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A SEARCH FOR NEW PARTICLES IN Z DECAY*

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ABSTRACT

We have searched 310 hadronic Z decays for evidence of new quarks and leptons. We set lower mass limits of 40.7 GeV/c^2 for top, 45 GeV/c^2 for bottom prime, and 42.4 GeV/c^2 for a heavy neutral lepton assuming their decays are predominantly via the charged current. Limits are also set for other decay modes and for mixtures of decay modes.

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1. INTRODUCTION

The production of large numbers of Z bosons at the SLC opens up a new mass regime to searches for new particles. This talk is a report of searches for the top quark (t), the fourth-generation charge $-1/3$ quark (b'), and a heavy neutral lepton (L^0) which have been performed by the Mark II collaboration. Since these particles have already been ruled out at masses below 30 GeV/c^2 by previous experiments, we are looking for signatures of the decay of very massive particles. We use isolated charged particles, isolated photons, four jet kinematics, and large M_{out}.

2. THE DECTECTOR AND THE DATA SAMPLE

The Mark II has been described elsewhere.[1] The components of the apparatus used in this analysis are the central drift chamber (CDC) the liquid-argon-lead calorimeter (LA) and the lead-proportional-tube endcap calorimeters.

Charged particles are accepted if they appear to pass through a cylindrical volume 6 cm in length and 1 cm in radius around the interaction point, their polar angles satisfy $|\cos\theta| < 0.82$, and their momenta transverse to the beam are > 150 MeV/c.

Electromagnetic showers are accepted in the LA if they have a polar angle satisfying $|\cos\theta| < 0.68$, the azimuthal angle is within the fiducial volume of one of the eight modules, the energy is greater than 1 GeV, and the energy is greater than twice the momentum of any associated charged particle. Showers are accepted in the EC if their polar angle satisfies $0.69 < |\cos\theta| < 0.95$. Energy requirements for the EC are the same as for the LA.

Events are used if the number of charged tracks is ≥ 6, the sum of the charged particle energy and shower energy is more than 10% of the center of mass energy, and the thrust angle satisfies $|\cos\theta_{th}| < 0.8$. All of the selection criteria are designed to ensure that the detector response can be accurately modeled. Redundant triggers allow us to prove that the trigger efficiency is greater than 99% for the selected sample.

3. PROCEDURE

To set a limit on the possible mass of a new particle we express its signature as a single value for each event. We use a Monte Carlo calculation of "old" physics, i.e., decay to u, d, s, c, b quarks, to establish a cut on the signature value such that few old physics events are expected to pass. We then count the number of data events which pass and assume that these may be due to a new particle. We then calculate the number of new particle events which are expected to pass the cut for a particular new particle of a particular mass. Next we calculate probability of observing a number of data events which is less than or equal to the actual number observed given the number of new particle events expected. We repeat these last steps for all particle masses of interest. The 95% CL mass limit is then that mass for which the probability is 0.05.

To illustrate this procedure I will describe in some detail the isolated charged particle search. For the isolated particle searches, we impose the additional event requirement that the thrust be less than 0.9. In this case, the signature value is the isolation parameter ρ_{max}. To calculate ρ_{max} we perform the LUND cluster (jet) algorithm[2] on an event excluding a candidate track. The cluster forming parameter *djoin* is set to 0.5 during this procedure; this leaves smaller mass clusters than the default value. We then calculate the track isolation parameter:

$$\rho_i \equiv \min_{jets\ j} \sqrt{2E_i(1-\cos\theta_{ij})} \ ,$$

where θ_{ij} is the opening angle between candidate track i and jet j. Repeating this procedure for each track we obtain the event isolation parameter:

$$\rho_{max} \equiv \max_{tracks\ i} \rho_i \ .$$

Figure 1 shows the distribution of ρ_{max} for old physics and the cut of 1.8 derived from this distribution. Also shown are the data, in which no events pass the cut, and the distribution expected for typical signals, in this case, a 35 GeV/c^2 b' and t quarks which decay 100% of the time via a W^*, i.e., the charged current.

In fig. 2 we show the predicted partial width for the Z decay to b-prime quark antiquark. We use the first order α_s calculation less the theoretical uncertainty due to higher order QCD corrections.[3]

Figure 3 shows the number of events which are expected to pass the selection criteria and the isolation cut. Since no data events passed the cuts, we find the 95% CL mass by observing where the expected number of events becomes less than 3. For a b' quark this is 45 GeV/c^2, and for a t quark it is 40.7 GeV/c^2.

4. SYSTEMATIC ERRORS

The only problematic step in this procedure is the estimate of the expected number of events. This is given by :

$$N_{exp} = \epsilon_\rho \frac{\Gamma_x N_h}{\epsilon_q \Gamma_q + \epsilon_x \Gamma_x} \quad .$$

- $N_h = 310$ is the number of observed hadronic Z decays in a sample selected by a set of very loose cuts. It provides the normalization and contributes a statistical error to N_{exp}.

- $\epsilon_q = 0.945 \pm 0.04$ is the efficiency for finding old physics events in N_h.
- $\epsilon_x(M_x)$ is the efficiency of finding the new particle events in N_h. This is usually larger than 0.85 and in some cases as large as 0.95. Its uncertainty contributes little to the uncertainty in N_{exp}.
- $\Gamma_q = 1.725$ GeV is the decay width of the Z to old physics (*udscb* quarks) and is given by the standard model.
- Γ_x is the decay width of the Z to the new particle pair in question. It may involve many assumptions about the new particle, but once these assumptions are given the remaining uncertainty is due to uncalculated higher order (than α_s) QCD corrections. These are 25% of Γ_x or less.
- $\epsilon_{\rho_{cut}}(M_x)$ is the efficiency for new particle events to pass the isolation cut. Estimating this efficiency involves a Monte Carlo simulation of any QCD processes involved in the new particle production and decay. In the case of isolated particle searches the result is not very sensitive to the details of the calculation since the main fact which determines whether or not an event passes the cut is whether or not one of the new particles decayed semileptonically. The Monte Carlos used have been tuned to data at 29 GeV. They fit our Z data if only old physics is assumed. We use the LUND Jetset 6.3 Monte Carlo,[4] and in the case of new quarks, LUND symmetric fragmentation, to get the central values of our estimates. To estimate the systematic error we compare the central value with the results of a calculation using the Webber 4.1 Monte Carlo[5] and with one using the LUND Monte Carlo with Peterson fragmentation.[6] The biggest deviations seen at any mass were less than 12% of value of the efficiency. This maximum value was used as the systematic error due to fragmentation at all masses.

