SLAC-PUB-4194
February 4, 1987
(T/E)

A Search for the Lepton Family Number Violating Decay $D^0 \rightarrow \mu e$

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Abstract

A search for the lepton family number violating decay $D^0 \rightarrow \mu e$ is reported. No signal is observed in a data sample of 9.3 pb^{-1} collected at the $\psi(3770)$ resonance with the Mark III detector, where $0.18 \pm 0.06 \pm 0.05$ background events are expected. A 90% confidence level upper limit on the branching fraction $B(D^0 \rightarrow \mu e)$ of 1.5×10^{-4} is obtained. This limit can be used to place a lower bound on the masses of leptoquarks and other new particles that characterize models of family unification and other theories beyond the Standard Model.

Submitted to *Physical Review Letters*

* **Work supported by the Department of Energy, contract DE–AC03–76SF00515.**

Interest has recently intensified in searching for lepton family number violating processes such as $\mu \to e\gamma$, $\mu \to eee$, $K_L^0 \to \mu e$, $D^0 \to \mu e$, and ν oscillations.[1] The decay mode[2] $D^0 \to \mu e$ could be induced by massive leptoquarks whose existence is predicted in various extensions of the Standard Model. Within certain models,[3] scalar leptoquarks are expected to couple the "up-type" quarks (u,c,t) to charged leptons, and the "down-type" quarks (d,s,b) to neutral leptons (Figure 1). Thus, the decay $D^0 \to \mu e$ can be enhanced with respect to the experimentally more accessible $K_L^0 \to \mu e$ decay.[4] We present herein the most sensitive search to date for the decay $D^0 \to \mu e$.

The experiment is carried out at the $\psi(3770)$ resonance, allowing the establishment of a model-independent limit on the $D^0 \to \mu e$ branching fraction. A total integrated luminosity of 9.3 pb^{-1}, collected with the Mark III detector at the e^+e^- storage ring SPEAR, is employed. The apparatus has been described in detail elsewhere.[5] This luminosity corresponds to $41400^{+3100}_{-2700} \pm 2700$ produced D^0's.[6] As the $\psi(3770)$ lies below $D\bar{D}^*$ threshold, D^0's are produced monochromatically ($\mathrm{p}_{D^0} = 0.27\,\mathrm{GeV}/c$) in the laboratory frame; this provides a unique kinematic constraint on the μe decay and thus reduces background.

The data are first searched for events containing at least two lepton candidates: one muon and one electron. The kinematics of the two-body D^0 decay require that both leptons have momentum $\mathrm{p} > 0.75\,\mathrm{GeV}/c$ in the laboratory frame. Leptons are selected on the basis of the energy (E) deposited in the shower counter, the momentum (p) as determined with the drift chamber, the time-of-flight (TOF) measured with scintillation counters, and range in the muon system.

A loose selection of electron candidates is made by requiring a value of E/p larger than 0.45, and a TOF within 1.4 ns ($\sim 6\sigma$) of that predicted for an electron. All tracks satisfying these conditions are then passed through a more restrictive algorithm designed to separate electrons from pions using variables which parametrize the shape of the shower in the finely segmented barrel shower counter.[7] This procedure rejects 96% of the pions with $p > 0.75\,\mathrm{GeV}/c$, while retaining 89% of the electrons.

Muon candidates are required to have a TOF within 1.4 ns of that predicted for a muon. Tracks within the acceptance of the muon system ($|\cos\theta| \leq 0.65$, θ being the polar angle with respect to the beam axis) must have two (one) layers hit for muon momentum $p_\mu \geq 1\,\mathrm{GeV}/c$ ($p_\mu < 1\,\mathrm{GeV}/c$). This provides $> 90\%$ rejection of π and K decays and punch-through .[8] The muon detection efficiency rises to 70% for momenta between 0.55 and 0.70 GeV/c, and exceeds 90% above 0.9 GeV/c. The muon coverage is extended beyond the muon system to the region $0.65 \leq |\cos\theta| \leq 0.78$ by accepting as muons those tracks which deposit less than 0.3 GeV in the shower counter. Within this limited solid angle, 31% of the pions and 34% of the kaons are rejected as determined from data on the kinematically similar process $D^0 \rightarrow K^-\pi^+$.

