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CHARM TAGGING IN HEAVY PARTICLES DECAYS AT SLC AND LEP: A LARGE WINDOW ON NEW PHYSICS[*]

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ABSTRACT

A new, high-efficiency technique for tagging charm quarks in heavy particle decays produced at the Z^o is described. This technique is based on inclusive $D^{\star\pm}$ counting, using the special kinematic properties of the decay $D^{\star\pm} \to \pi^{\pm}\ D^o$. The importance of charm tagging in the discovery and/or identification of new heavy particles such as a heavy quark or a Higgs boson is illustrated.

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1. Introduction

The discovery of a new particle is usually based on the detection of leptons in the final state. This has been the case since 1974 with the discovery of the J/ψ signal at Brookhaven, the τ lepton at SLAC, the Υ at Fermilab, and the $W^{\pm}$ and Z^{o} bosons at CERN. In the energy domain that will shortly be available with the onset of the new machines such as SLC, LEP and the Tevatron , it is certain that leptons will still dominate the search procedures. However, two problems may arise. First, in the case of a discovery of a new particle, lepton tagging may not be sufficient to pin down the exact nature of the new particle, since this signature is common to many hypothetical particles. A straightforward example would be the discovery of heavy, quark-like objects. Lepton analysis will not be sufficient to distinguish between a top quark and a fourth generation down-type quark (referred to here as b'). Second, some new particles do not decay significantly into leptons. This is the case in the Higgs sector, where a neutral Higgs may decay preferentially into $b\bar{b}$ or $c\bar{c}$ pairs and a charged Higgs into $b\bar{c}$ or $s\bar{c}$ pairs. Such Higgs particles may even prevent heavy quarks from decaying semileptonically. These examples clearly show that the tools necessary for discovering and/or identifying new particles must include efficient b and c quark tagging.

It is possible to take advantage of the B particles long lifetime to tag b events by counting the numbers of tracks with large impact parameter. This requires a powerful vertex detector close to the interaction point. Other methods are also possible, such as the identification of the b semileptonic decays, which requires good identification of leptons inside jets, or based on the somewhat larger mass of the b jets compared to lighter quarks. Although b tagging requires good detector performance, it will probably be operational in most of the future experiments.

On the other hand, a high-efficiency method to detect the presence of c quarks has not been proposed up to now. A new method is described below to solve this problem. This method requires the reconstruction of low momentum tracks and therefore is mainly suited to e^+e^- colliders. We will use, for the purpose of illustration, such a machine running at the Z^o peak, but the method can be used at much higher energies.

2. The Inclusive Tagging of Charm Quarks

The proposed method is an extension of a technique recently used by the HRS group on PEP data.[1] It is based on the fact that the $\pi^\pm$ involved in the decay $D^{\star\pm} \rightarrow \pi^\pm D^o$ (referred to as the bachelor $\pi^\pm$ in the following) has an especially small p_T relative to the charm jet production axis. This is due to the very small Q value of this decay, which produces a pion aligned with the $D^\star$ line of flight. Since the bachelor pion takes only a small fraction of the $D^\star$ momentum (around 7%), its mean p_T is around 30 MeV/c instead of the 300 MeV/c typical for the other stable particles.

To use this method, two quantities have to be measured for each track: its p_T relative to the local jet axis and z, the fraction of the jet momentum it carries. These two quantities are readily available in two-jet events where the jet axis is given by the overall thrust axis (or better by the thrust axis of the hemisphere opposite to the considered track, to avoid any bias) and the jet energy is simply given by the beam energy. To extend this method to heavy particle decay events, p_T has to be measured relative to a local thrust axis. Therefore, a clustering algorithm is required to separate the event into different jets. The thrust axis of each cluster can then be computed. The bachelor candidate track should not to be included in this computation, so as to avoid any bias towards low p_T. In contrast to two-jet events, the cluster momentum is not known exactly but it is possible to use the measured cluster energy. The accuracy of such a measurement depends on the detector capabilities, such as the presence of an hadronic calorimeter. Without an hadronic calorimeter, 70% of the cluster energy is detected on average. However, the smearing introduced by this measurement is not critical and only leads to a small loss of efficiency. Therefore, this method is readily applicable to multi-jet events and does not require a very sophisticated detector.

