# Search for CP-Violation in $D^0 \rightarrow \pi^0 \pi^0 \pi^0$ Decays

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NSF Research Experience for Undergraduates
2001

## Abstract:

I have searched for a CP violating asymmetry in the neutral charm meson decay of $D^0 \rightarrow \pi^0 \pi^0 \pi^0$. I present here a brief description of CP violation and the CLEO II.V detector, the methods used to conduct this search, and the initial measured branching ratio of the studied decay, as well as the initial measured asymmetry of the final state of the decay.

## Background information:

Symmetries and their conservation laws form, together with elementary particles and their interactions, the basis of the fundamental physical description of nature. Until approximately 1956 it was assumed that the laws of physics remained unchanged when one changes the sign of spatial coordinates (i.e. changing x, y, or z into –x, -y, or –z) in a given system. This mirroring is called the parity operation P. However, C.S. Wu observed that the mirror image of the left-handed neutrino, the right-handed neutrino, does not exist and that therefore the symmetry of the weak interaction is broken by the P operation [1]. The symmetry is restored when the P operator is not applied alone, but when the combined operation CP is applied. C, charge conjugation, is the operation that transforms a particle into its anti-particle. CP transformation changes a left-handed neutrino into a right-handed anti-neutrino, which does exist.

In 1964, a symmetry violation of the CP-transformation was observed by James Cronin and Val Fitch in the case of the neutral K-meson at a level of 0.2% [2]. Since then precise measurements have taken place to determine the origin of CP violation in the K-meson system. However, the K-meson effects due to the strong interaction are too large to draw any definitive conclusions about the origin of CP violation. Thus finding and studying CP violating decays of other mesons is important to better understand this phenomenon.

An interesting side note on the subject of CP violation is that it is considered a leading idea in the explanation of the baryon asymmetry in the universe, that is, why our universe contains more matter than antimatter.

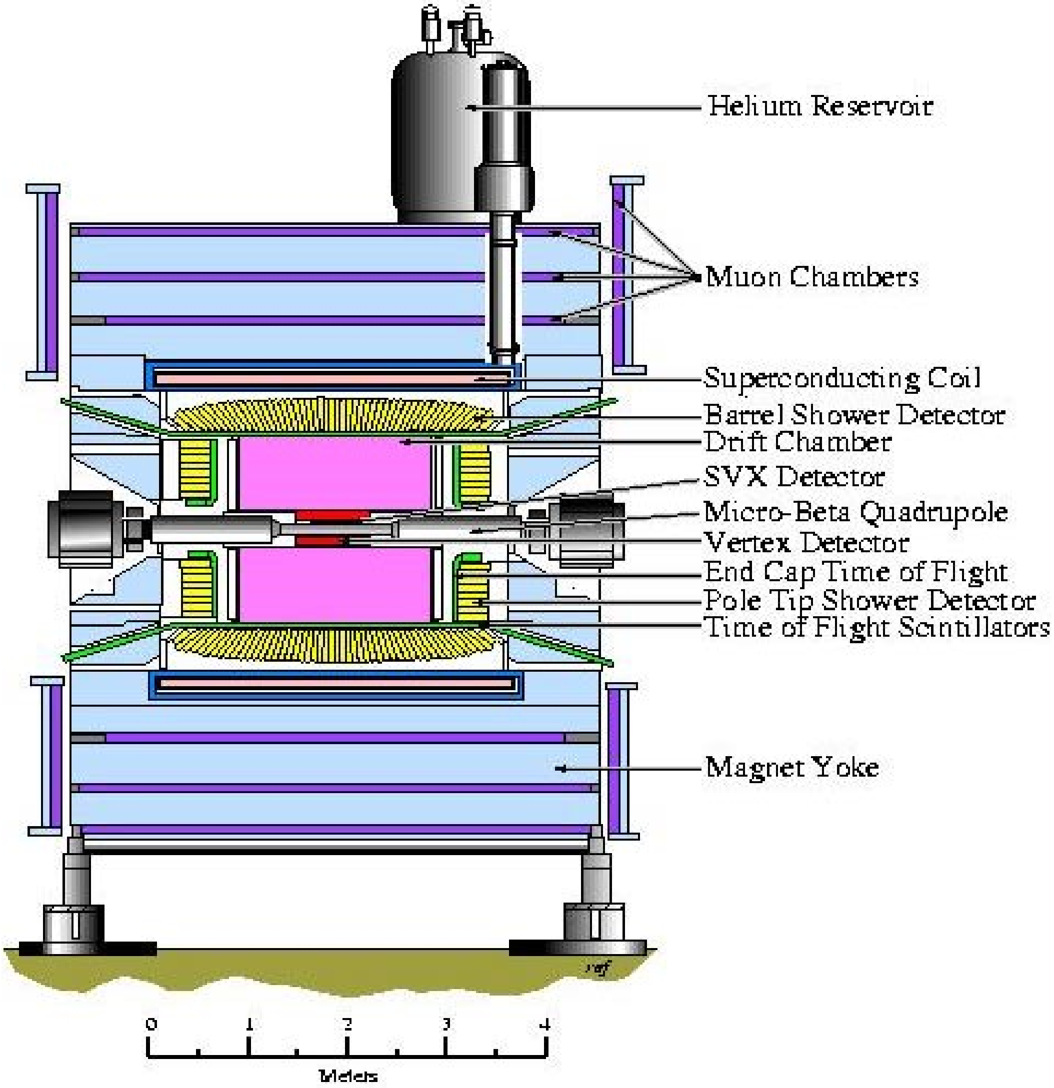
The decay that I studied is of interest because no one has ever looked for it, meaning any results I find are the first evidence of this decay occurring. Another interesting aspect of this decay is due to the fact that the $\pi^0$ is its own antiparticle, so the decay of $D^0$ (composed of $c\overline{u}$ quarks) to three $\pi^0$s should happen exactly the same amount of time as the decay of $\overline{D}^0$ (composed of $u\overline{c}$ quarks) to three $\pi^0$s. Thus, if CP violation occurred the branching ratio of $D^0$ to three $\pi^0$s would NOT equal the branching ratio of $\overline{D}^0$ to three $\pi^0$s.