All the above errors were combined in quadrature and subtracted form the central value to get the value of N_{exp} used in setting limits.

5. LIMITS ON NEUTRAL HEAVY LEPTONS

We have also used the isolated charged track signature to look for a heavy, sequential, Dirac, neutral lepton. Figure 4 shows the expected number events with isolated charged tracks for the three cases $L^0 \rightarrow \mu W^*$, $L^0 \rightarrow e W^*$, and $L^0 \rightarrow \tau W^*$. The mass limits are 44.4, 44.1, and 42.4 GeV/c^2, respectively. Since all these limits are derived from the same observation we may set a limit of 42.4 GeV/c^2 for an arbitrary admixture of these decays.

Since we have assumed $M_{L^0} > M_{L^-}$, these decay modes depend on generation mixing, and the L^0 lifetime could be very long if the mixing is small. If the lifetime is too long the decay tracks will fail the requirement that the tracks come from the interaction point. The above limits assumed that all the L^0s decay such that all their tracks pass through track acceptance volume. Figure 4 shows the limits versus the square of the mixing matrix element where the mixing matrix is defined by $\nu_l = \sum_{i=1}^{4} U_{li} L_i^0$.

6. THE *b*-PRIME STORY

We have already set a limit on the mass of a *b*-prime quark if it decays entirely to cW^*, i.e., to a virtual W boson. This involves a two-generation jump and the mixing angle may be small. In this case, the lifetime may be relatively long and loop diagrams be important. In particular, the flavor changing neutral current decays $b' \rightarrow b\gamma$ and $b' \rightarrow bg$ may have amplitudes large enough to contribute to b' decay.[7] To set a limit on the $b\gamma$ mode we use an isolated photon search. This is exactly the same as the isolated charged particle search except that the candidate particles are calorimeter showers.

Figure 6 shows the expected old physics distribution of the isolation parameter from which we set a cut at 3.0. Also shown are the expected distribution from $b' \rightarrow b\gamma$ and the data. No data passes the cut.

Figure 7 shows the number of events expected to pass the cuts versus b' mass, from which we set a limit of 45 GeV/c^2.

The bg mode is more difficult. This manifests itself as four jets. Two heavy particles each decaying to four jets have very distinctive kinematics which may be used as a signature. The following analysis is the same one that the TASSO collaboration used in their charged Higgs search.[8] We apply the LUND cluster algorithm to the event insisting that it find four clusters. We find the velocity of each cluster and then determine the cluster masses by energy and momentum conservation. The clusters are then paired by a b'-mass-dependent algorithm designed to put sibling clusters together. We then calculate the opening angles of the pairs, and the masses of the pairs. From these we calculate the difference in opening angles, the average opening angle, the average mass, and the difference in energy of the pairs. We then make a mass dependent cut on the average opening angle. Our b' events are found in a restricted volume in a space described by the opening angle difference, the energy difference, and the average pair mass. We make a mass dependent cut around this restricted volume and count the number of events within. We found no events in the data and set a limit on the b' mass of 41.2 GeV/c^2 for any combination of decay to $b\gamma$ or bg.

We can now address the possibility of a mixture of charged and neutral current decays. Figure 8 shows the mass limit versus fraction of b' which decays via the charged current. The solid curve comes from the isolated charged track search. The three dotted curves come from the isolated gamma search. The three curves are for different fractions of neutral current decays going to $b\gamma$. We see that if all neutral current decays go to $b\gamma$, we set a limit on the b' mass of 44 GeV/c^2. The dashed curve shows the limit from the four jet analysis. It is independent of the ratio of $b\gamma$ to bg. Using it and the isolated charged particle limit we set limit of 38 GeV/c^2 on the b' mass independent of the decay mode.

7. M_{out} AND DECAYS TO HIGGS MESONS

There is another decay mode of b' quarks which I haven't mentioned, that is $b' \to qH$. If there is an Higgs meson at a mass which makes this possible and it is charged, this will be the dominant decay. To search for this process we use the M_{out} analysis.

$$M_{out} = \frac{E_{cm}}{E_{vis}} \sum_{tracks} \left| \frac{p_t^{out}}{c} \right| ,$$

where p_t^{out} is the momentum of a track perpendicular to the event plane as defined by a sphericity analysis.

The distribution of this observable for the data, and for the old physics Monte Carlo is shown in fig. 9. The cut is set so several events are expected to pass, and indeed five events do so. The cut must be set this way because the background does not drop away from the new physics signal as decisively as it does with the other signature variables we have described. Our estimate for the number of events due to old physics is 6.1 ± 2.4 where the error is derived as described above. Using 3.7 as the expected number due to old physics, together with the observation of 5 events in the data we get a $95\% CL$ limit of 7.1 events.[9]

Figure 10 shows the expected signal versus mass for the decay modes $b' \to bH^0 \to bb\bar{b}$ and $b' \to cH^- \to cc\bar{s}$. The mass limit for both of these processes is 45.0 GeV/c^2 for a Higgs mass of 25 GeV/c^2. Similarly the t mass limit for $t \to bH^+$ is 41.7 GeV/c^2. This signature can also be applied to all the previously treated t and b' charged current decays and set limits only slightly less stringent than the ones already set.

8. SUMMARY

We have searched a sample 310 hadronic Z decays for evidence of new particles expected as simple extensions of currently known physics. Using several signatures for the decay of very heavy particles we have set mass limits near the kinematic bounds in Z decay for the existence of a t quark, a b' quark, and a neutral heavy lepton for all the expected decay modes. These results are tabulated below.

Summary of mass limits.