This initial selection reduces the data sample to 6517 events containing at least one electron-muon pair candidate with opposite charges. The two principal sources of background to the decay $D^0 \rightarrow \mu e$ are hadronic charged two-body D^0 decays, and $\tau^+\tau^-$ pairs. Semileptonic decays of the D^0 are a negligible background. Rejection of $D^0 \rightarrow K^-\pi^+$, $\pi^+\pi^-$ decays through the lepton selection described above is augmented by use of the two-body decay kinematics.

The invariant mass M_{inv} of each two-body combination is calculated using electron and muon masses. The $K^-\pi^+$ decays of the D^0 contaminating the sample are kinematically reflected to lower masses (Figure 2). All candidate pairs with M_{inv} differing from the D^0 mass by more than $0.05\,\mathrm{GeV}/c^2$ are rejected. This cut does not reject the Cabibbo-suppressed decay $D^0 \rightarrow \pi^+\pi^-$. Thus, although the absolute rate of $D^0 \rightarrow \pi^+\pi^-$ is small, it remains a significant background.

The second major background source is τ pair production where the τ's decay to $e\nu\bar{\nu}$, $\mu\nu\bar{\nu}$, $\pi\nu$, or $\rho\nu$, $\rho \rightarrow \pi\pi^0$. Leptons from the τ decays or pion punch-through from the $\rho\nu$ and $\pi\nu$ decay chains feed into the $D^0 \rightarrow \mu e$ candidate sample. Since τ background consists mainly of two-prong events accompanied by undetected neutrinos, a cut on the missing energy E_{miss}[9] in two-prong events eliminates this contamination. Figure 3 shows the expected E_{miss} distribution from Monte Carlo simulations of $D^0\bar{D}^0 \rightarrow (\mu e + \text{no charged tracks})$ and $\tau^+\tau^-$ production. By rejecting two-prong events with $E_{miss} > 1\,\mathrm{GeV}$, the τ events are removed, with a 2% reduction in μe efficiency.

After all particle identification and kinematic cuts have been applied, the beam-constrained mass M_{bc} is calculated for each surviving candidate pair by constraining its energy to the beam energy. Two events with $M_{bc} > 1.82\,\mathrm{GeV}/c^2$ are found. A study of the M_{bc} distribution of $D^0 \rightarrow K^-\pi^+$ in the same data sample shows that 90% of those two-body decays lie within $\pm 0.0055\,\mathrm{GeV}/c^2$ of the D^0 mass (Figure 4). No μe candidate falls within this range.

The efficiencies for a μe signal and for each background channel are calculated using a Monte Carlo simulation of the detector. The efficiency for $D^0 \rightarrow \mu e$ is found to be $0.433 \pm 0.004 \pm 0.029$, while that for $D^0 \to \pi^+\pi^-$ is $0.0024 \pm 0.0004 \pm 0.0002$. Radiative corrections have a negligible effect on the efficiency. The contribution of initial state radiation, expected to be the same (to lowest order) for the μe and $K^-\pi^+$ final states, is accounted for by the method chosen to determine the range of the cut on M_{bc}. Energy loss due to multiple scattering of the electron in the detector is accounted for in the Monte Carlo simulation. Final state radiation shifts the tail to the high side of the M_{bc} peak, resulting in a loss of efficiency of $< 1.3\%$;[10] this effect has been included in the systematic error. After all analysis cuts, neither $D^0 \to K^-\pi^+$ decays nor $\tau^+\tau^-$ pair production contribute significantly.

The background to a μe signal is estimated to be $0.18 \pm 0.06 \pm 0.05$ $\pi^+\pi^-$ events.[6] The observation of no events of the type $D^0 \to \mu e$ yields a 90% confidence level (C.L.) upper limit ($N_{0.9}^{sb}$) of 2.30 on the total number of signal and background events. When all systematic errors are propagated linearly, this result leads to an upper limit on $B(D^0 \to \mu e)$ of 1.5×10^{-4}.[11] This bound, which is model-independent, is approximately an order of magnitude lower than previous model-dependent measurements.[12]

Both[13] Bayesian[14] and "classical"[15] interpretations of the 90% confidence interval are evaluated. These two techniques yield the results 2.77 and 2.70 events, respectively, after errors are propagated. The upper limit on the branching fraction $B(D^0 \to \mu e)$ was obtained by dividing by the efficiency and the total number of produced D^0's. Since the expected background is small, both methods yield the same 90% C.L. upper limit.