## The CLEO II.V detector:

The Cleo II.V detector is used at the Cornell Electron Storage Ring (CESR). CESR is a ring in which an electron beam is circulated in one direction and a positron beam is circulated in the opposite direction. The beams are kept on a circular path by magnets. After reaching a certain energy, the electrons and positrons collide inside the CLEO detector and the energy caused by their annihilation creates different particles. The

CLEO detector is a multipurpose high energy physics detector incorporating charged and neutral particle detection and measurement, used to analyze electron-positron collision events generated by CESR. The detector itself is about 6 meters on a side, containing about 900,000 kilograms of iron and over 25,000 individual detection elements [3]. A picture of a side cross-section of the detector is shown in Figure 1, with the electron-positron beam passing through the center of the detector in the plane of the figure.

**Figure 1: the CLEO II.V detector**



Methods:

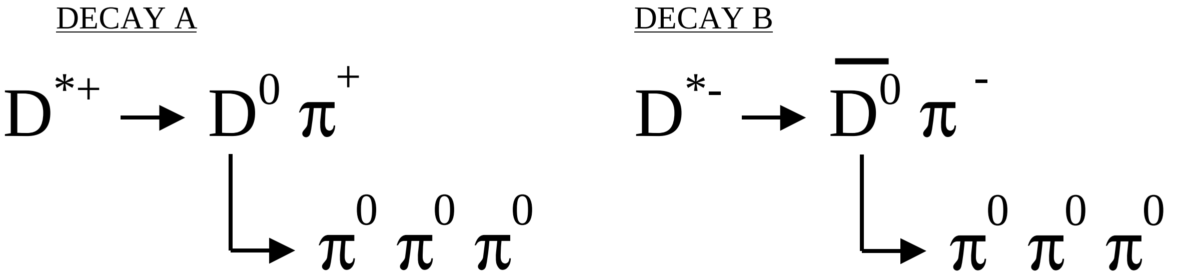
There are several steps to complete in order to look for CP violation in a decay mode. These steps are: 1. Writing (or modifying) a computer program that reconstructs the decays and extracts the data; 2. Using that program on Monte Carlo simulated data; 3. Using that program on real data taken from the CLEO detector; and 4. Comparing the branching ratio of the decay of the particle to the branching ratio of the decay of the anti-particle. I have completed the first three of these steps and have done initial calculations of the fourth step this summer, and I describe them in more detail below.

Step one: Writing code in FORTRAN

To begin, a computer program must be created that will collect the desired data and present it in a way that can be analyzed. I modified a program written in FORTRAN 77 to reconstruct the decays I was studying. Charge conjugation is implied throughout unless explicitly stated otherwise. In order to reconstruct these decays, I had to select photons that came from $\pi^0$s. I placed certain requirements (or "cuts") on what the code should accept as a photon. These cuts are designed to remove photons which may have come from particles similar to $\pi^0$s, but which are not. One cut was that the mass of the particle formed by the di-photon combination had to be within 2.5 standard deviations from the nominal $\pi^0$ mass of 135 MeV/$c^2$ [4]. Another cut required that one of the two photons from which the particles were built had to lie within the main section of the detector. The accepted pions were then kinematically combined to form the $D^0$ candidates. Cuts are placed on the $D^0$ later on, but not at this point because we want to test what sort of features all the $D^0$

candidates exhibit and to know how many $D^0$s are found. There is another step to the reconstruction process, namely finding out whether the $\pi^0$ s came from a $D^0$ or a $\overline{D}^0$. We do this by requiring the $D^0$s to have occurred in the decay chain $D^*$-> $D^0$ $\pi_{slow}$ . Measuring the charge of the slow pion produced in the decay will identify the flavor of the meson (either a $D^0$ or a $\overline{D}^0$). If the pion is a $\pi^+$ we have a $D^0$, which came from a $D^{*+}$. If the pion is a $\pi^-$ we have a $\overline{D}^0$, which came from a $D^{*-}$. The decay processes are shown in figure 2.

Figure 2: A $D^*$ decays into a $D^0$ and a pion, and the $D^0$ then decays into three neutral pions. If CP symmetry is conserved, decays A and B should happen in equal amounts.



Step two: Using code on Monte Carlo simulated data

Before being able to use the code on real data from the CLEO detector, the code must be used on simulated data to test the efficiency of the code. First, a dataset is created where all decays are of the mode being studied; this is called “signal” Monte Carlo. Thus, if the code and the detector are both 100% efficient (which they aren’t), all the decays should be measured. Out of 1000 signal events created, my code measured 82 events, which means that the efficiency of my code is approximately 8%. This efficiency is used when calculating the branching ratio of the decay. Figure 3 shows the mass difference between the $D^*$ and the $D^0$ fit to a gaussian curve. The area under the curve within three standard deviations from the mean (1.865 GeV/$c^2$ [4]) is equal to the number of events registered.