Particle	Decay	Mass Limit (GeV/c^2)
t	bW^*	40.7
	bH^+	41.4
b'	cW^*	45.0
	$b\gamma$	45.0
	bg	41.2
	bH^0	45.0
	cH^-	45.0
L^0	μW^*	44.4
	eW^*	44.1
	τW^*	42.4

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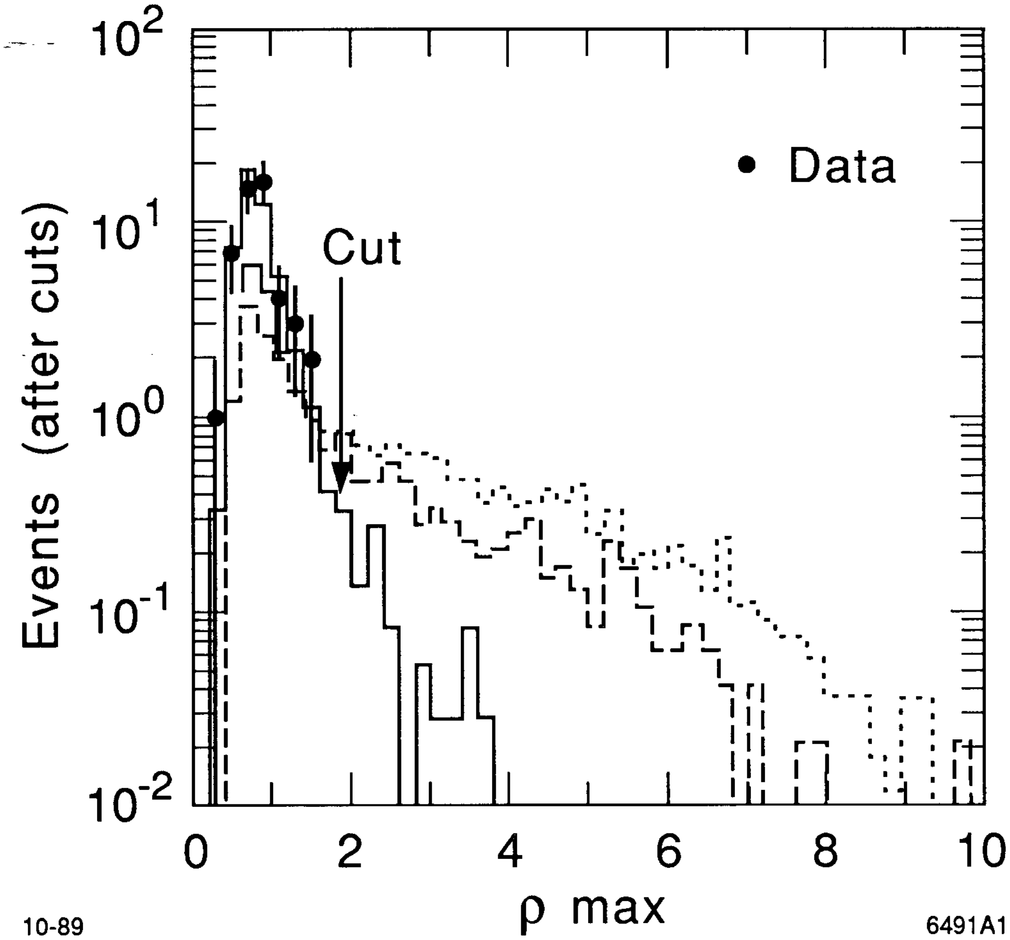
7. C. Peterson et al., Phys. Rev. **D27** (83) 105.
8. W. Hou et al., Phys. Rev. Lett. **62** (89) 55.
9. M. Althoff et al., Phys. Lett. **122B** (83) 95.

FIGURE CAPTIONS

1. The distribution of ρ_{max}. The points are the data. The solid curve is the distribution expected from old physics. The dotted curve is that expected from a 35 GeV/c^2 b' quark, while the dashed is for a 35 GeV/c^2 t quark.
2. The partial width of Z decay to b'. The solid curve is the Born calculation, the dashed curve includes first order α_s corrections, and the dotted curve has the remaining theoretical uncertainties subtracted.
3. The expected number of events from b' (solid curve) and t (dashed curve). The combined estimated errors have been subtracted.
4. The expected number of events from $L^0 \rightarrow \mu W$ (solid curve), $L^0 \rightarrow eW$ (dotted curve), and $L^0 \rightarrow \tau W$ (dashed curve).
5. Mass limits versus mixing matrix element: $L^0 \rightarrow \mu W$ (solid curve), $L^0 \rightarrow eW$ (dotted curve), and $L^0 \rightarrow \tau W$ (dashed curve).
6. Distribution of ρ_{max} for photons. Solid curve shows the expected distribution for old physics, while the dotted curve shows distribution expected from $b' \rightarrow b\gamma$.
7. Expected number of b' events passing the isolated photon cut assuming 100% decay to $b\gamma$.
8. Mass limit for b' quarks versus branching fraction. The solid curve shows the limit from the isolated charged particle search. The dotted curves show the limits from the isolated photon search for the indicated values of $b\gamma/(b\gamma + bg)$. The dashed curve is the limit from the four jet analysis.
9. Distribution of M_{out}. Solid curve shows the expected distribution for old physics, and the dotted curve shows that expected from $b' \rightarrow cH^+$, $H^+ \rightarrow c\bar{s}$, $M_{H^+} =$ 25 GeV/c^2.
10. The number of events expected to pass the M_{out} cut. The solid curve is for $b' \rightarrow bH^0$, $H^0 \rightarrow b\bar{b}$, H^0 mass is 25 GeV/c^2. The dotted curve is for $b' \rightarrow cH^-$, $H^+ \rightarrow c\bar{s}$, H^+ mass is 25 GeV/c^2.