Choosing a particular model of family unification,[3] a lower bound on the mass of certain scalar leptoquarks with non-SU(5) symmetric couplings may be calculated:[16]

$$M_{LQ}^4 > \frac{\tau_{D^0} \cdot m_{D^0}^5 \cdot f_D^2 \cdot (|\bar{\lambda}_{ue}\xi^{(RL)}\lambda_{c\mu}|^2 + |\bar{\lambda}_{u\mu}\xi^{(RL)}\lambda_{ce}|^2)}{B(D^0 \to \mu^+ e^-) \cdot 128\pi(m_u + m_c)^2}$$

where λ is the general coupling strength of the leptoquark to quark-lepton pairs and ξ denotes the general propagator matrix. Figure 5 shows the C.L. versus the mass M_{LQ} derived from the limit for various values of the D meson decay constant f_D. The calculation of M_{LQ} is premised on a constant matrix element and coupling (both set to unity).

We gratefully acknowledge the efforts of the SPEAR staff. One of us (G.E.) wishes to thank the A. von Humboldt Foundation for support. This work was supported in part by the U.S. National Science Foundation and the U.S. Department of Energy under Contracts DE–AC03–76SF00515, DE–AC02–76ER01195, DE–AC03–81ER40050 and DE–AM03–76SF00034.

References

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2. Throughout this paper reference to a particle state also implies reference to its charge conjugate.

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5. D. Bernstein, *et al.,* Nucl. Inst. Meth. **226**, 301 (1984).

6. R. M. Baltrusaitis, *et al.,* Phys. Rev. Lett. **56**, 2140 (1986). The number of D^0's has been scaled to reflect the different integrated luminosity used in this analysis. The branching fractions employed: $\mathrm{B}(D^0 \rightarrow K^-\pi^+) = 0.056 \pm 0.004 \pm 0.003$; $\mathrm{B}(D^0 \rightarrow \pi^+\pi^-) = 0.0018 \pm 0.0006 \pm 0.0004$

7. See R. M. Baltrusaitis, *et al.,* Phys. Rev. Lett. **54**, 1976 (1985). An alternate electron selection procedure which uses the shower energy and one shape variable yields a slightly higher efficiency, while accepting more background. Separate analyses using the two algorithms give consistent results.

8. R. M. Baltrusaitis, *et al.,* Phys. Rev. Lett. **55**, 1842 (1985).

9. We define $\mathrm{E_{miss}} = \mathrm{E_{cm}} - (\mathrm{E}_e + \mathrm{E}_\mu + \sum_i \mathrm{E}^i_{\mathrm{neutral}})$. All neutral tracks are used in this calculation, which benefits from the full solid angle coverage of

the calorimeter. No photon selection cuts are applied.

10. F. A. Berends and R. Kleiss, Nucl. Phys. **B178**, 141 (1981).

11. The total statistical error (7.1%) and all separate systematic errors (6.5% for the number of D^0 and 6.7% for the efficiency) are added linearly to obtain the total relative error. This procedure increases $N^{sb}_{0.9}$ from 2.3 to 2.77.

12. H. Palka, *et al.,* CERN-EP/87-10 (1987); a 90% C.L. upper limit of 1.0×10^{-3} is reported; K. Riles, *et al.,* SLAC-PUB-4156 (1986) state 2.1×10^{-3}. These limits rely on knowledge of the production mechanisms, fragmentation functions, and D^0 branching ratios.

13. There is no generally accepted convention on how to define a 90% C.L. upper limit on a signal in the presence of expected background. Two common techniques addressed herein, the Bayesian and Classical approaches, in general may yield significantly different results.

