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Search for Z rare decays on CDF: $Z^0 \to J/\psi\gamma$ and $Z^0 \to \Upsilon\gamma$

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Abstract. We present status of a search for two rare of the Z boson, $Z^0 \to J/\psi\gamma$ and $Z^0 \to \Upsilon\gamma$ at CDF. The state of analysis is described at the time of this worksop.

1. Introduction

Fermilab (Fermi National Accelerator Laboratory) is a High Energy Physics Laboratory located in Batavia, Illinois, United States. The highest energy Fermilab accelerator, the Tevatron, collides protons and antiptotons at energies of up to 1.96 TeV. In this process, conditions similar to those of the very early universe are reproduced.

One of the interaction points of the particle beams is the location of the CDF (Collider Detector at Fermilab) Experiment. Its goal is to discover the identity and the properties of the elementary particles that form the universe and carry the fundamental forces. CDF is a general purpose detector that allows the identification of different particles, products of the interaction and some of their characteristics. The search for rare decays in this work is done using data from the CDF Run II detector (collected from 2001 to 2011).

1.1. Understanding the CDF Detector

In order to work with data from the detector, an understanding of it is required. Some of its characteristics establish observational limitations. Understanding its behavior helps us determine the expected distributions of important traits in the particles we want to observe.

The CDF detector is divided into layered components. Each layer detects distinct characteristics of the particles. Combining the data obtained from each layer allows us to properly identify particles.

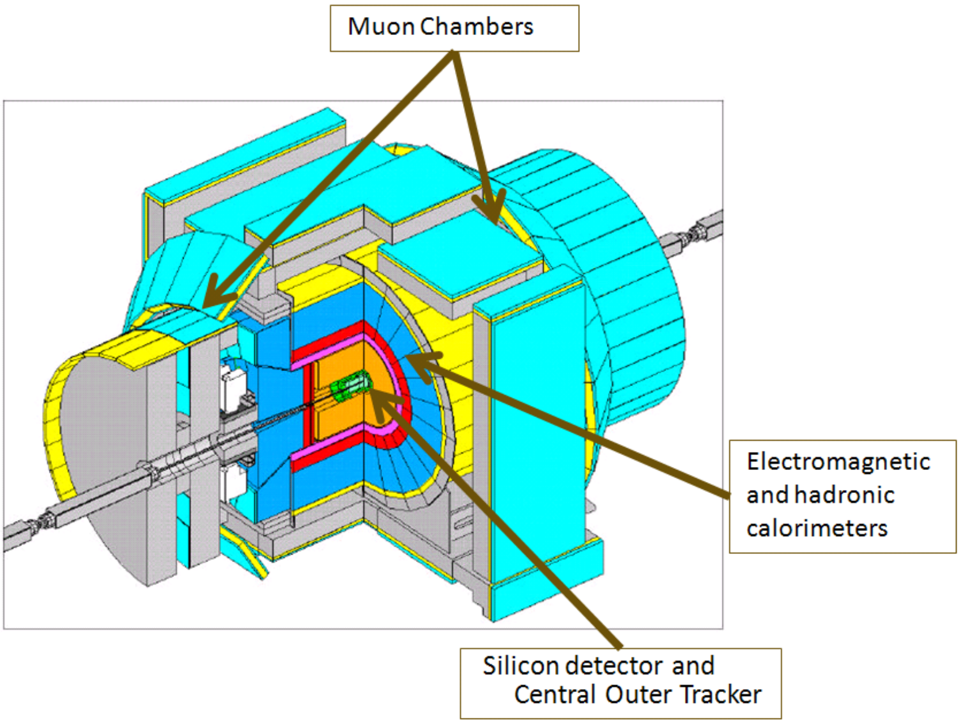

Figure 1. Diagram of the CDF detector.

Layers of the CDF detector

- *SVX (Silicon Vertex Tracker)*: Detects only charged particles as they ionize the silicon. It can also determine whether a track comes directly from the collision point.