The Mark II analysis system was employed for this study. Monte Carlo events have been generated using LUND 6.1 computer code with symmetric fragmentation and have been digitized using the Mark II detector in its SLC configuration.[2] The events have then been reconstructed using the analysis chain employed for real data. Since this detector simulation has already been checked with real data taken at PEP, we are confident that the different effects introduced by the event reconstruction are properly taken into account. The efficiencies given here reflect the Mark II detector geometry but are typical of the other LEP/SLC detectors.

We have considered samples of 10,000 Z^o, typical of an early SLC run, to 1,000,000 Z^o typical of a year of data taking at LEP.

Figure 1 shows, as an example, the p_T distribution obtained in the case of a b' quark decay. p_T^2 is used as the variable with a vertical logarithmic scale, to transform the expected gaussian distributions into straight lines. One can readily see the peak at low p_T. To demonstrate that this peak is indeed solely due to $D^\star$ production, the p_T distribution for tracks not coming from a $D^\star$ is also shown by the histogram on Fig.1. No peak at low p_T is observed and the distribution is well described by a straight line, corresponding to a gaussian of $\sigma = 300$ MeV/c. The hatched histogram corresponds to all the tracks indeed coming from a D^*, and can be fitted by a straight line with a corresponding σ of 30 MeV/c.

To extract from the experimental distribution the number of produced D^*, a fit with two Gaussians is performed. The width of the Gaussian corresponding to the $D^\star$ signal is fixed to the value measured above, while the other width is left free to take into account the effect of possible kinematical biases. This straightforward background subtraction is a great advantage over the difficult estimate of the background associated to non-isolated leptons. The detector performances needed to use our method successfully are also much less stringent.

The momentum spectrum of the bachelor pions is also distinctive. When the $D^\star$ are produced from the fragmentation of a c quark, their fragmentation function is peaked around 60% of the quark momentum. As a consequence, the bachelor pions fragmentation function is peaked around 4.5% of the quark momentum, which corresponds approximately to 6% of the visible energy, as shown in Fig. 2. Therefore, the p_T distribution can be studied only for tracks in a narrow momentum region in order to improve the signal-to-noise ratio. This cut is also useful to reject $D^\star$ coming from b decays since these $D^\star$ are slower than primarily produced ones. ($D^\star$ coming from b decays are also suppressed because of the large p_T of the B meson decay.)

3. Some Possible Scenarios

In this chapter, we will illustrate the usefulness of c tagging for the discovery of new heavy quarks or Higgs bosons.

3.1 HEAVY QUARK DECAYS

- b' decays

The c quark tagging technique will be important in the search for heavy quark decays because a b' quark will have a very large branching ratio into a c jet plus a W, leading to copious production of energetic $D^\star$'s.

To suppress $D^\star$ production coming from $c\bar{c}$ events, the thrust is required to be less than 0.9. To reduce the background, candidate bachelor pions are required to have a z between 0.04 and 0.08. The resulting p_T^2 distribution is plotted in Fig. 3 for a sample of 10,000 Z^o decays containing 500 pairs of a 45 GeV b' quark. The mass of the b' quark fixes the production rate but does not affect the p_T distribution. Therefore, this example is an extreme one, because the heavy quark mass is quite close to the threshold, i.e., $\frac{m_{Z^o}}{2}$. A very clear signal of about 100 $D^\star$ can be seen, where no peak is seen on the udscb sample distribution corresponding to the histogram in Fig.3.

The anomalous charm production caused by the decay of a 45 GeV b' quark can be clearly detected even with only 10,000 Z^o decays. This result holds true even in the presence of a charged Higgs boson,which could suppress the semileptonic decays of the heavy quark if the main decay mode was to be $b' \rightarrow c + H^-$.

The yield of the observed $D^\star$ can be related to the mass of the b' quark and thus provide an indirect mass measurement. This method is valuable for quark masses very close to the threshold where direct mass measurements are more difficult to perform.