14. A Bayesian 90% confidence interval is so constructed that there is a 90% "rational degree of belief" in the statement "the true value of the quantity in question lies within the interval" (cf. H.B. Prosper, Nucl. Inst. Meth. **A241**, 236 (1985)). In the case of a small number of observed and predicted events, this is calculated by performing an integral over all possible means, $n_s + n_b$, of the Poisson probability function (*i.e.*, all possible hypotheses), weighted by an *a priori* distribution function of these hypotheses. The choice of this distribution function is arbitrary; a uniform distribution of $(n_s + n_b)$ is usually selected. The C.L. is then chosen by determining

the value of n_s ($N^s_{0.9}$) below which 90% of the integral is found. In this experiment, the measurement of zero events causes all terms involving n_b to drop out when the integral is normalized, leaving a value of $N^s_{0.9} = 2.77$ after all errors are included.

15. In the case of a Poisson distribution, the Classical confidence level is defined as the probability that a given hypothesis (here, the sum of the signal n_s and background n_b) will give an observed number of events that is greater than the number actually seen by the experiment. See A. G. Frodesen *et al.*, **Probability and Statistics in Particle Physics** (Universitetsforlaget, Bergen, 1979), pp. 167–168, 378–379; H.B. Prosper, Nucl. Inst. Meth. **A241**, 236 (1985); G.L. Tietjen, **A Topical Dictionary of Statistics** (Chapman and Hall, New York, 1986), p.35; M. Aguilar-Benitez *et al.*, Phys. Lett. **B170**, 53 (1986). The limit on n_s ($N^s_{0.9}$) is derived from the limit on $N_{0.9} = (n_s + n_b)$ by subtraction of n_b from $N_{0.9}$. Within this framework, both the C.L. and the probability for the outcome of the experiment should be stated. In this experiment, the probability of observing no events in the presence of 0.07 expected background events (*i.e.*, the difference of the central value, 0.18, and the total error, 0.11)[11] is 93%. Thus $N^s_{0.9} = 2.70$ after all errors are included.

16. The following values are used : $m_{D^0} = 1.8646\,\mathrm{GeV}/c^2$, $m_u = 0.31\,\mathrm{GeV}/c^2$, $m_c = 1.65\,\mathrm{GeV}/c^2$, and $\tau_{D^0} = 4.3 \times 10^{-13}$ s.

FIGURE CAPTIONS

1. Diagram for the process $D^0 \to \mu e$, induced by a scalar leptoquark (LQ).

2. Monte Carlo generated distributions of $\mathrm{M_{inv}}$ for the μe signal and for the $K^-\pi^+$ and $\pi^+\pi^-$ backgrounds. The invariant mass is required to lie within $\pm 0.05\,\mathrm{GeV}/c^2$ of the D^0 mass. Lepton selection criteria have already been applied.

3. Monte Carlo generated distributions of $\mathrm{E_{miss}}$ for *two-prong events only* from $D^0\bar{D}^0 \to$ (μe + no charged tracks) and from $\tau^+\tau^-$ pair production. As the former channel constitutes 6% of all $D^0 \to \mu e$ events, the cut at $\mathrm{E_{miss}} = 1\,\mathrm{GeV}/c^2$ reduces the $D^0 \to \mu e$ efficiency by only 2%. All lepton selection criteria have been applied.

4. $\mathrm{M_{bc}}$ distribution for $K^-\pi^+$ events in the data (used to determine the $\pm 0.0055\,\mathrm{GeV}/c^2$ cut on $\mathrm{M_{bc}}$). Superimposed are the two closest $D^0 \to \mu e$ candidates, that pass all other cuts.

5. The solid lines show the confidence level (C.L.) for our result (including errors), calculated for different values of f_D (in MeV), as a function of M_{LQ}. The shaded regions reflect the effect of propagating the errors in the limit calculation.