- *COT (Central Outer Tracker)*: Detects the position of the charged particles. A magnetic field forces particles to deviate from their original trajectories, allowing this part of the detector to also determine their momentum.

- *Electromagnetic Calorimeter*: Consists of lead plates, alternated with scintillating material. The amount of light emitted is related to the energy the particle deposits in the material. This calorimeter detects this amount of energy deposited, which helps us identify different particles like electrons and photons.

- *Hadronic Calorimeter*: Consists of iron plates, alternated with scintillating material. It works under the same principle as the electromagnetic calorimeter. In this calorimeter we many observe the energy deposited by hadrons and other particles, given that all the other particles tend to deposit all their energy in the electromagnetic calorimeter.

- *Muon Chambers*: Most hadrons do not reach these chambers. In other words, any particle that reaches this part of the detector can be considered a good muon candidate, provided that it satisfies other requirements.

1.2. Particle decays

The decay channels that we will search for are the following rare decays of the Z boson:

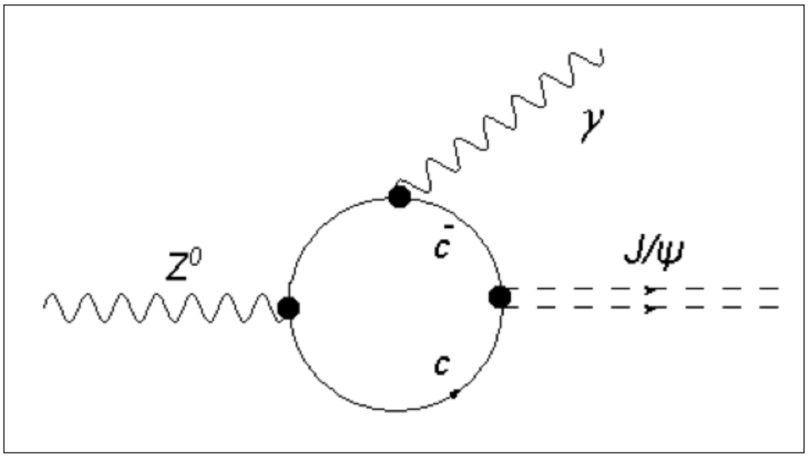

Figure 2. Feynman diagram for the $Z^0 \to J/\psi\gamma$ decay

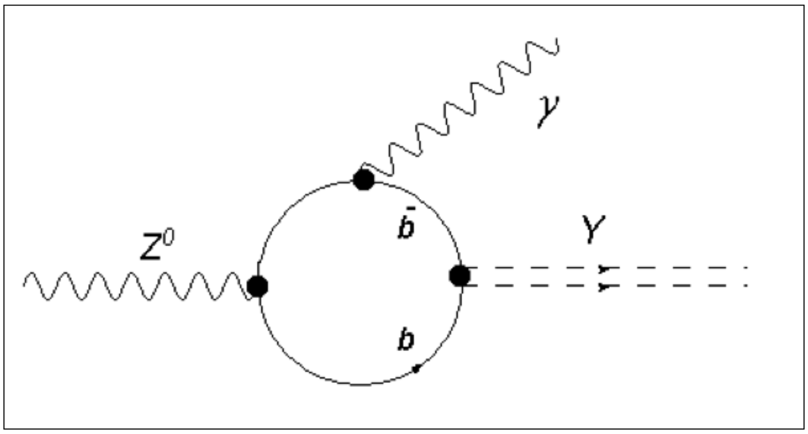

Figure 3. Feynman diagram for the $Z^0 \to \Upsilon\gamma$ decay

This search is done for an energetic photon and a pair of oppositely charged muons in the final state for both decays.
The branching ratios have been predicted theoretically [2] to be within the following ranges:

$$B(Z^0 \to J/\psi\gamma) = [1.1 \times 10^{-5}, 1.64 \times 10^{-7}]$$

$$B(Z^0 \to \Upsilon\gamma) = [1.28 \times 10^{-4}, 4.27 \times 10^{-7}]$$

1.3. Physics Motivation
Number of the W and Z boson decays decays which have have been studied experimentally is suprizingly small [3]. Among yet unobserved decay modes, the radiative decays $V \rightarrow P\gamma$, where V is a Z or a W boson and P is a light pseudoscalar boson, could have branching ratios close to the limit of the experimental sensitivity of the Tevatron experiments. The most recent Tevatron searches for $W^{\pm} \rightarrow \pi^{\pm}\gamma$ decay [1] have significantly improved previously existing limits. However no experimental searches for the $Z^0 \rightarrow J/\psi\gamma$ or $Z^0 \rightarrow \Upsilon\gamma$ decays have been published. Together with the clean experimental signatures of these decays, this gives a strong motivation to search for them. It is also worth mentioning that the background and trigger considerations could favor searches for the rare radiative decays of W and Z bosons at the Tevatron, compared to LHC.

2. Analysis Strategy
The search for these rare decays must begin with a search for the particles in their final states. A photon and a pair of oppositely charged muons must be identified from the data. In order to do this, we must determine how they interact with the detector and how that behavior will manifest itself in the data that we analyze.

The first step towards identifying the particles is deciding which dataset should be used. The data, coming from the detector is stored in different datasets depending on particular characteristics of the data. When the characteristics of a particle observed in the detector coincide with the expected behavior of a specific particle, it is stored in a dataset associated with it. For example, if a particle in an event is identified to be a good photon candidate the information for that event will be stored in a set called *photon-triggered dataset1*. Because the high Pt photon trigger identification efficiency is high, we have chosen to use datasets with this trigger for the analysis. With this selection, only the muon identification is required.

In order to identify muons from the data, we must establish certain requirements or cuts that events must meet in order to be considered a good J/ψ or Υ candidate. The process to establish these cuts requires us to study the decay through simulations. Once cuts are established we can take a better look at the data and search for the expected decay. Finally, the branching ratio of the decay will be calculated if the decay is found, or an upper limit to it in case it is not found. The steps in the methodology have been split into different core activities. They will be described in the following sections.

2.1. Monte Carlo Event Generation
Monte Carlo (MC) simulation of the signal processes is important to reach a better understanding of the behavior we will expect from them. It helps us to take a closer look at the distribution of different variables, allowing us to get familiarized with the decay mode and specific traits of the outcome. We also use simulations to calculate the signal acceptance and study the efficiencies of different cuts.

The MC events are generated with PYTHIA event generator, customized to include the radiative decays of the Z boson into heavy quarkonia. The generated events are simulated in the CDF detector using the GEANT3-based simulation code. We use the MC samples to optimize the analysis selection cuts. Several examples are shown in the following figures.

Acceptance of the muon chambers in limited to $-1.5 < \eta < 1.5$, as shown in figure 4. Only particles in that area will be detected. Knowing this, we show the fraction of the generated J/ψ that will reach the detector in black. A distribution for their Pt (transversal momentum) is shown in figure 5.