Signal Monte Carlo is important to calculate the efficiency of the code, but it doesn't reflect what the actual data from the detector will look like, since the branching ratios have been set to go to the decay mode being studied 100% of the time. So it is necessary to look at "generic" Monte Carlo, which will more accurately depict what is expected to be seen in the data. In generic Monte Carlo, it is much more difficult to see a peak where it is expected because there are other events besides the desired events picked up by the code. Generic Monte Carlo is used to determine which cuts will eliminate the most background (events which aren't the events being studied), while keeping the most signal (events which are the events being studied). Cuts that I found to be the most effective are shown in Table 1. In generic Monte Carlo, I fit the mass difference between $D^*$ and $D^0$ to a gaussian curve, and define the signal region to be within 3 standard deviations of the actual mass difference of 0.1454 GeV/$c^2$ [4]. Figure 4 shows the generic Monte Carlo data before the cuts were applied, and Figure 5 shows the same data after the cuts were applied.

**Table 1: Cuts used for extracting the signal**

| Quantity | $\pi^0$ | $D^0$ | $D^*$ | $\pi_{soft}$ |
|---|---|---|---|---|
| Mass ($GeV/c^2$) | [.1349, .1351] | [1.80, 1.93] | | |
| Momentum (GeV/c) | > 0.25 | > 2.0 | > 2.5 | >0.095 |

### Step three: Using the program on actual data

Once the data has been studied in generic Monte Carlo, the next step is to look through actual data. I ran my program on 2.21 $fb^{-1}$ of data taken from the CLEO II.V detector at a center of mass energy of 10.58 GeV. Applying the cuts I chose from my analysis of the generic Monte Carlo data, I was able to see a signal in the real data. Figure 6 shows the peak in the mass difference between $D^{*+}$ and $D^0$. The background was fit to a third order Chebyshev polynomial, and the signal was fit to a gaussian curve with the sigma set by that found in the fit of the generic Monte Carlo data. The area of the gaussian is approximately 105 +/- 25 events. This signal is the first observed evidence of the $D^0$ to $\pi^0\pi^0\pi^0$ decay. Figure 7 shows the peak in the mass difference between $D^{*-}$ and $\overline{D}^0$. The area of the gaussian for this decay is approximately 93 +/- 23 events.

### Step four: Calculating the branching ratio

Once a signal has been found in actual data, it is possible to calculate a rough estimate of the branching ratio. The branching ratio of this decay is defined as the number of $D^0$s that decay to three $\pi^0$ s divided by the total number of $D^0$s, or

$$BranchingRatio = \frac{N(D^0 \rightarrow \pi^0\pi^0\pi^0)}{N(totalD^0)}.$$

This number must also be multiplied by the efficiency of my code, which was found from the signal Monte Carlo. The total number of $D^0$s is defined to be the total number of events times the percent of events that involve charm quarks times the percent of events with charm that create a $D^{*+}$times the branching ratio of $D^{*+}$-> $D^0 \pi^+$. Thus the expression of the branching ratio of $D^0$ -> 3 $\pi^0$s becomes:

$$BranchingRatio = \frac{N(D^0 \rightarrow \pi^0\pi^0\pi^0)}{efficiency * totalevents * \%charmevents * charmeventsw/D^* * BR(D*^+ \rightarrow D^0\pi^+)}$$

The number of $D^0$ -> $\pi^0$ $\pi^0$ $\pi^0$ is taken from the signal region of the data, 105. The percent of events with charm is known to be approximately 40% and the percent of charm events involving a $D^*$ was calculated with generic Monte Carlo to be 20%, and the branching ratio of $D^{*+}$ to $D^0$ and a pion is known to be 68%. Using these numbers, the branching ratio is calculated to be 0.13%. A similar calculation was done for the $\overline{D}^0$, and the branching ratio was found to be 0.11%. Please note that these are very rough estimates, and to be entirely accurate the branching ratios would be calculated by comparing the efficiency of the code to detect $D^0$ to three $\pi^0$s to the efficiency of the code to detect $D^0$ to a decay such as $K^-$ $\pi^+$, whose branching ratio is known. To compare the asymmetry of the decay rates, a simple calculation is done. The asymmetry, A, is defined as

$$A = \frac{N(D^0 \rightarrow \pi^0\pi^0\pi^0) + N(D^0 \rightarrow \pi^0\pi^0\pi^0)}{N(D^0 \rightarrow \pi^0\pi^0\pi^0) - N(D^0 \rightarrow \pi^0\pi^0\pi^0)}.$$

The asymmetry calculated from the data is .06 +/- 0.17. This result indicates that no CP violation has occurred in this decay.

## Conclusion / Future Work

To reiterate, the branching ratio of $D^0$ to 3 $\pi^0$s has been initially calculated to be roughly 0.18%, and $\overline{D^0}$ to 3$\pi^0$s 0.16%. These numbers were calculated by first designing a code that recreated these decays, and that code ran on both simulated data and actual data. A rough calculation of the asymmetry of this decay indicates that the decay is not CP violating. Further analysis should be conducted to reduce error on these calculations. As well, other decay modes that produce a final result of 3 $\pi^0$s should be studied in order to find cuts that will eliminate the possibility that these decays are being classified as signal events.

## Acknowledgements

I would like to thank the National Science Foundation for funding the Research Experience for Undergraduates program, Tom Lemberger and William Palmer for putting on a great program this summer, Shirley Royer for collecting all my mail, and Tom Kelch for his help in the machine shop. I would also like to give a special thanks to my advisor Richard Kass and graduate students Chul Gwon and Terry Hart for all their help.

