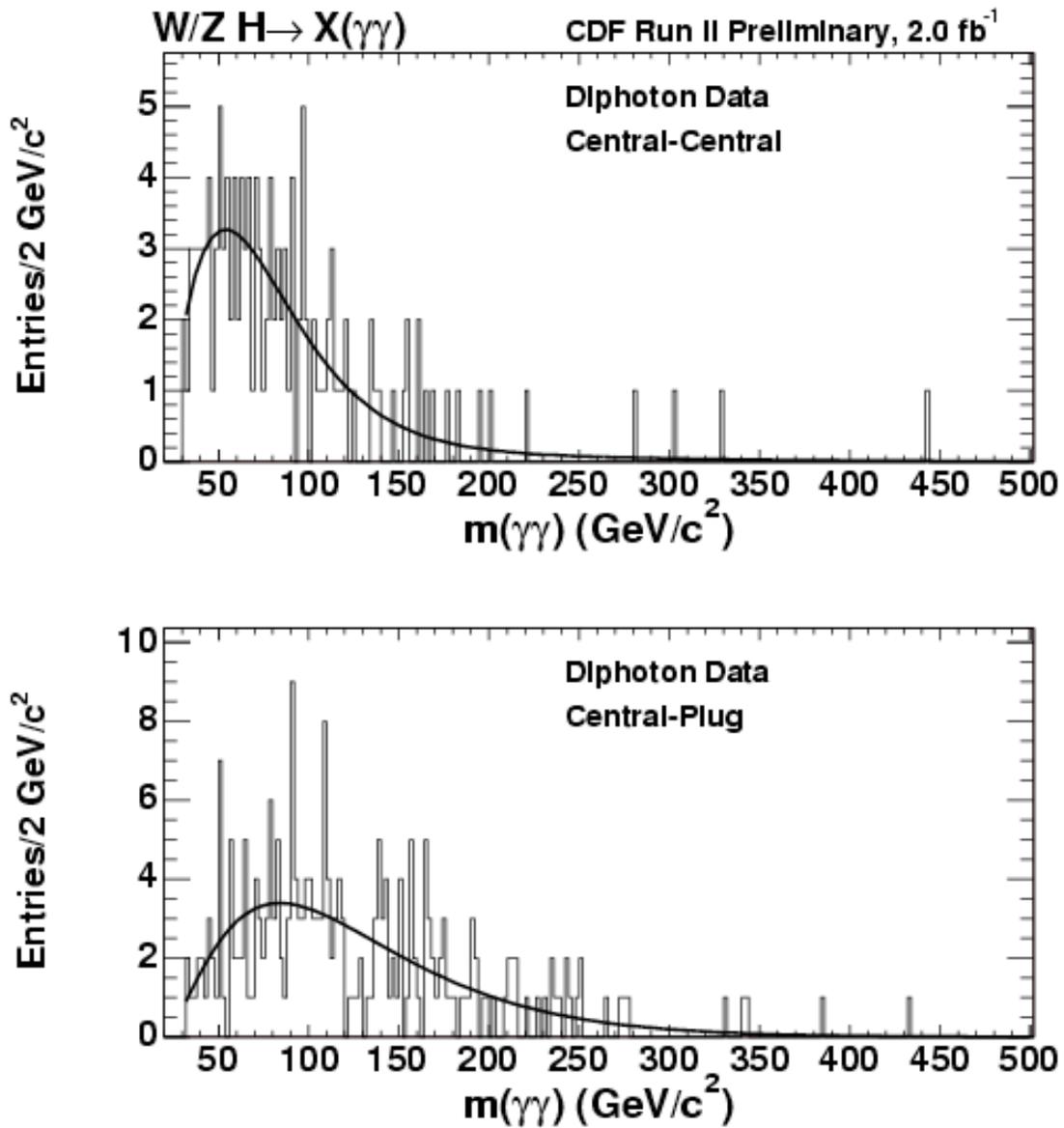


Figure 7: Background fit to data for central-central and central-plug detectors.