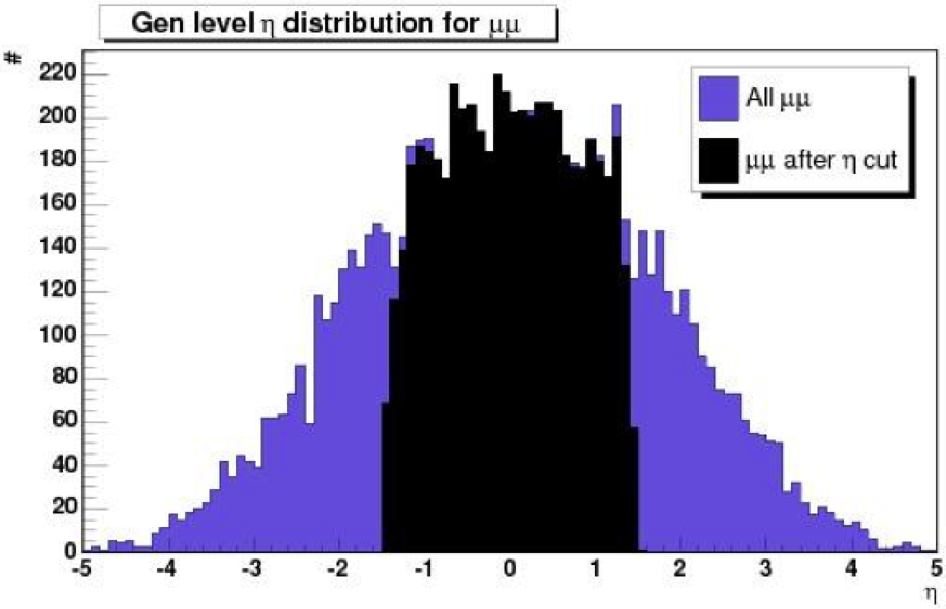

Figure 4. Distribution of the quantity η for every pair of muons in events generated by Pythia. In blue: The entire distribution. In black: The events for which $-1.5 < \eta < 1.5$ for both muons.

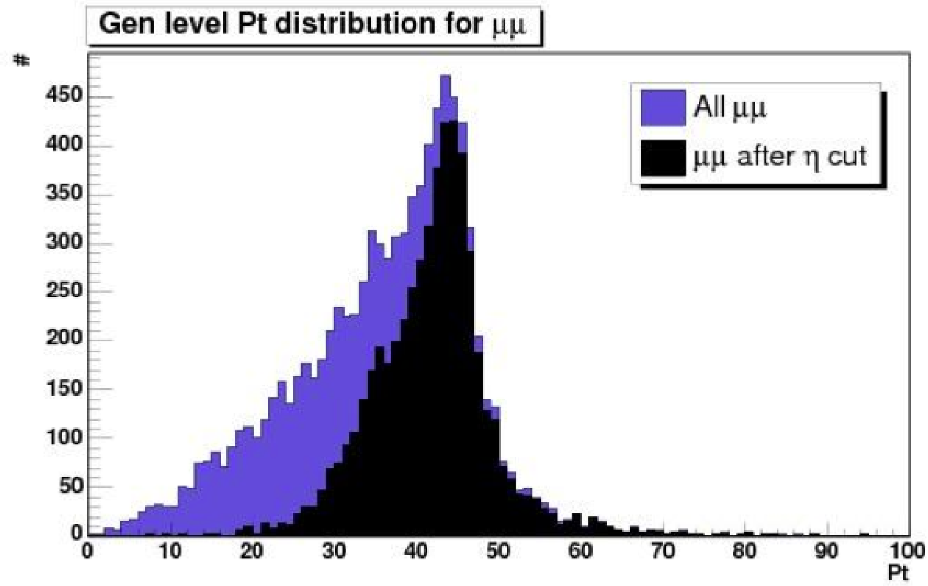

Figure 5. Distribution of transverse momentum for every pair of muons in events generated by Pythia. In blue: The entire distribution. In black: The events for which $-1.5 < \eta < 1.5$ for both muons.

From this we can observe that the efficiency of the Pt $>$ 15 GeV cut is close to 100%. As a consequence, we choose to reject or cut out of our data sample all muon candidate pairs which do not have this minimum Pt value

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2.2. Establishing cuts

Based on what we learned from the simulations, we established the necessary cuts that would be made to the data from the detector in order to have a clean signal from the particles of interest. It is important to note that for every pair of muon candidates in the data, different cuts are made to each of the two. We call the leading muon the one to which stricter, or tight cuts will be made. The following is a list of the cuts made.

- *Leading Muon Chamber Stubs:* This cut requires all leading muon candidates to have been detected by the CMX, CMUP or BMU muon chambers.

- *Subleading Muon Chamber Stubs:* This cut requires all leading muon candidates to have been detected by any of the muon chambers.

- *Pt* > 3*:* Transversal momentum is required for the second muon due to an observation made on the simulations. A peak is observed in 5 at Pt of around 2 GeV. We assume this peak to be background from hadrons so we want to reject it.