Glossary:

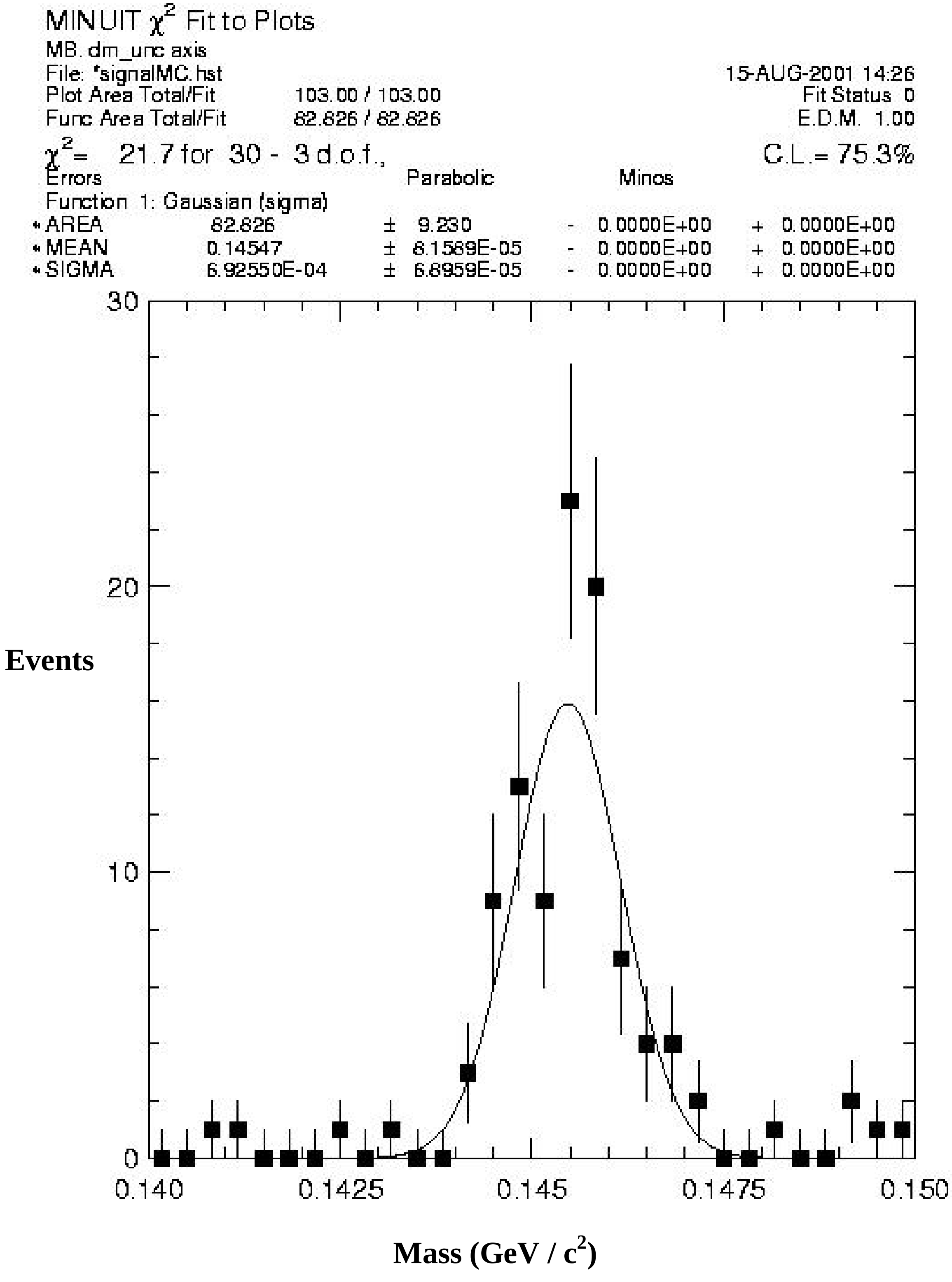
Antiparticles: Particles predicted by combining the theories of special relativity and quantum mechanics. For each particle, there must exist an antiparticle with the opposite charge, magnetic moment and other internal quantum numbers (e.g. lepton number, baryon number, strangeness, etc.) but with the same mass, spin, and lifetime. Note that some neutral particles, like the $\pi^0$, are their own antiparticle.

Charge Conjugation Symmetry: Charge Conjugation is the operation that turns particles into antiparticles. This symmetry implies that if physical laws predict the behavior of a set of particles, then they will predict exactly the same behavior for the corresponding set of antiparticles.

Monte Carlo: Monte Carlo simulations play a very important role in high-energy physics; they are used as a means of understanding how the detector responds to particular processes. There are two types of Monte Carlo used in analysis: signal and generic. Signal Monte Carlo is simulated data in which only certain decays occur (usually those which you wish to study), while in generic Monte Carlo all decays that are known to us occur.