The search for exclusive $D^\star$ reconstruction can also be very useful in this matter. In the case of a semileptonic b' quark decay where both the $D^\star$ and the lepton have been reconstructed, the b' quark mass can be computed without combinatorial ambiguity[♯1] by taking advantage of the sign correlation between the lepton and the $D^\star$. Two masses can be computed for each event, one for the semileptonic side and the other for the hadronic side. For 10,000 Z^o, ten exclusive $D^\star$ can be reconstructed, using the following decay channels $D^{\star +} \rightarrow \pi^+ + D^o$ and $D^o \rightarrow K^-\pi^+$, $D^o \rightarrow K^-\pi^+\pi^0$ or $D^o \rightarrow K^-\pi^+\pi^+\pi^-$. The mass difference between the $D^\star$ and the D^o candidates for the $K\pi$ decay mode is plotted in Fig. 4. With the thrust cut of 0.8 and the z cut of $z > 0.6$ used in this analysis, the background from udscb is one event. Among those ten candidates, a few can be expected to be associated with a detected semileptonic decay. With such low statistics, this mass measurement can only be suggestive; however, for a modest LEP/SLC data set of 100,000 Z^o decays, this method will be quite useful. Another possible application of the exclusive technique will be to provide information on the b' lifetime. It will be possible to measure the lifetime of the reconstructed D^o and find if it is longer than the normal D^o lifetime.

- top decays

[♯1] Wrong sign correlations can occur when the $D^\star$ comes from a W decay, but this contribution is only of the order of 20%.

In the case of top decays, c quarks are not produced in the primary decay. However, c quarks are produced in virtual W decays (or in charged Higgs decays if the decay mode top $\rightarrow$ b + H^+ happens to exist). The kinematic properties of those c jets are not very different from the ones directly produced in b' decays and, therefore, the detection efficiency of the $D^\star$ will be approximately the same as before. The detected $D^\star$ yield for a top decay will be three times smaller than for a b' decay because of the W branching ratio into $s\bar{c}$. This difference is a very powerful way to distinguish the two heavy quarks. The discovery of a top quark using this method will be difficult and b tagging techniques are clearly more appropriate, but the $D^\star$ tagging method will provide important confirmation about its true nature. In summary, the c tagging method can be used to discover a b' quark and distinguish it from a top quark in the whole kinematic range opened by Z^o decays.

3.2 HIGGS DECAYS

Charm tagging may even be more important in the search for an Higgs decay because it is possible that there will be no isolated lepton signature available. For Higgs masses above 10 GeV, a large branching ratio to $b\bar{b}$ is generally expected since Higgs coupling to fermions is proportional to the square of the fermion mass. Therefore b tagging is expected to be the principal tool in the search for Higgs decays. However, there are some important cases where even large mass Higgs do not couple to b quarks. The first example is a charged Higgs which could decay only to $s\bar{c}$. (In the $b\bar{c}$ decay mode, it is clear that both methods can be used.) The second concerns some non minimal Higgs models[3] in which a particular Higgs can only couple to fermions of a given weak isospin. It is therefore possible to construct an Higgs model in which a heavy Higgs decays dominantly to $c\bar{c}$.

Thus motivated, we have chosen to use in the different examples a 100% branching ratio into charm. If, in practice, this branching ratio turns out to be small, it would just mean that the Higgs particles would couple to beauty and would be detected with b tagging techniques. Our examples are applicable in the domain where the b tagging method fails.

We have run the same analysis program used for the heavy quark search. The table below specifies the observed $D^\star$ yield for each different model and the discovery threshold, that is the minimum branching ratio Br($Z^o \rightarrow$ Higgs) × Br (Higgs $\rightarrow c + X$) needed to see a 3 σ effect for a given sample.

Table 1. Discovery thresholds (DT) for various Higgs models.

Model	# of observed D^* per 1000 events	DT for 10,000 Z^o	DT for 100,000 Z^o	DT for 1 M Z^o
b' quark	212 ± 25	3.5%	1%	0.3%
$Z^o \rightarrow H^0_2 + H^0_3; H^0_2 \rightarrow H^0_3 + H^0_3$ $H^0_3 \rightarrow c\bar{c}$	327 ± 31	2.3%	0.7%	0.2%
$Z^o \rightarrow H^0_2 + H^0_3; H^0_2 \rightarrow b\bar{b}$ $H^0_3 \rightarrow c\bar{c}$	154 ± 32	4.8%	1.6%	0.5%
$Z^o \rightarrow H^+ + H^-; H^- \rightarrow s\bar{c}$	155 ± 32	4.8%	1.6%	0.5%
$Z^o \rightarrow H^0 + Z^{o*}; H^0 \rightarrow c\bar{c}$	180 ± 33	4.1%	1.4%	0.4%

For all our examples, the discovery threshold is reached with a very reasonable number of Z^o decays, if one assumes that the Higgs branching ratio to the Z^o lies in a few percent range as predicted by most models.

In some cases, like the search for the charged Higgs, other methods such as four-jet analysis[4] may be more sensitive.