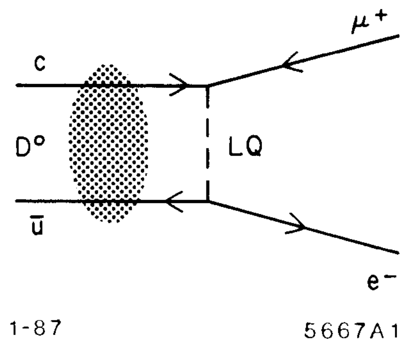


Fig. 1

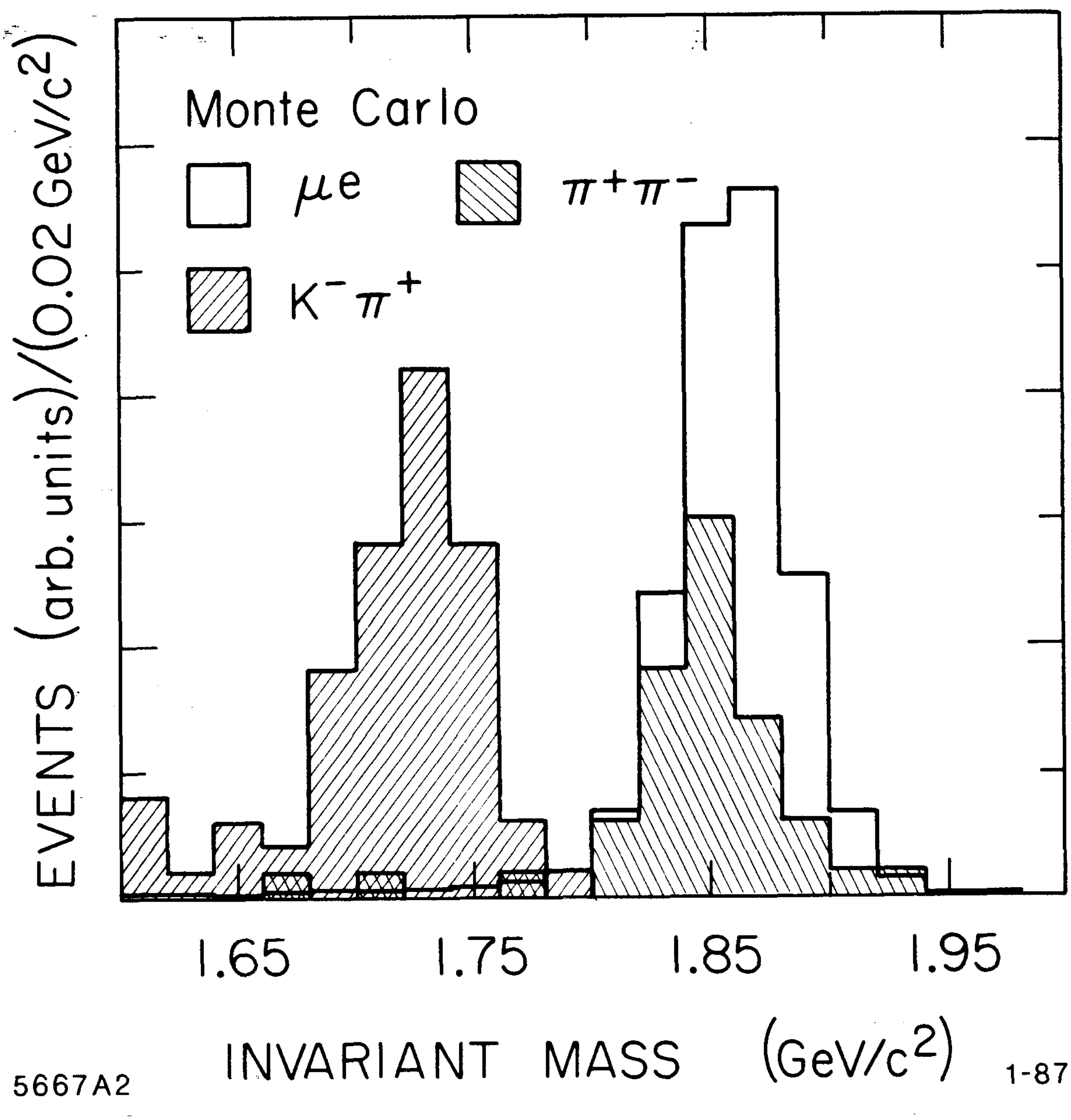

Monte Carlo
μe
π⁺π⁻
K⁻π⁺
EVENTS (arb. units)/(0.02 GeV/c²)
1.65
1.75
1.85
1.95
INVARIANT MASS (GeV/c²)
5667A2
1-87