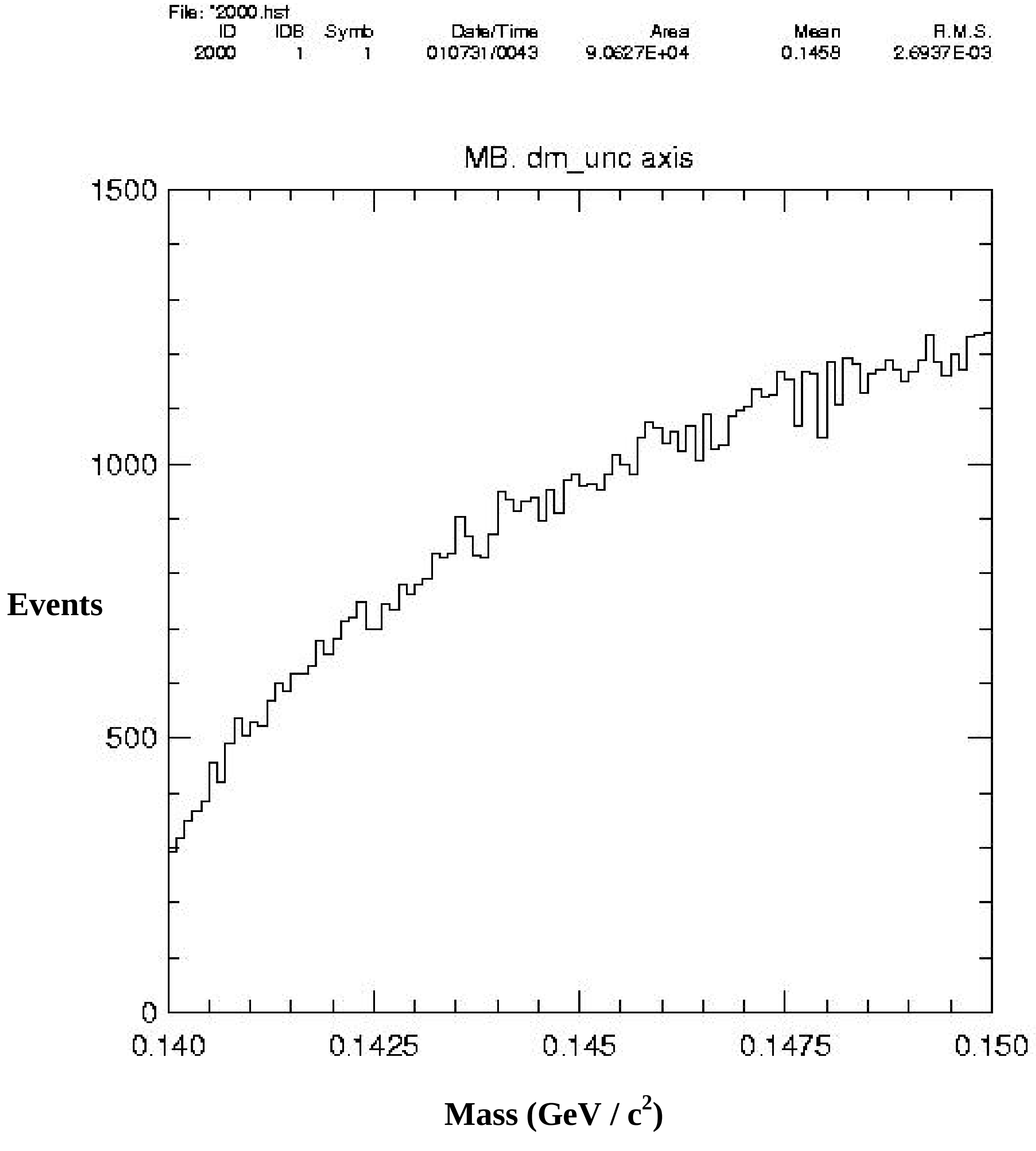
Parity: The operation which reverses the signs of the coordinate axes used to describe a system, i.e. (x, y, z) -> (-x, -y, -z)

## Figure 3: Mass Difference, Signal MC

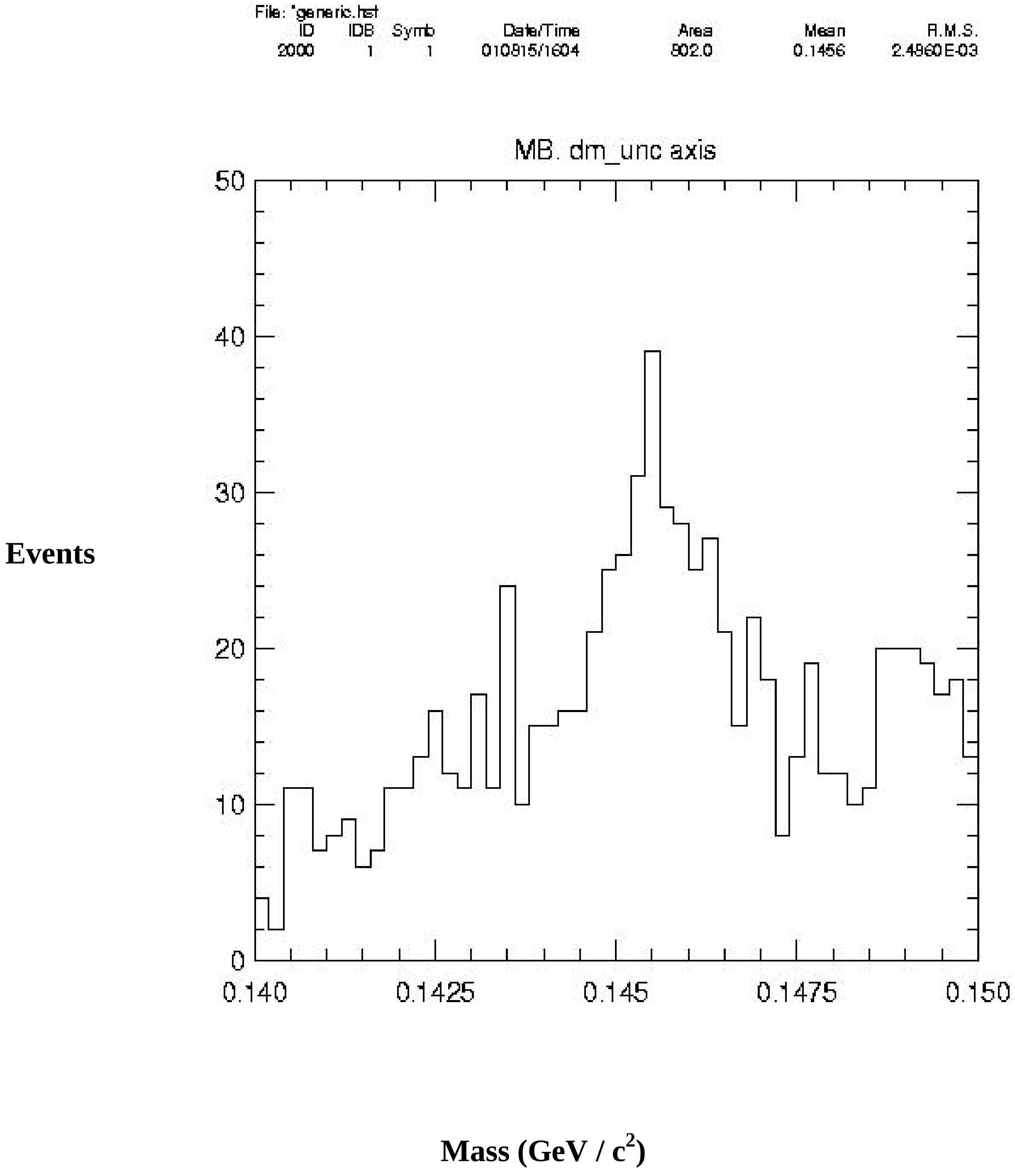


```
MINUIT χ² Fit to Plots
MB. dm_unc axis
File: *signalMC.hst                                              15-AUG-2001 14:26
Plot Area Total/Fit        103.00 / 103.00                          Fit Status  0
Func Area Total/Fit        82.826 / 82.826                          E.D.M.  1.00
χ²=    21.7 for  30 -  3 d.o.f.,                                   C.L.= 75.3%
Errors                                  Parabolic              Minos
Function  1: Gaussian (sigma)
* AREA             82.826        ±   9.230          -   0.0000E+00    +  0.0000E+00
* MEAN             0.14547       ±  8.1589E-05      -   0.0000E+00    +  0.0000E+00
* SIGMA            6.92550E-04   ±  6.8959E-05      -   0.0000E+00    +  0.0000E+00
```