It has to be pointed out also that the results quoted in Table 1 have been obtained using the same cuts for all the different cases. This means that it is possible to be sensitive to a very large variety of sources of anomalous charm production. Some of the quoted results can be improved by a more specific search, such as a more stringent thrust cut in the b' case.

It is clear that the observation of an anomalous charm production is not enough to prove the existence of an Higgs boson and to discriminate among possible scenarios. A detailed strategy to obtain this result is beyond our scope; however, we can indicate some general ideas. The coexistence of an anomalous charm production and of an isolated lepton signal will generally tag an heavy quark decay.[5] The jet multiplicity associated with the charm production will shed some light on the charm production mechanism. Mass reconstruction techniques can then be used to measure the Higgs mass, using the clusters in which a bachelor candidate has been found. Finally, the exclusive reconstruction of several D^* s will provide an almost pure sample of the exotic events, which can be studied in great detail.

4. Conclusion

We have developed a new and efficient method for charm tagging in heavy particle decays. A systematic search for anomalous charm production can then be performed to discover or to identify new particles. This method is particularly interesting in the search for heavy quarks or Higgs bosons. The discovery threshold for these particles can be reached with a small Z^o sample of 10,000 events.

5. Acknowledgements

I would like to thank A. Snyder for introducing me to this charm tagging method, T. Barklow for numerous discussions and for encouraging me to write this article and the Mark II Mock Data Analysis Group,[5] in which this work was originally started.

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FIGURE CAPTIONS

1. p_T^2 distribution for bachelor candidates (data points) obtained in the decay of a 45 GeV b' quark. The solid histogram corresponds to candidates not coming from a $D^\star$ and the hatched histogram to candidates coming from a D^*. The solid line is a fit to the data with two Gaussians (see text).

2. z distribution for bachelor pions from $D^\star$ decays.

3. p_T^2 distribution for bachelor candidates (data points) obtained in 10,000 Z^o decays containing 500 $b'\bar{b}'$ events. The histogram corresponds to only normal Z^o decays (udscb). The solid line corresponds to the fit of two Gaussians to the total sample.

4. $\Delta m = K^-\pi^+ \pi^+ - K^-\pi^+$ distribution when the $K^-\pi^+$ mass is between 1.8 and 1.92 GeV, obtained in 10,000 Z^o decays containing 500 $b'\bar{b}'$ events.