10^2
10^1
10^0
10^{-1}
10^{-2}
Events (after cuts)
● Data
Cut
0
2
4
6
8
10
ρ max
10-89
6491A1

Fig. 1

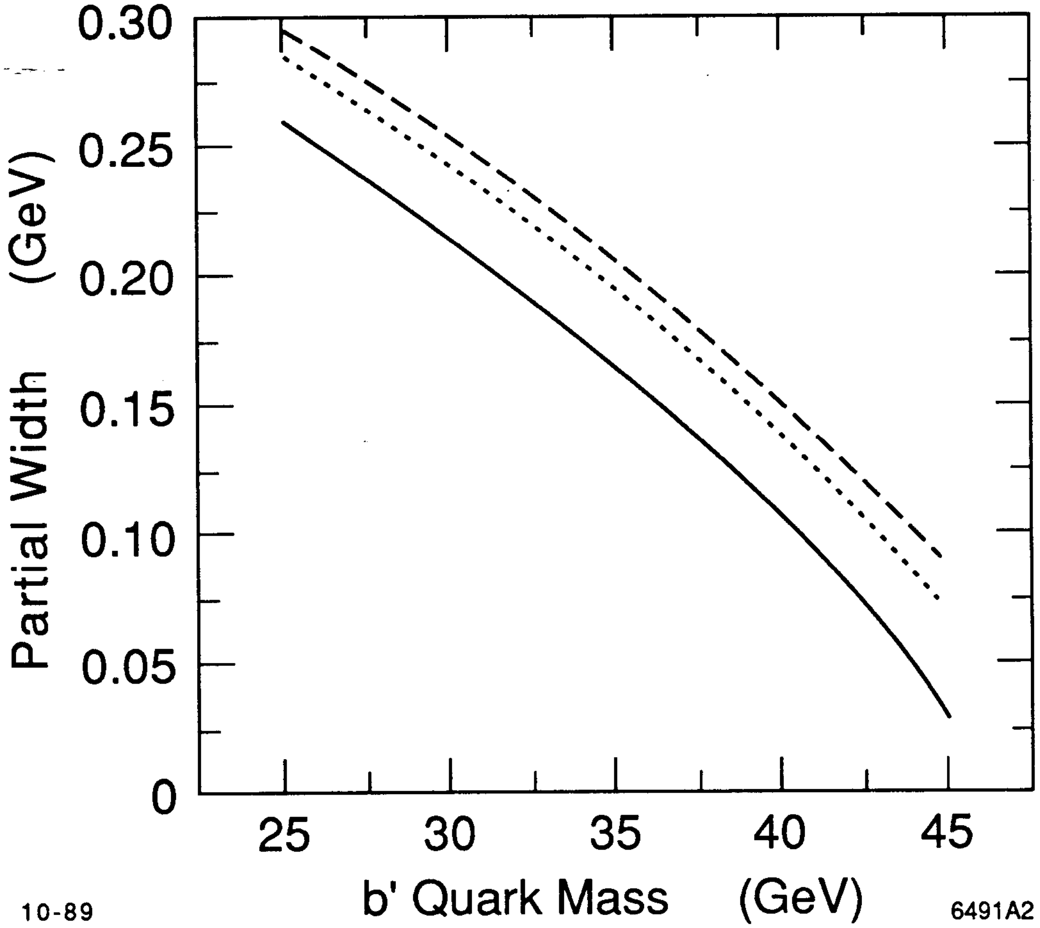

0.30
0.25
0.20
0.15
0.10
0.05
0
Partial Width (GeV)
25
30
35
40
45
b' Quark Mass (GeV)
10-89
6491A2

Fig. 2

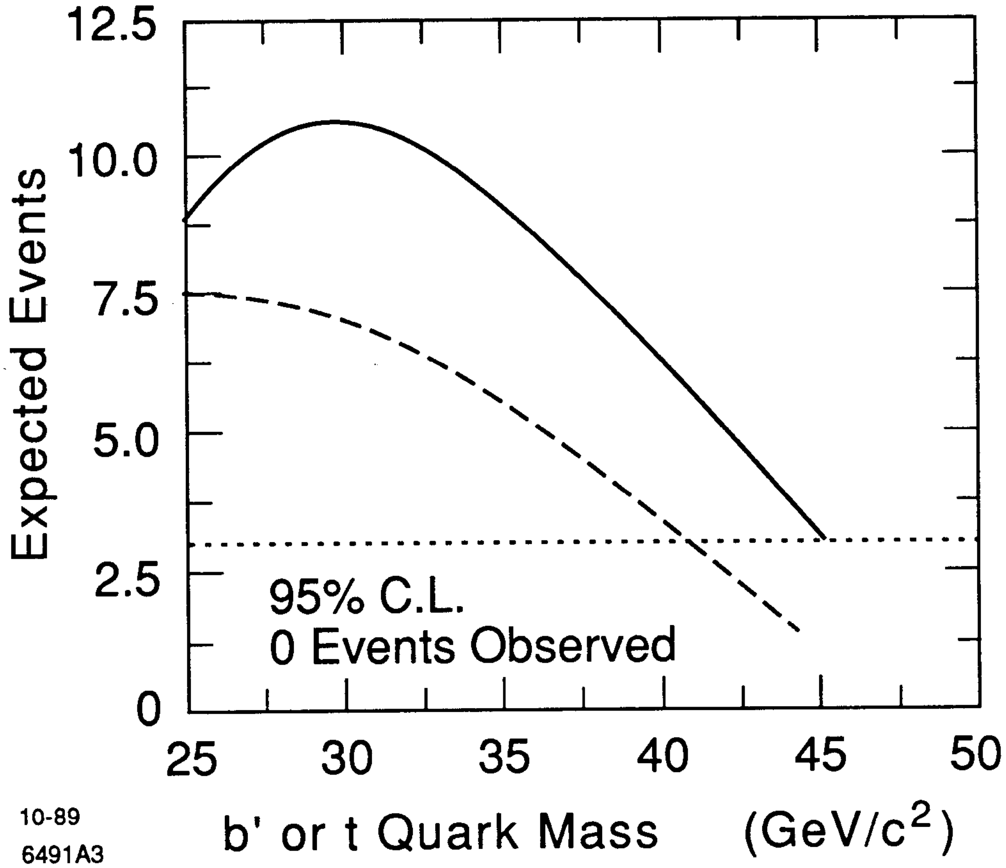

12.5
10.0
7.5
5.0
2.5
0
Expected Events
25
30
35
40
45
50
b' or t Quark Mass (GeV/c^2)
95% C.L.
0 Events Observed
10-89
6491A3