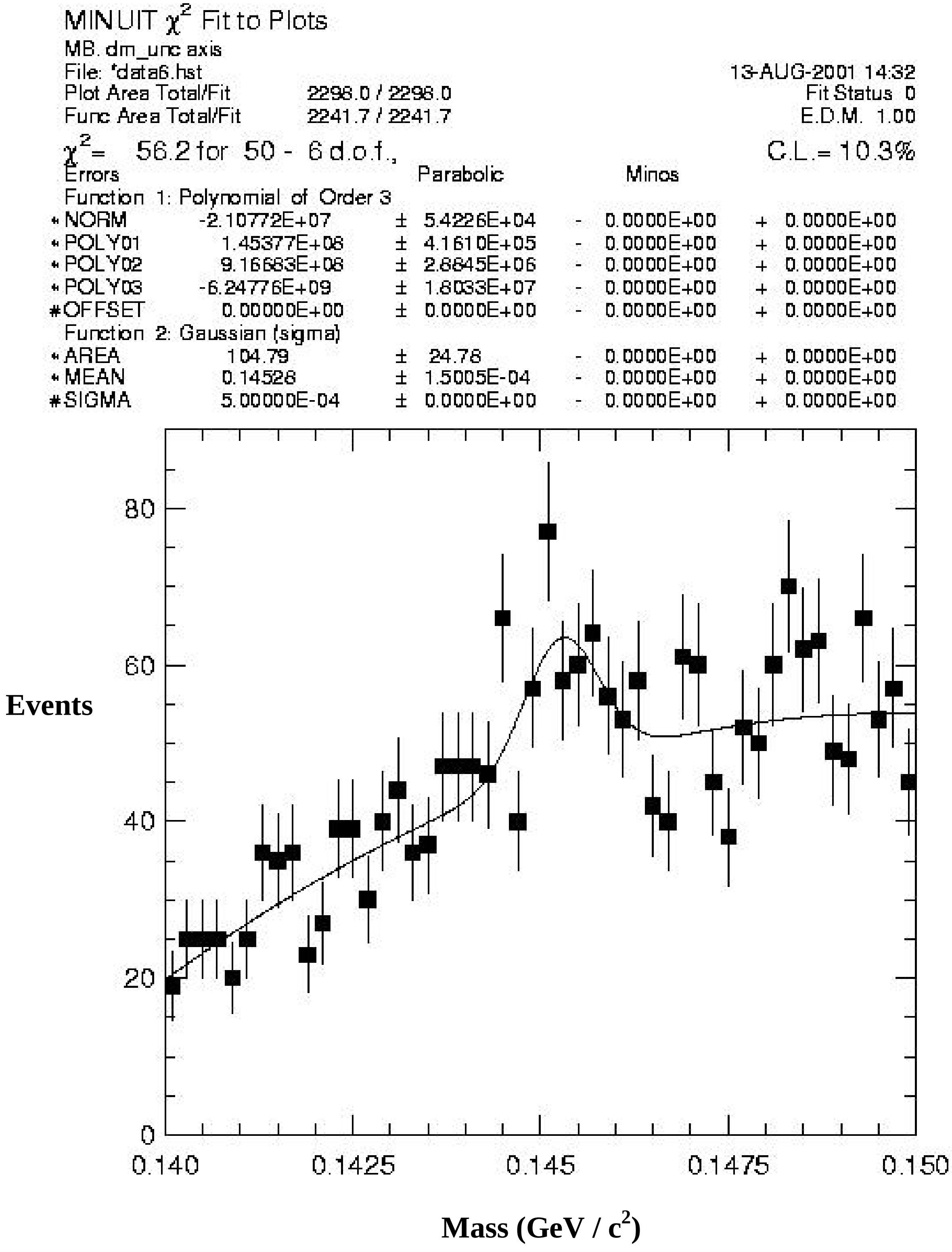
**Figure 4: Mass difference $D^{*+}$ - $D^0$, generic Monte Carlo, no cuts**