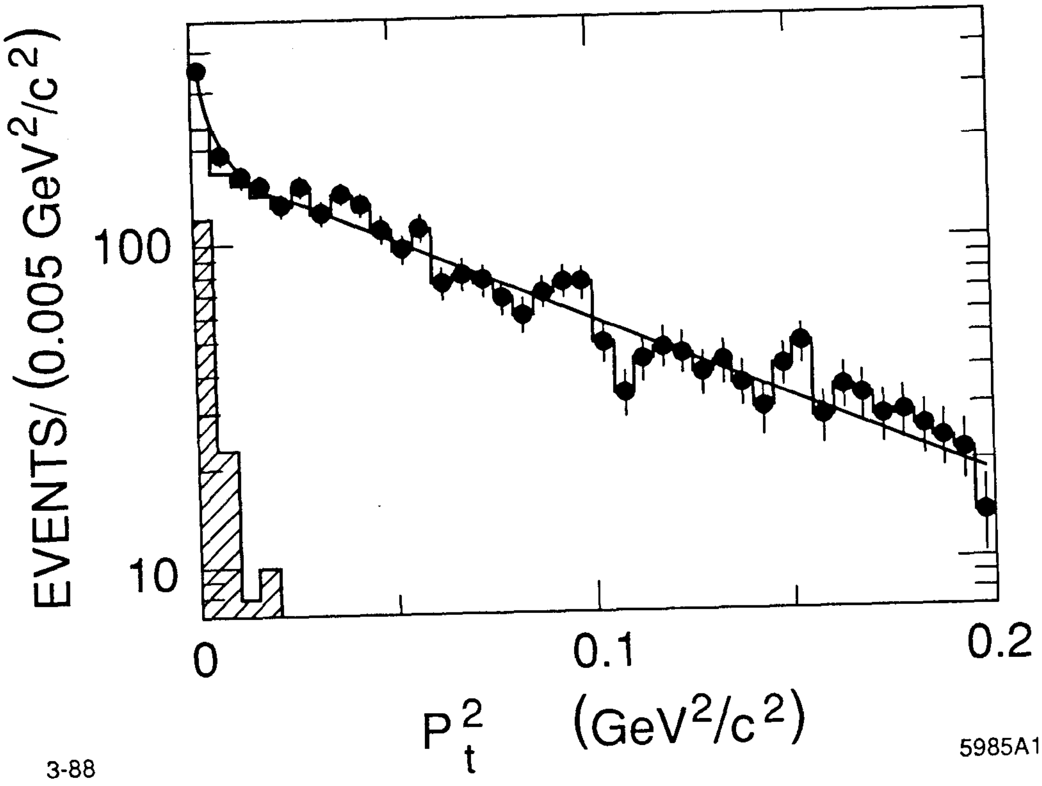

Fig. 1

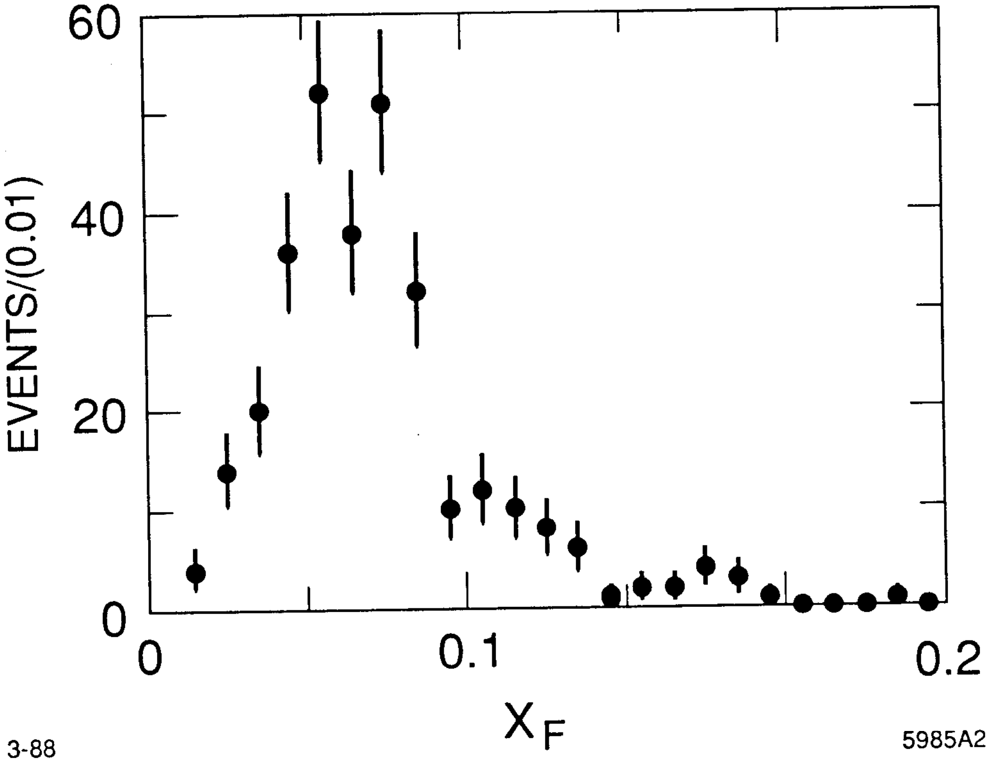

Fig. 2