Fig. 2

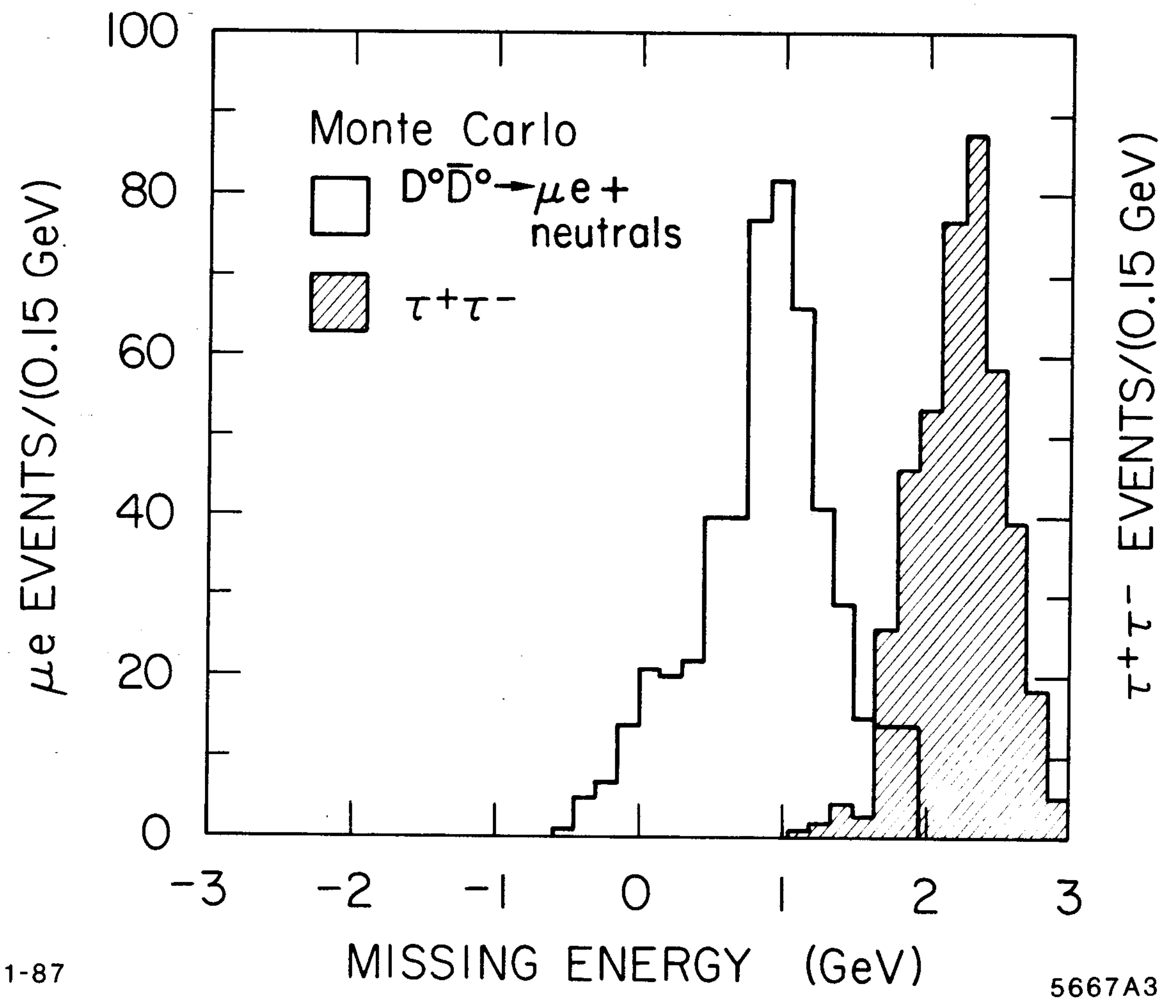

100
80
60
40
20
0
Monte Carlo
D°D̄°→μe + neutrals
τ+τ−
μe EVENTS/(0.15 GeV)
τ+τ− EVENTS/(0.15 GeV)
−3
−2
−1
0
1
2
3
MISSING ENERGY (GeV)
1-87
5667A3