- *Energy deposition cut:* Requires all muon candidate to have the following minimum values of deposited energy in the electromagnetic and hadronic calorimeter:

  $$E_{em} < 2 + 0.0115(p - 100)GeV \qquad E_{had} < 6 + 0.028(p - 100)GeV$$

  When a relativistic particle passes through matter, it ionizes the atoms or molecules it encounters, losing energy. The mean rate at which it loses its energy depends of the kind of particle it is and its momentum. If a particle loses a very small amount of energy through matter, it is called a minimum ionizing particle or MIP. Given that muons are MIPs, we expect their deposited energy to be low.

- *COT track quality cuts:* The COT is segmented into 8 super layers, alternating stereo and axial, with an angle difference of 2 degrees. Each super layer has 12 sense wires which detect passing particles. A minimum number of hits is required on each type of layer to ensure track quality.

  $$NAxialHits > 20 \qquad NStereoHits > 20$$

- $\chi^2 < 4$ *per degree of freedom:* This is a cut related to track reconstruction quality. χ^2 is the average deviation of a detected track hits from its reconstructed track. It is normalized over the COT resolution so that for a perfectly modeled track, the distribution for χ^2 would peak at $\chi^2 = 1$.

- *Distance to interaction point* $DZ0 < 5cm$*:* Reconstructed tracks of the particles are required to be close to the interaction point to ensure that they come from the collision.

- *Dimuon* $Pt > 15$ *GeV:* This requirement comes from the distribution observed in figure5 from generator level data.

- *Dimuon Isolation* < 0.1*:* This is another cut related to data quality. It is required that the energy coming from the muon pair in a part of the detector has a more significant value than energy coming from any other particle. Energy deposited by other particles in a defined area around the dimuon must not be greater than 0.1 of the total energy in that area.

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Figure 6. $\mu\mu\gamma$ invariant mass distribution in the data. The data in this histogram has passed all the previously mentioned selection cuts

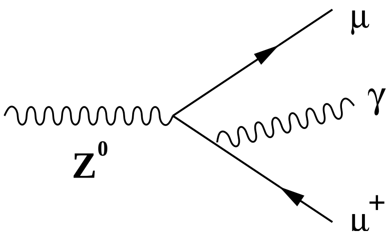

Figure 7. Example decay diagram.

The events in figure 6 have passed the selection cuts, however, there are still some that are shown in that histogram which are not of our interest. Figure 7 is an example of a decay that does not get filtered with any of the cuts applied to the data, so far. In order to filter out these background from the signal we want to look for, an additional selection cut was needed. With this purpose the 3 dimensional angle distribution for the dimuons was examined.
The histogram in figure 8 shows what is already implicit from the decay of the energetic Υ meson: The muons product of this decay are separated by a small angle. Based on this an extra requirement was decided upon:

- *3D angle between muons > 60 degrees:* This requirement is established due to the expected distribution for the angle of separation of the muons coming from the J/ψ or Υ decay.