Fig. 3

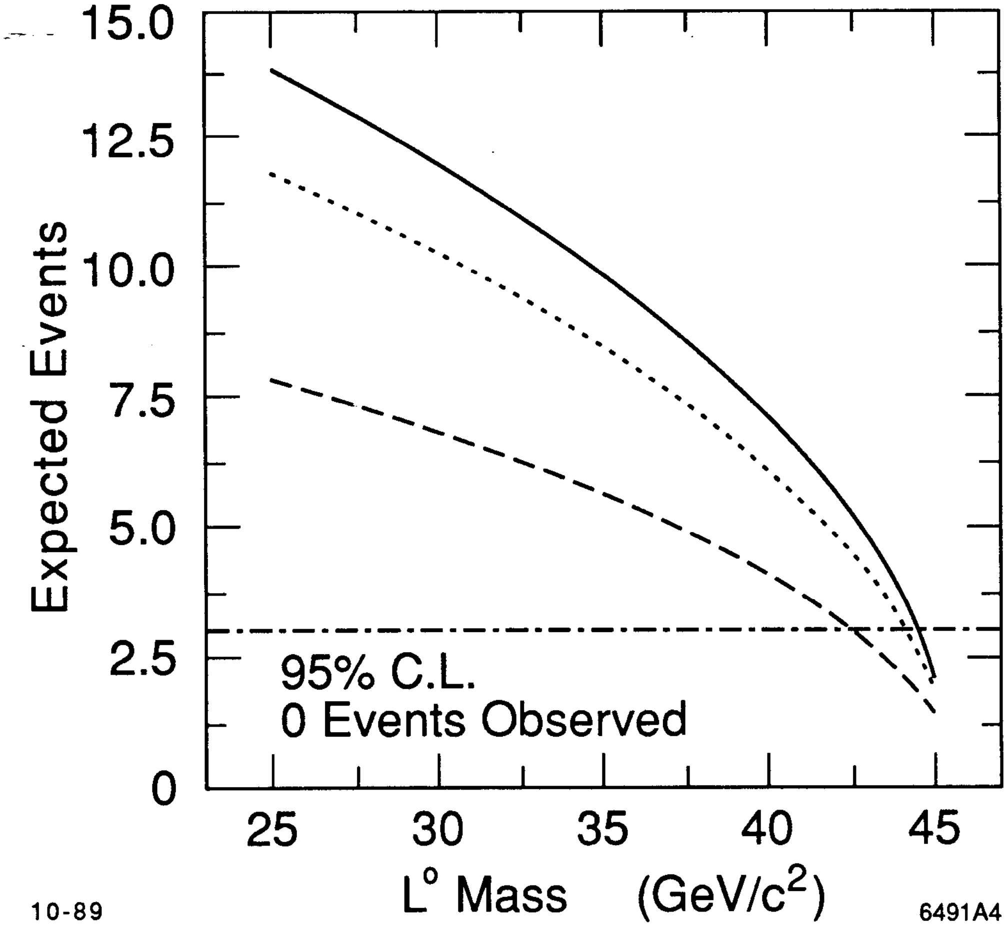
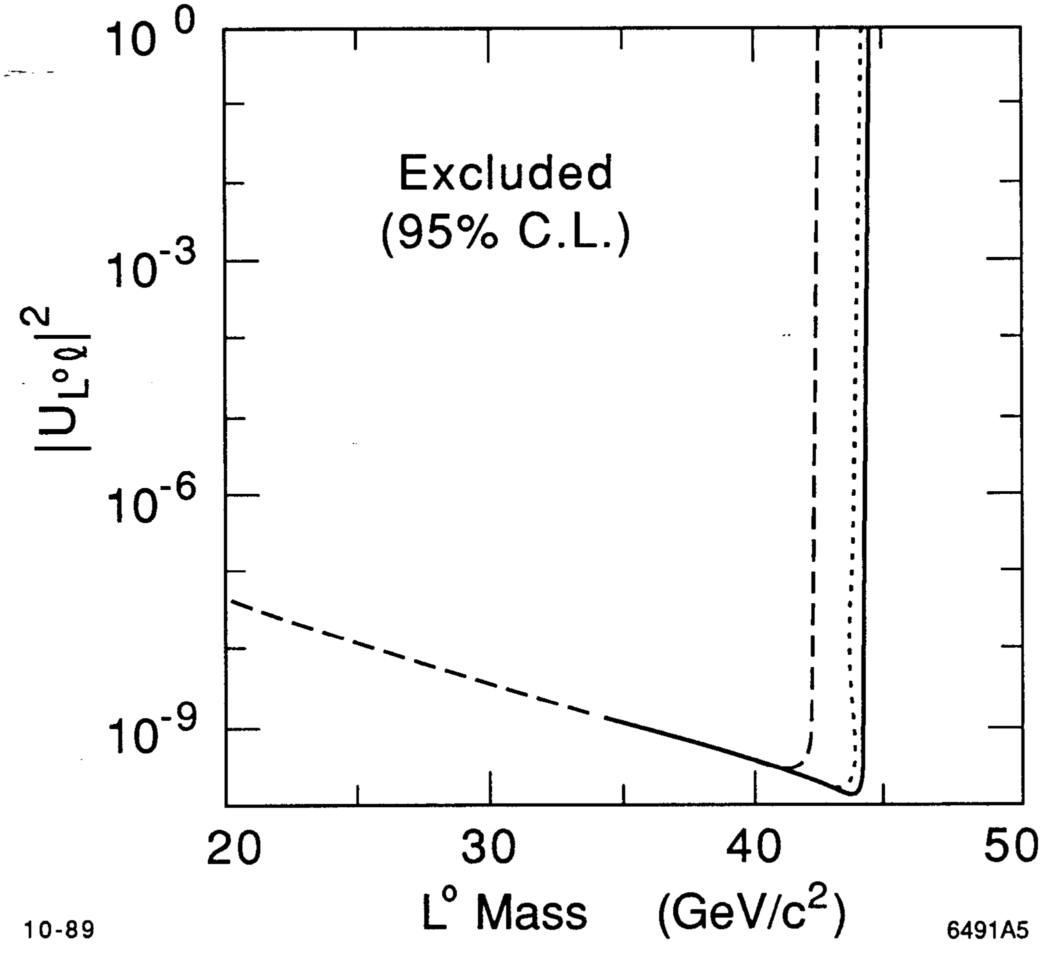