Fig. 3

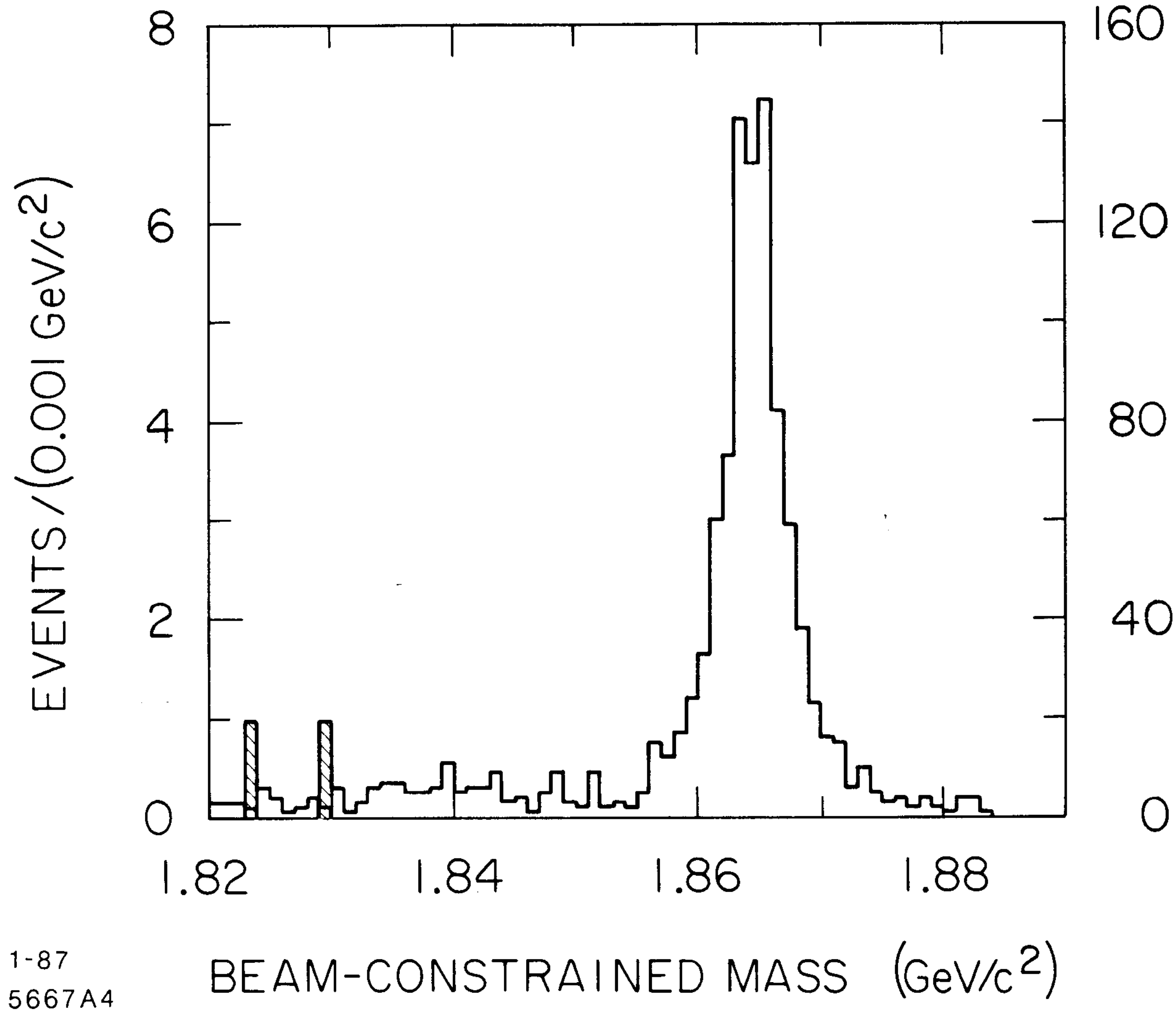
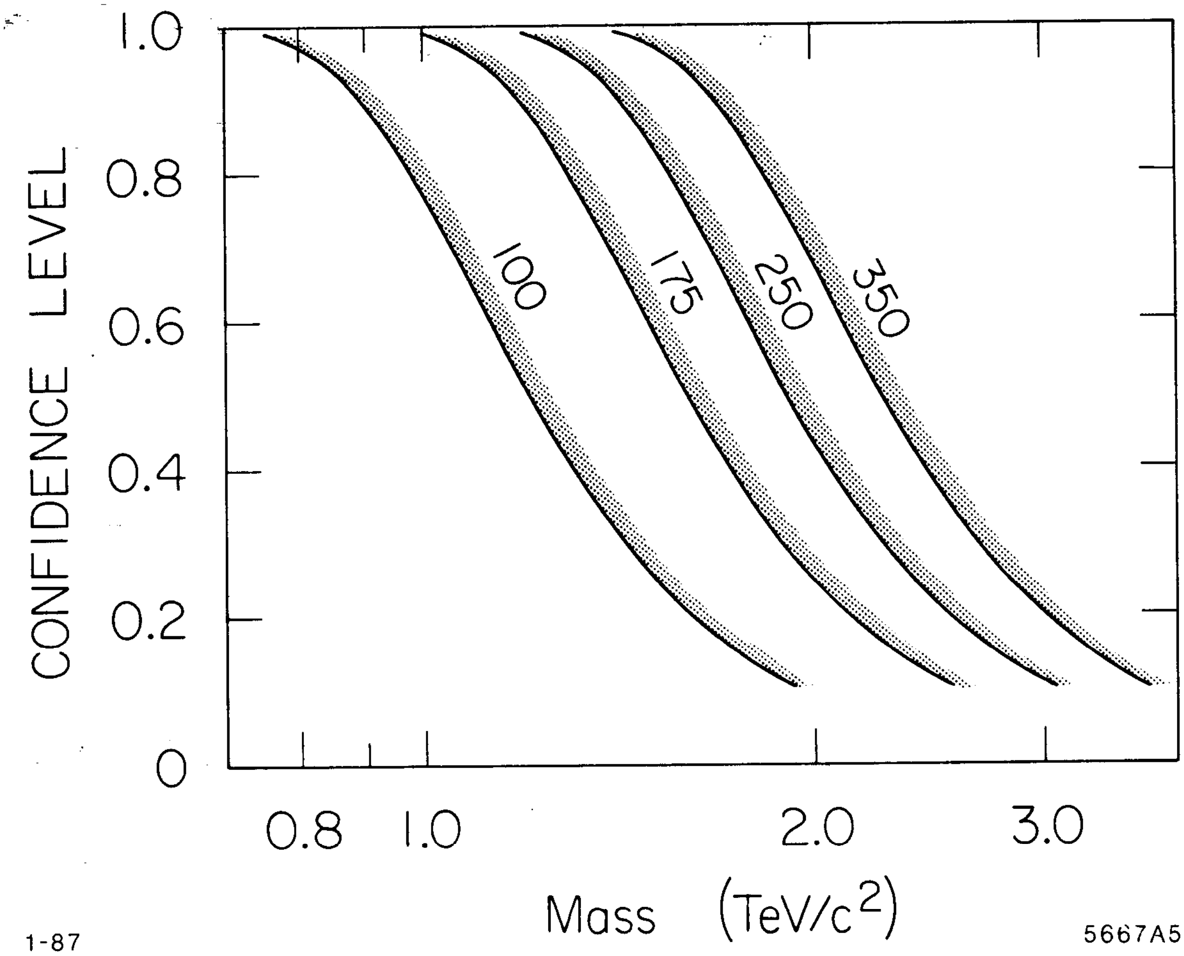

8
6
4
2
0
160
120
80
40
0
EVENTS/(0.001 GeV/c²)
1.82
1.84
1.86
1.88
BEAM-CONSTRAINED MASS (GeV/c²)
1-87
5667A4

Fig. 4



CONFIDENCE LEVEL
1.0
0.8
0.6
0.4
0.2
0
100
175
250
350
0.8
1.0
2.0
3.0
Mass (TeV/c^2)
1-87
5667A5

Fig. 5