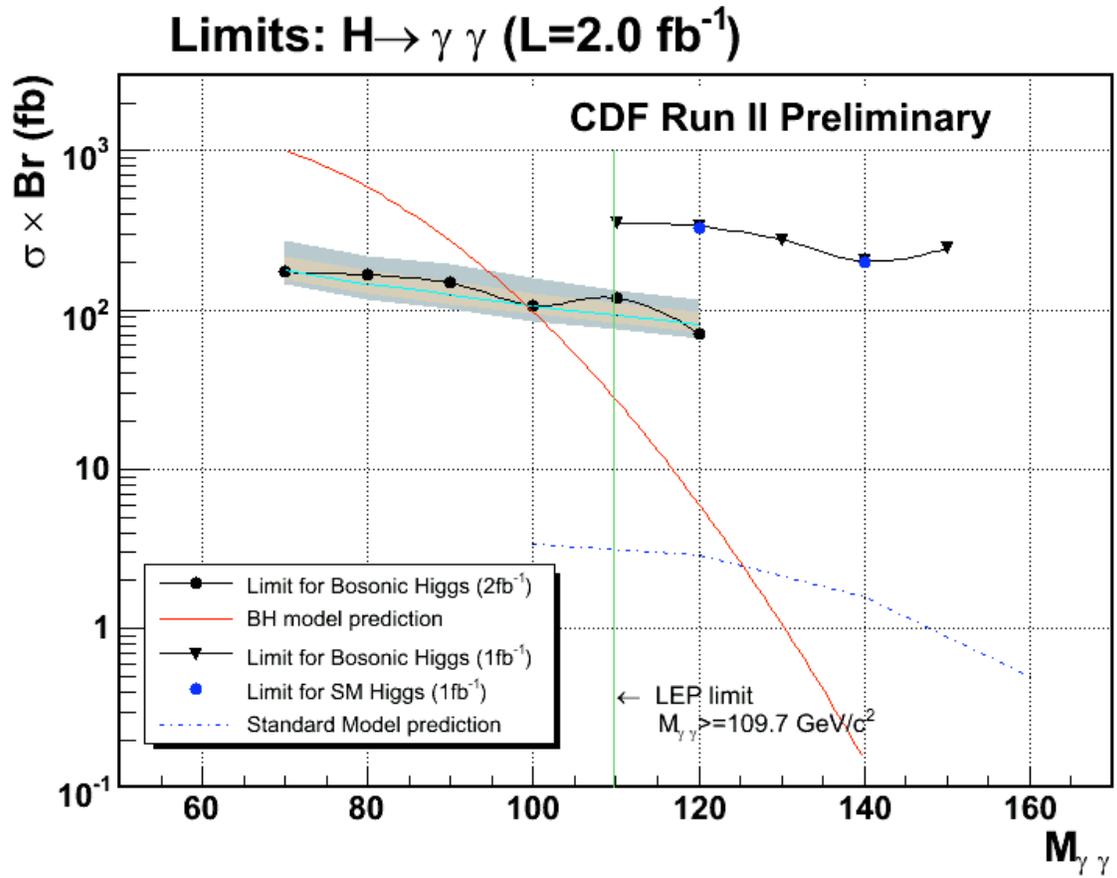


Figure 8: Current limits placed on the mass of the Higgs decaying to two photons.

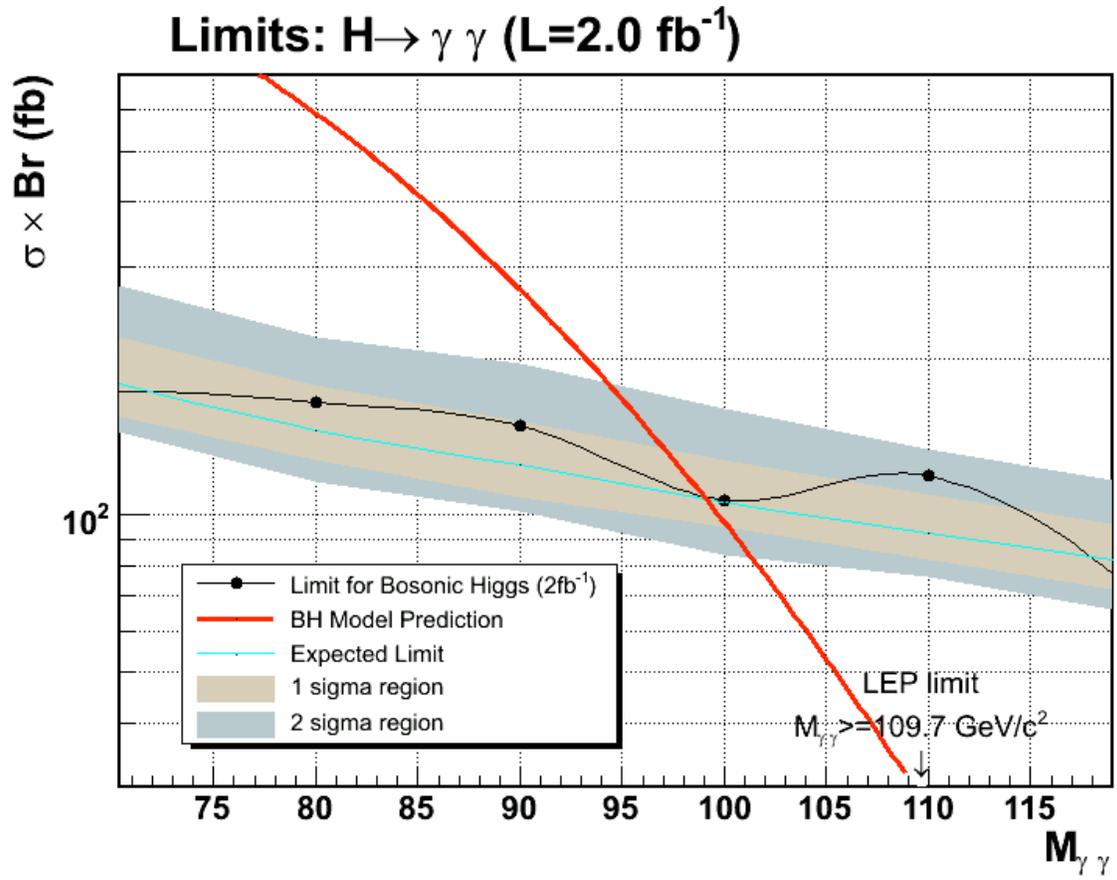


Figure 9: Zoomed-in view of the cross section limit for the mass of the Higgs decaying to two photons.