# Figure 5: Mass difference $D^{*+}$ - $D^0$, generic Monte Carlo, with cuts

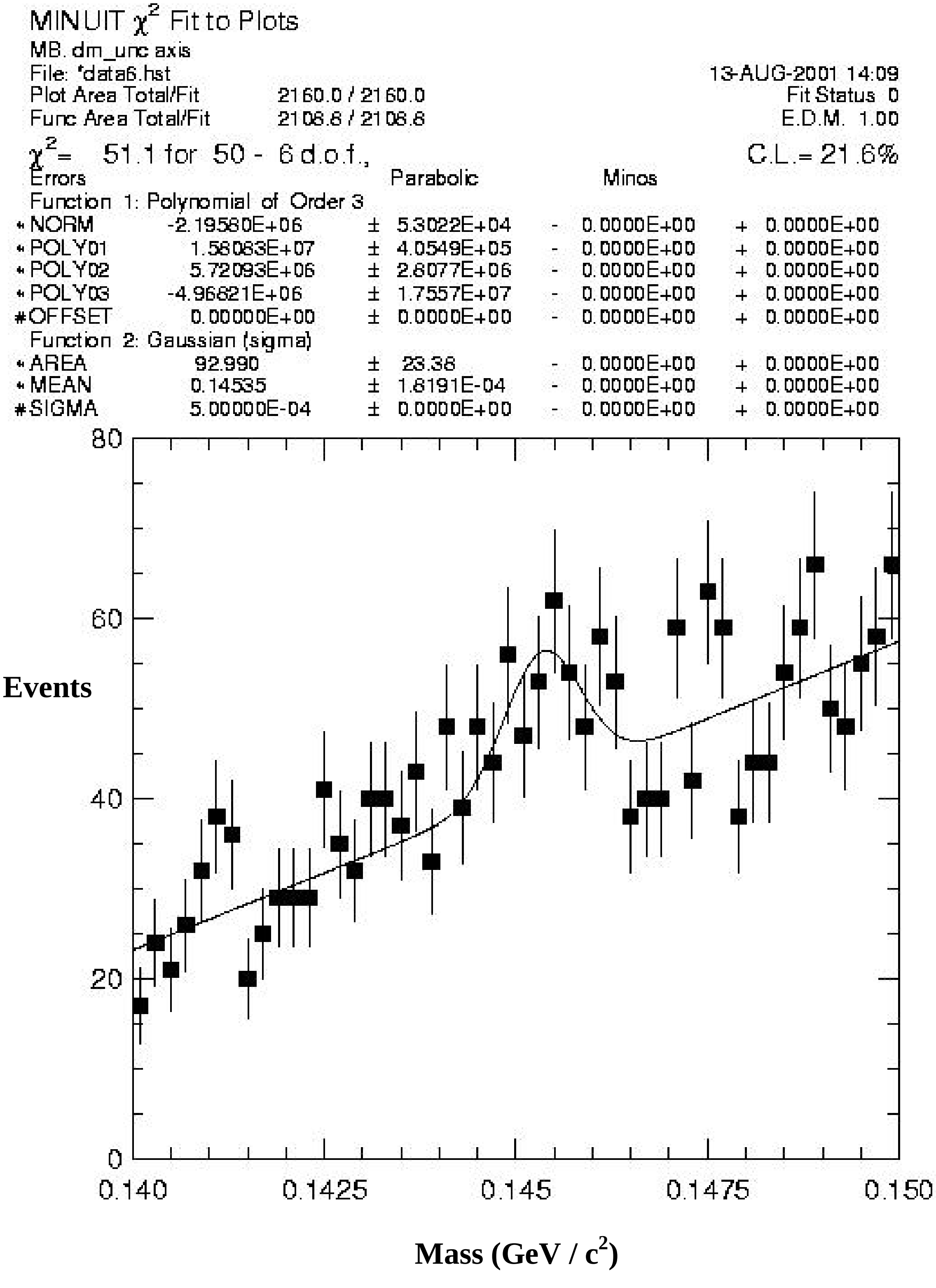


# Figure 6: Mass difference $D^{*+}$ - $D^0$, data



```
MINUIT χ² Fit to Plots
MB. dm_unc axis
File: *data6.hst                                                   13-AUG-2001 14:32
Plot Area Total/Fit        2298.0 / 2298.0                              Fit Status  0
Func Area Total/Fit        2241.7 / 2241.7                              E.D.M.  1.00
χ²=   56.2 for  50 -  6 d.o.f.,                                         C.L.= 10.3%
Errors                                Parabolic              Minos
Function  1: Polynomial  of  Order 3
*NORM        -2.10772E+07       ±  5.4226E+04    -   0.0000E+00     +  0.0000E+00
*POLY01       1.45377E+08       ±  4.1610E+05    -   0.0000E+00     +  0.0000E+00
*POLY02       9.16683E+08       ±  2.8845E+06    -   0.0000E+00     +  0.0000E+00
*POLY03      -6.24776E+09       ±  1.8033E+07    -   0.0000E+00     +  0.0000E+00
#OFFSET       0.00000E+00       ±  0.0000E+00    -   0.0000E+00     +  0.0000E+00
Function  2: Gaussian (sigma)
*AREA          104.79           ±   24.78        -   0.0000E+00     +  0.0000E+00
*MEAN         0.14528           ±  1.5005E-04    -   0.0000E+00     +  0.0000E+00
#SIGMA        5.00000E-04       ±  0.0000E+00    -   0.0000E+00     +  0.0000E+00
```