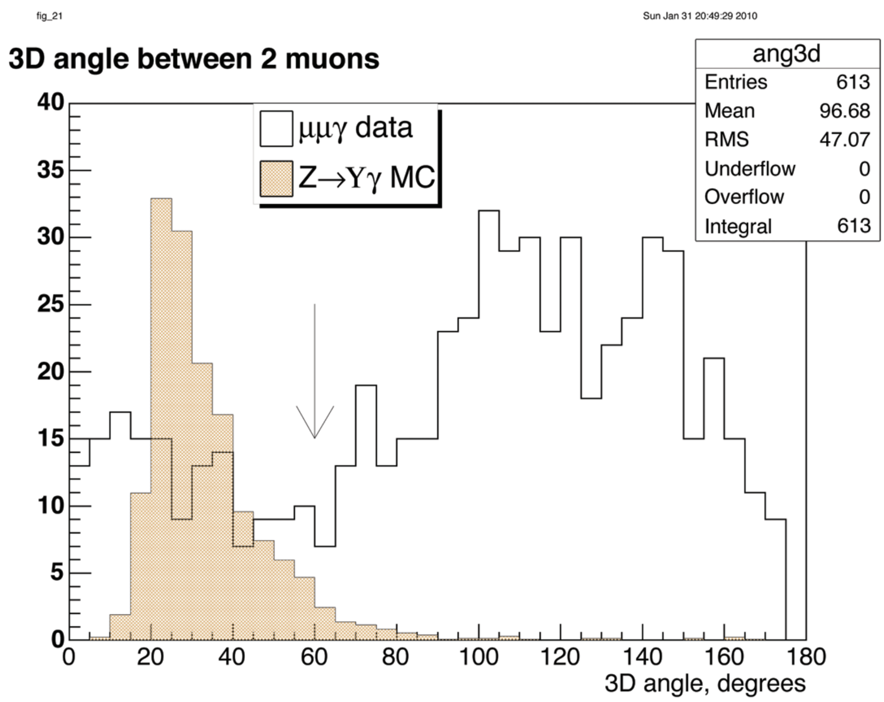

Figure 8. Angular distribution in 3D for the pairs of muons. Brown: $Z^0 \rightarrow \Upsilon\gamma$ MC. White: data.

2.3. Full Simulation

While the events generated by Pythia may describe the behavior of the particles, that alone does not give us enough information about the signal. With the geometry of the detector and the read out process involved it is hard to determine what percentage of the events generated in a collision will be lost with the cuts and what percentage will be lost in the detector. We use a full CDF detector simulation program to simulate and study the performance and efficiency of the detector. This helps us achieve a better understanding of our expected signal. The generated events by Pythia are run though a detector simulation. This introduces numerical boundary conditions of the detector to the data. It models the interaction of the particles with the detector. The output contains simulated digitized hits, as if that information was coming from the detector itself. This output is then run through the offline reconstruction code, as would be done with real detector data. The final result is a sample of simulated events with information given exactly as it would be for real events observed by the CDF detector.

The analysis code, which has in it the selection cuts, is then run in the MC (MonteCarlo) events. The outcome can be studied to observe the behavior of the expected signal in detail. After running this code in the MC for $Z^0 \to J/\psi\gamma$ and $Z^0 \to \Upsilon\gamma$ events, we looked into the reconstructed invariant mass distributions that is shown in figure 9:

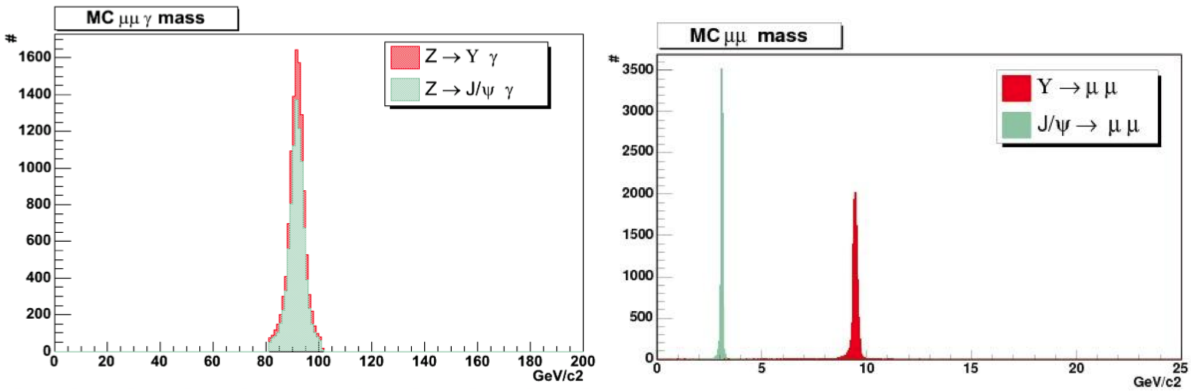

Figure 9. MC Events histograms. Left: $\mu\mu\gamma$ invariant mass distribution. Right: $\mu\mu$ invariant mass distribution. Green: $Z^0 \to J/\psi\gamma$ MC. Red: $Z^0 \to \Upsilon\gamma$ MC

The distributions in figure 9 show the mass peaks from the simulated data. These are the distributions that we must look for in the data; it is what our expected signal will look like if the decay is found.