15.0
12.5
10.0
7.5
5.0
2.5
0
Expected Events
95% C.L.
0 Events Observed
25
30
35
40
45
L° Mass (GeV/c²)
10-89
6491A4

Fig. 4



10^0
10^{-3}
10^{-6}
10^{-9}
$|U_{L^\circ \ell}|^2$
Excluded
(95% C.L.)
20
30
40
50
L° Mass (GeV/c^2)
10-89
6491A5

Fig. 5

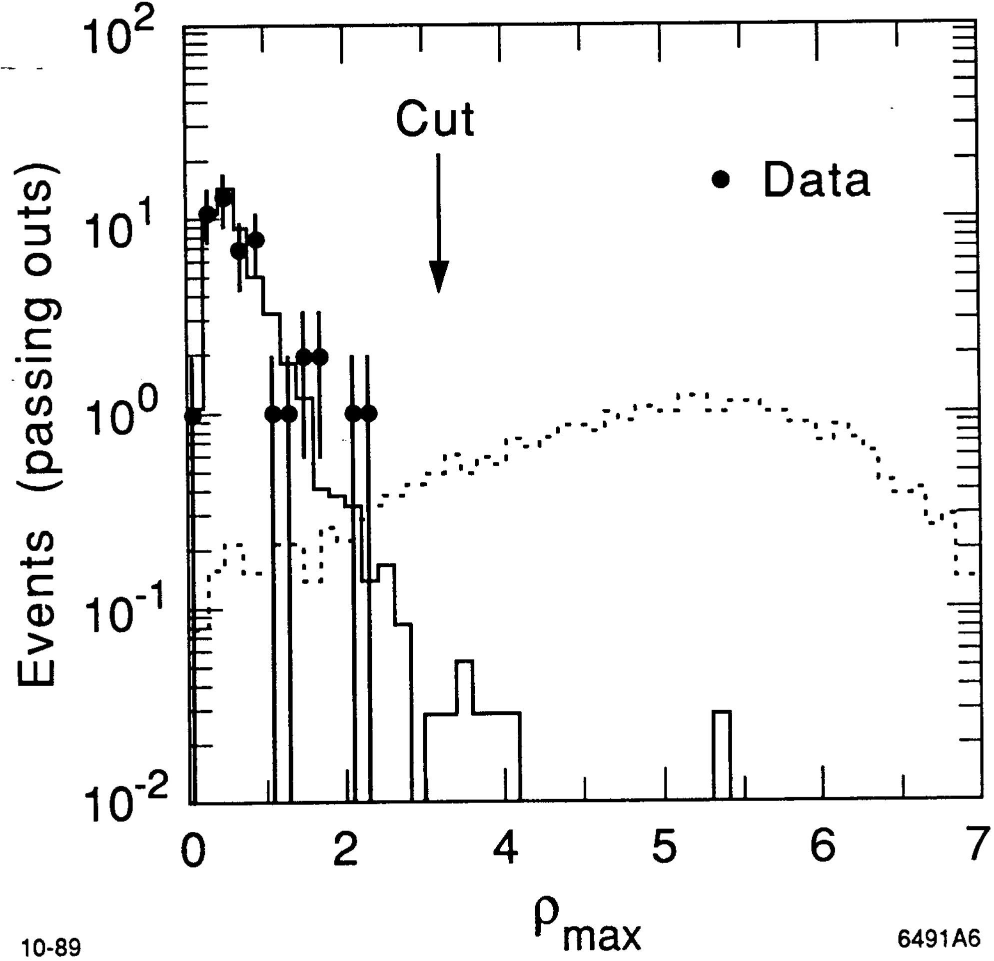

10²
10¹
10⁰
10⁻¹
10⁻²
Events (passing cuts)
Cut
● Data
0
2
4
5
6
7
ρ max
10-89
6491A6