# Figure 7: Mass difference $D^{*-}$ - $\overline{D}^{0}$, data



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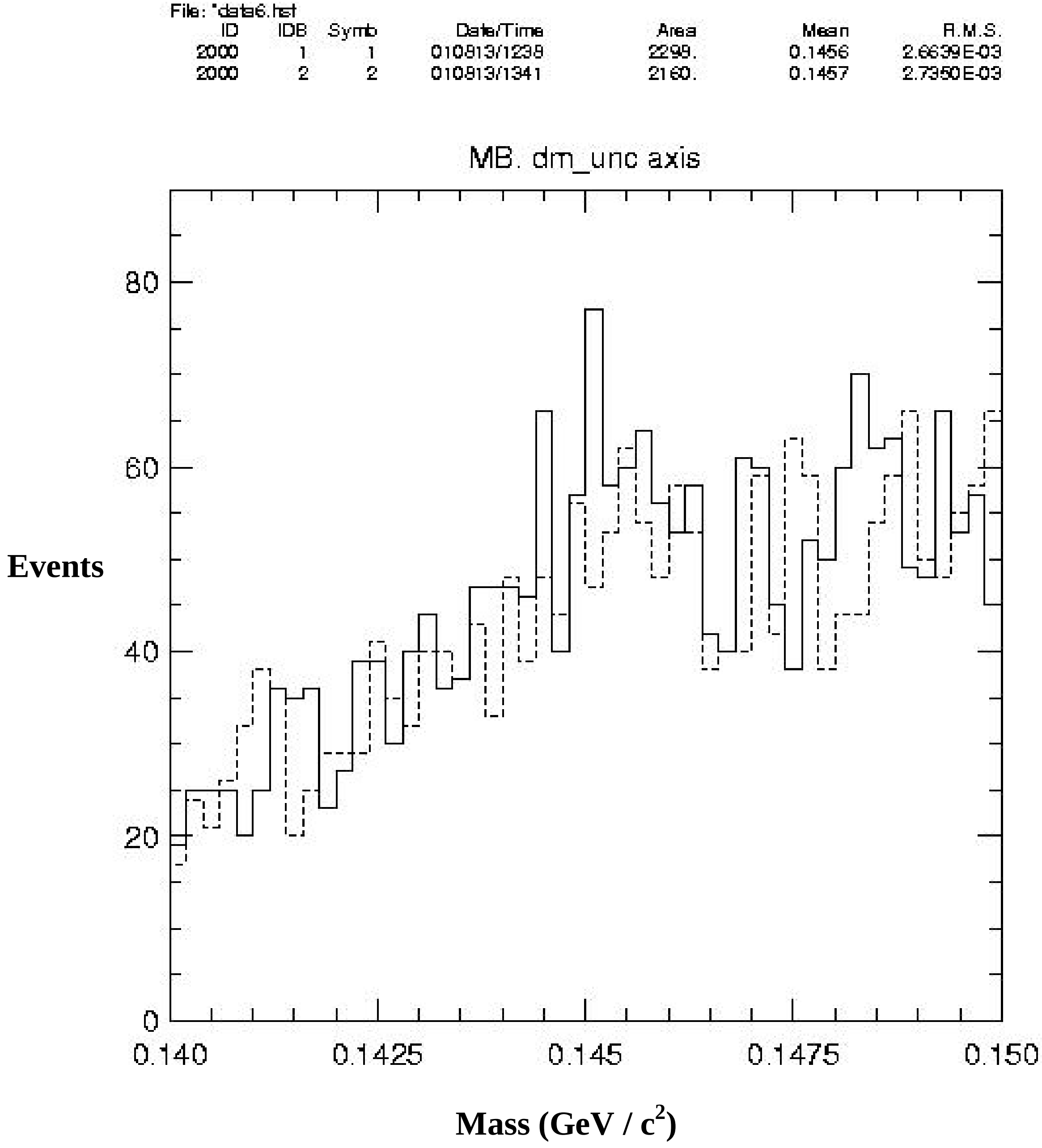
MINUIT χ² Fit to Plots
MB. dm_unc axis
File: *data6.hst                                                13-AUG-2001 14:09
Plot Area Total/Fit          2160.0 / 2160.0                         Fit Status  0
Func Area Total/Fit          2108.8 / 2108.8                         E.D.M.  1.00
χ²=    51.1 for  50 -  6 d.o.f.,                                  C.L.= 21.6%
Errors                                  Parabolic              Minos
Function  1: Polynomial  of  Order 3
*NORM       -2.19580E+06       ±  5.3022E+04    -   0.0000E+00    +  0.0000E+00
*POLY01       1.58083E+07      ±  4.0549E+05    -   0.0000E+00    +  0.0000E+00
*POLY02       5.72093E+06      ±  2.6077E+06    -   0.0000E+00    +  0.0000E+00
*POLY03      -4.96821E+06      ±  1.7557E+07    -   0.0000E+00    +  0.0000E+00
#OFFSET       0.00000E+00      ±  0.0000E+00    -   0.0000E+00    +  0.0000E+00
Function  2: Gaussian (sigma)
*AREA          92.990          ±   23.38        -   0.0000E+00    +  0.0000E+00
*MEAN          0.14535         ±  1.6191E-04    -   0.0000E+00    +  0.0000E+00
#SIGMA        5.00000E-04      ±  0.0000E+00    -   0.0000E+00    +  0.0000E+00
```

# Figure 8: Overlay of Mass Differences, data



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