2.4. Data

Once we had reached a better understanding of the expected signal and different distributions it was time to run the analysis code on real data. We analyzed the data coming from the detector in the same way we did for the MC simulations. We ran the analysis code on approximately 5 fb^{-1} of integrated luminosity. The results are shown on the following histograms.

The histogram in figure 10 shows how we found the Z mass peak in the data, reconstructed from the photon and the two muons. However, this is not enough to claim that this is indeed the final state of either the $Z^0 \to J/\psi\gamma$ or the $Z^0 \to \Upsilon\gamma$ decays. In order to do that we must confirm that the muon-antimuon pair are coming from either a J/ψ or an υ decay. The following histograms show the results for the expected distributions.

As we can see in figure 10, there is no strong evidence for the expected decays. We can also confirm, by the small amount of events in the region, that we are close to the experimental sensitivity for this decay. There is, however, one event which is found close to the J/ψ peak. Regardless of the analysis process

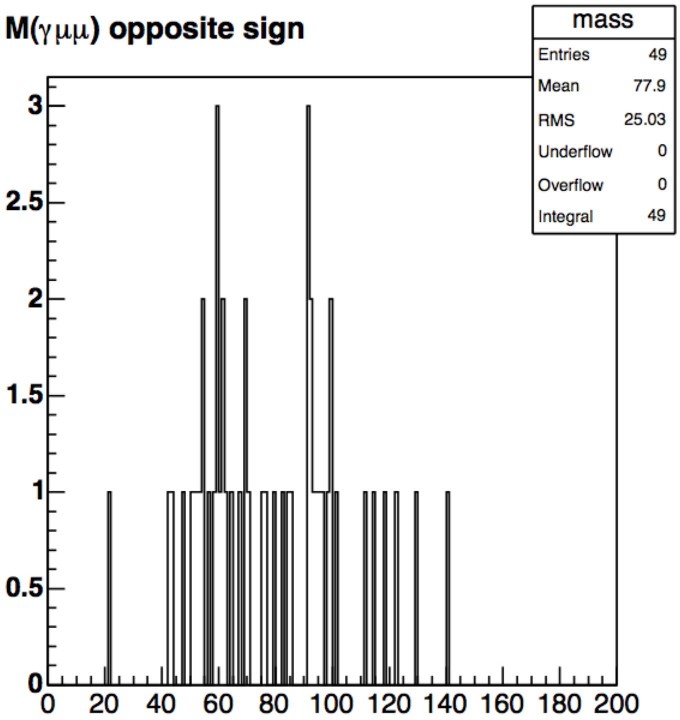

Figure 10. Final data $\mu\mu\gamma$ invariant mass distribution. This histogram shows the events that have met all requirements, including the 3D angle requirement.

that we have used in the data, more information is needed to establish whether or not this dimuon pair comes from a J/ψ decay.

2.4.1. Branching Ratio The following equation will be used for the branching ratio calculation:

$$N = L_{integ} \cdot \sigma_{p\bar{p}\to Z^0} \cdot B(Z^0 \to J/\psi + \gamma) \cdot B(J/\psi \to \mu^+\mu^-) \cdot A$$

$$\text{where } A = A_{MC} \cdot SF \quad \text{and} \quad SF = \frac{ID_{Eff\ Data}}{ID_{Eff_{MC}}}$$

N — Number of events with this decay
A — Acceptance
$L_i nteg$ — Integrated luminosity
SF — Scale factor
$\sigma_{p\bar{p}\to Z^0}$ — $p - \bar{p}$ to Z cross section
ID_{Eff} — Identification efficiency

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3. Future Work

We plan to complete the analysis using full statistics of approximately 10 fb^{-1} collected by the CDF experiment in Run II.

References

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