Fig. 6

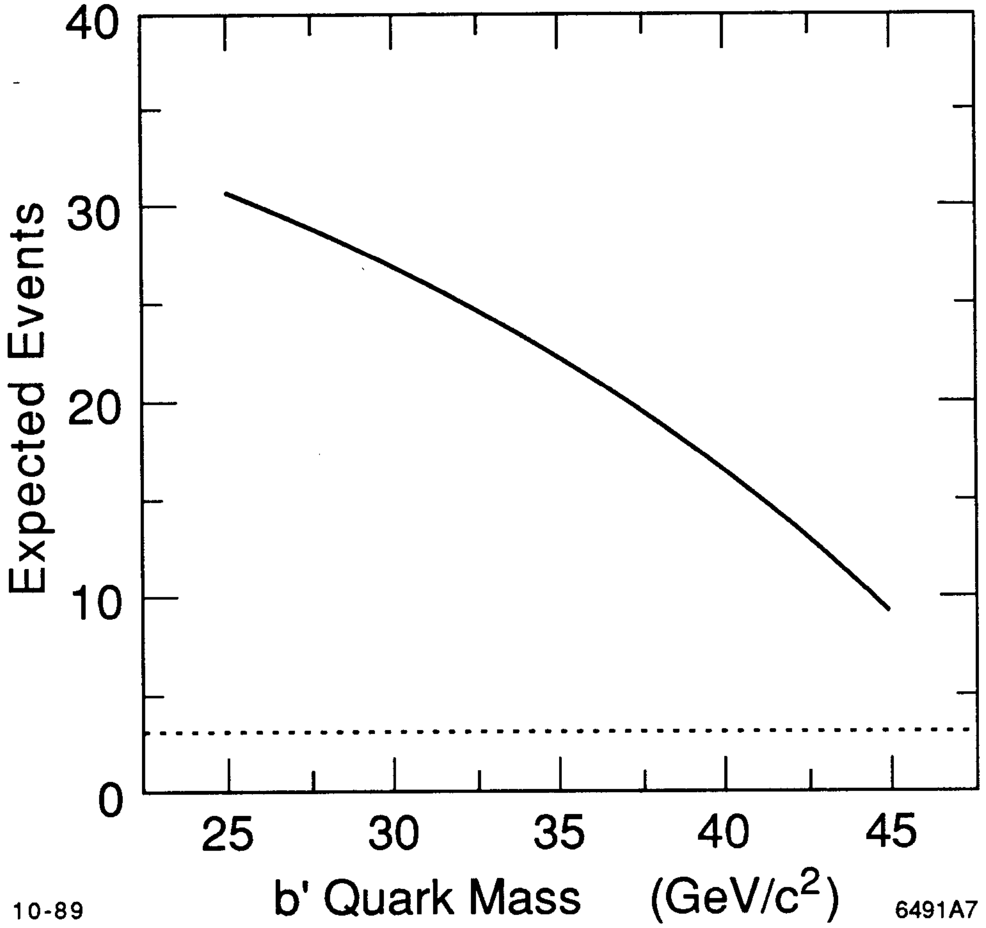

40
30
20
10
0
Expected Events
25
30
35
40
45
b' Quark Mass (GeV/c²)
10-89
6491A7

Fig. 7

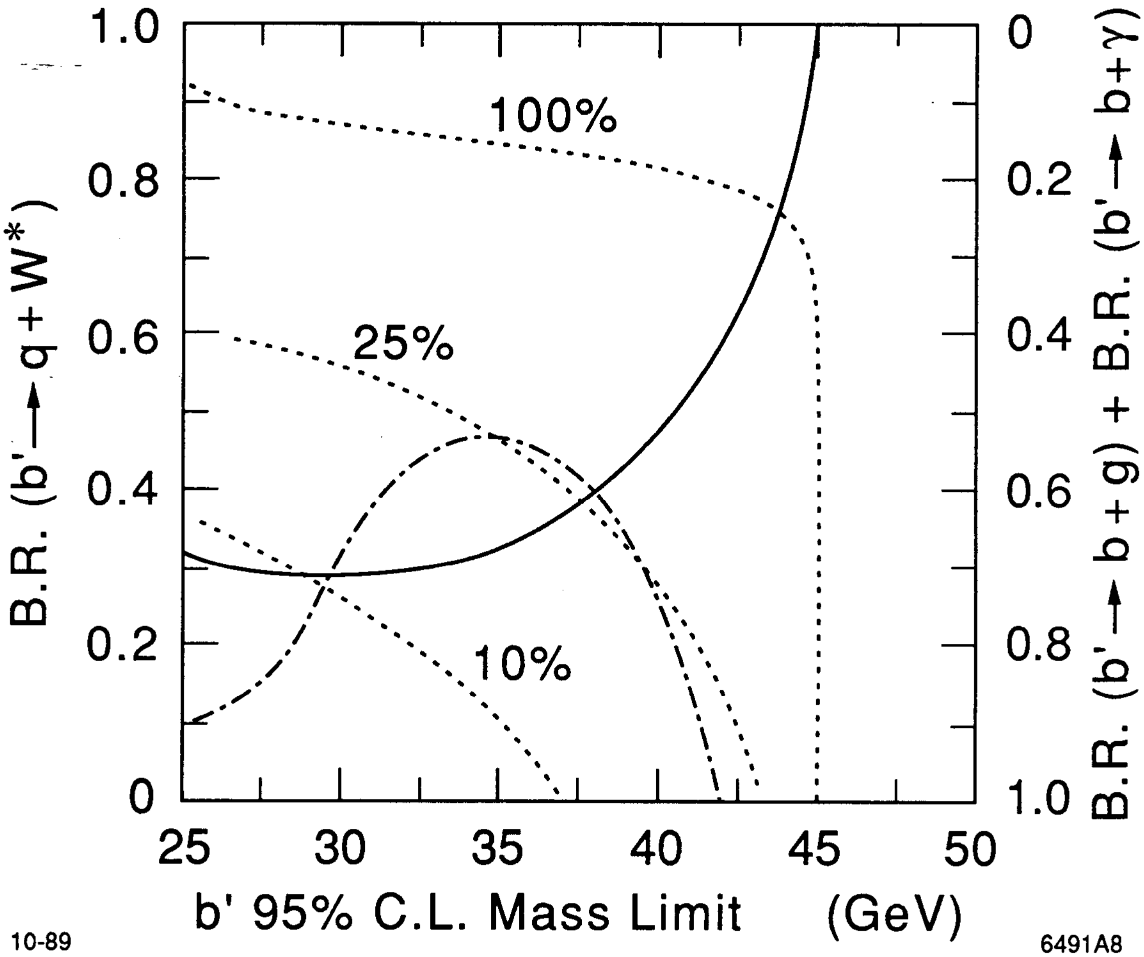

1.0
0.8
0.6
0.4
0.2
0
B.R. (b'→ q+W*)
0
0.2
0.4
0.6
0.8
1.0
B.R. (b'→ b+g) + B.R. (b'→ b+γ)
100%
25%
10%
25
30
35
40
45
50
b' 95% C.L. Mass Limit (GeV)
10-89
6491A8