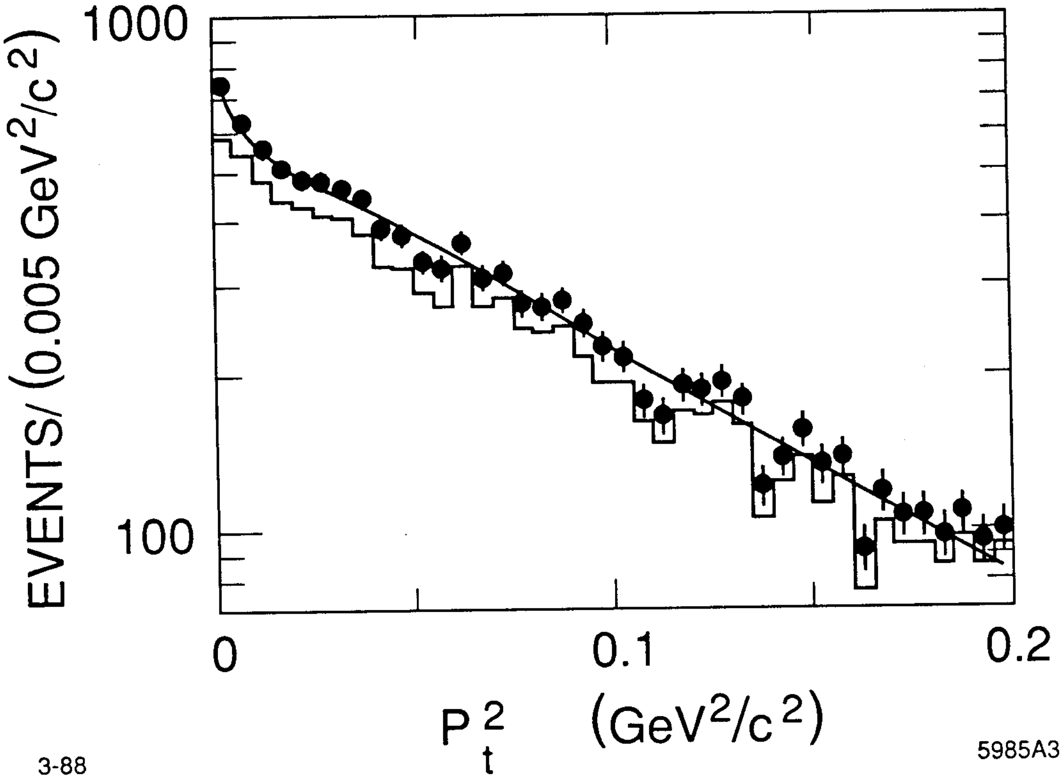

Fig. 3

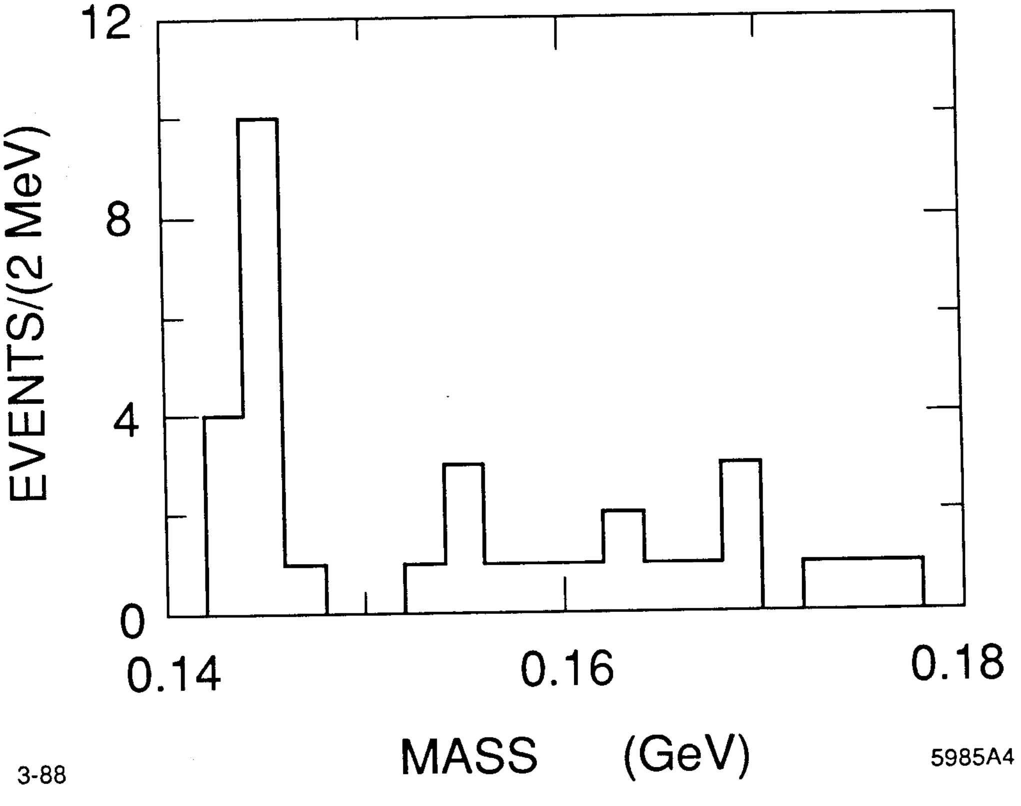

Fig. 4