Fig. 8

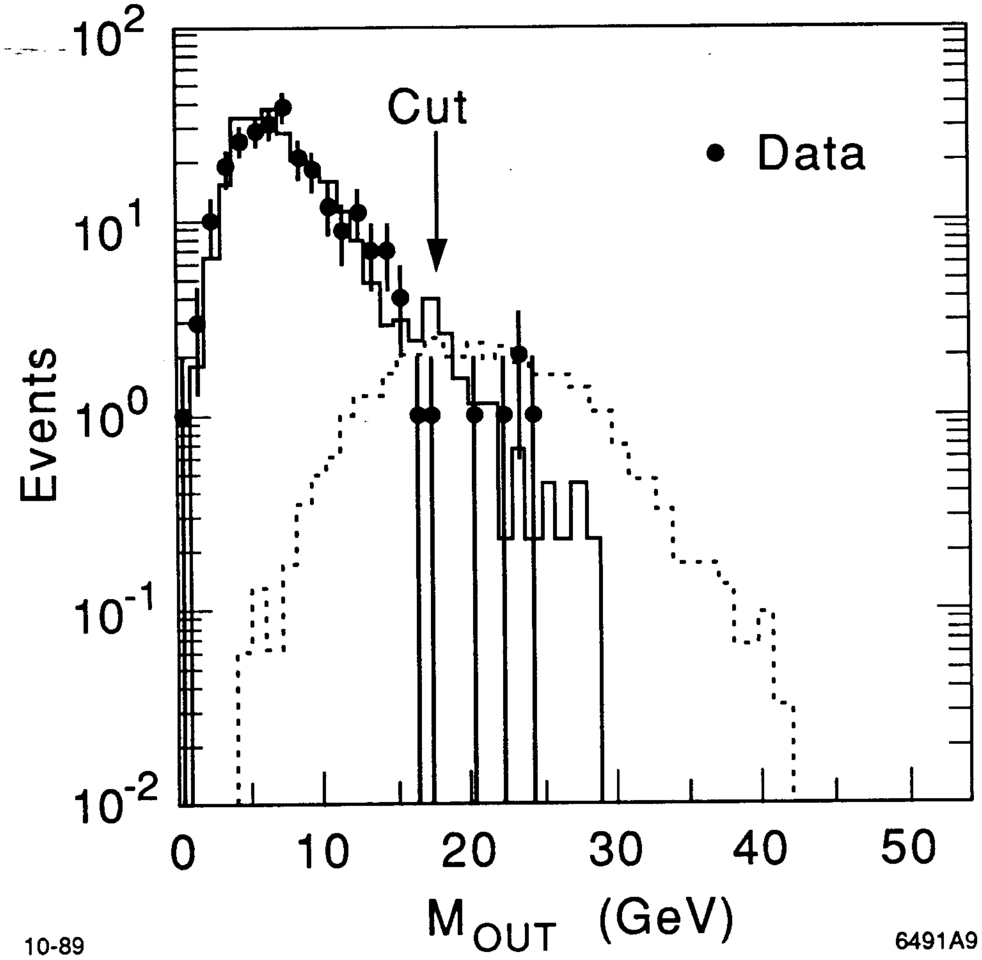

10^2
10^1
10^0
10^{-1}
10^{-2}
Events
Cut
● Data
0
10
20
30
40
50
M_{OUT} (GeV)
10-89
6491A9

Fig. 9

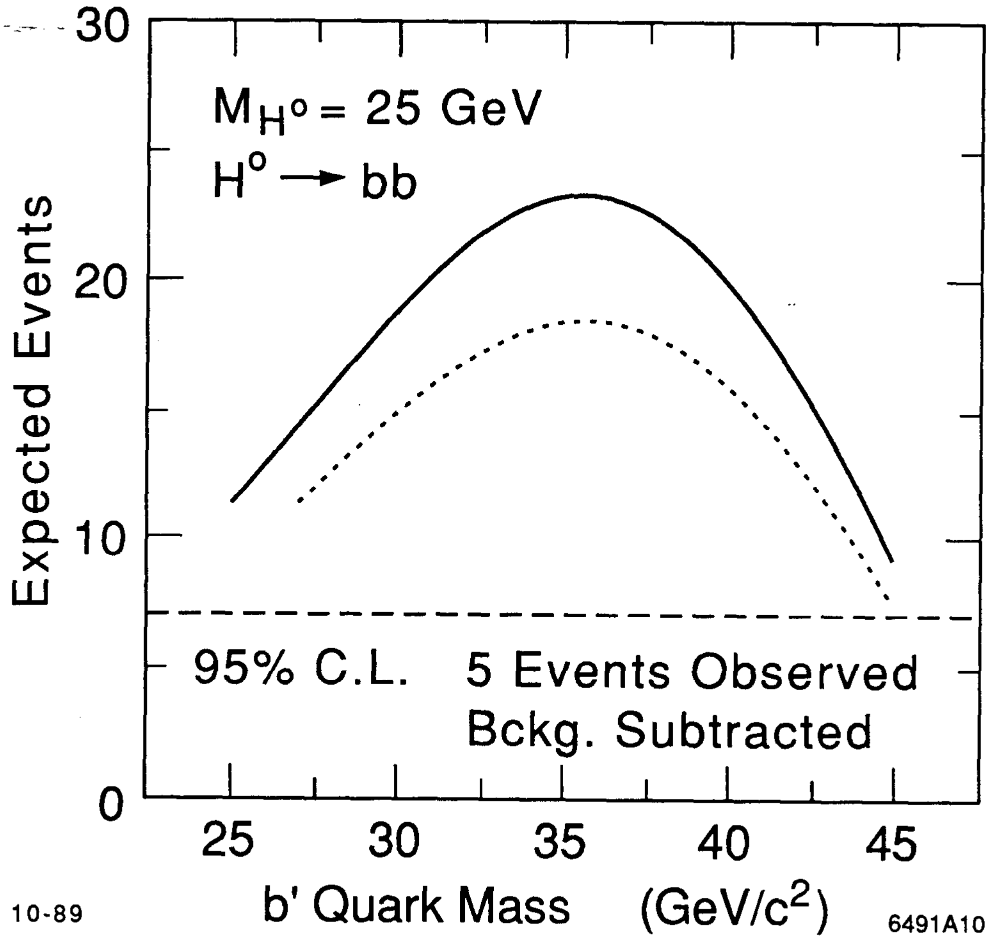

30
20
10
0
Expected Events
M_{H^o} = 25 GeV
$H^o \rightarrow bb$
95% C.L.
5 Events Observed
Bckg. Subtracted
25
30
35
40
45
b' Quark Mass (GeV/c^2)
10-89
6491A10

Fig. 10