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Search for Monojet Production in e^+e^- Annihilation*

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ABSTRACT

A search for monojet production in e^+e^- annihilation has been performed at $\sqrt{s} = 29$ GeV with the MAC detector at PEP. No events beyond those expected from tau decays have been found. The result has been interpreted as an upper limit for Z^0 decays into monojets, giving an upper limit for the branching ratio of 0.5% at the 90% confidence level. This limit excludes an interpretation that the monojets discovered by the UA1 collaboration are due to Z^0 decays into light Higgs pairs.

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The standard electroweak theory has proven very successful in describing present high energy experiments. The discovery of the intermediate vector bosons at the CERN $\bar{p}p$ collider has placed the theory on even more solid ground. On the other hand, the collider experiments have found some classes of anomalous events[1] which may not fit in the standard model and which have stimulated considerable theoretical speculation.[2] Monojet events are one such class of events. There have been proposed interpretations speculating that the monojets are direct products of Z^0 decay into either new neutral lepton pairs[3] or light Higgs particle pairs.[4] These models also predict an observable rate for monojet production in the currently operating e^+e^- storage rings via virtual Z^0 production.

This report describes a search for monojet events in e^+e^- annihilation. The data were collected with the MAC detector at the PEP storage ring at SLAC. The integrated luminosity for the sample is 238 pb^{-1} at a center of mass energy of 29 GeV.

With minimal dead regions and nearly 4π sr coverage from both tracking and calorimetry, the MAC detector is well suited for the identification and study of reactions with missing energy, as demonstrated by previous searches for single electron[5] and single photon[6] events. The detector consists of a 10 layer drift chamber covering polar angles greater than 17° from the beam axis with at least 5 layers. Surrounding the drift chamber is a hexagonal barrel of calorimeters for detecting electromagnetic and hadronic showers. Planar endcap calorimeters and scintillation counters provide additional polar angle coverage down to $\approx$10° from the beam axis. Hadronic calorimeters consisting of about 6 absorption lengths of steel plates provide good detection for hadronic jets including K_L^0 and neutrons. Therefore, any large missing energy is due to the escape of neutrinolike particles. About 94 pb^{-1} of the total data was accumulated with small angle veto calorimeters constructed from proportional chamber planes and 8.5 radiation lengths of lead. These chambers extend the polar angle coverage to 5° from the beam axis. A detailed description of the detector is given elsewhere.[7]

The major triggers for this search require: 1) one or more penetrating tracks, defined by a cluster of central drift chamber hits in coincidence with energy deposition of 500 MeV or more in the associated calorimeter sextant; or 2) at least 1.5 GeV of energy deposition in the central shower chamber in coincidence with energy deposition of 1.5 GeV or more in the hadron calorimeter. About 124 pb^{-1} of the data was accumulated with an additional trigger which required only energy deposition characteristic of a single electromagnetic shower of more than 1.5 GeV in the central shower chamber.

The monojets found by the UA1 collaboration are quite different from typical quark and gluon jets at high energy, namely the charged multiplicity is small ($1 \leq n_c \leq 4$), and the charged particle invariant mass is also small (0.5 GeV/$c^2 \leq m_c \leq 3.1$ GeV/c^2). In the present search for such unusual single jets, the following data selection criteria have been developed: 1) at least two charged tracks are reconstructed in the central drift chamber; 2) the polar angle of the thrust axis calculated from the calorimeter hits satisfies $|\cos\theta_{\mathrm{thrust}}| \leq 0.8$; 3) $P_{\perp}$, the total transverse momentum of the jet calculated from charged tracks, is greater than 3 GeV/c; and 4) one hemisphere defined by the plane normal to the thrust axis must contain energy deposition less than 0.5 GeV and no charged tracks. Events were rejected if there was energy deposition at small angles in the endcap calorimeters or scintillators, or in the small angle veto calorimeters. The total transverse momentum distribution of the selected monojet candidates is shown in Fig. 1. Fig. 1(a) corresponds to the data taken without the small angle veto chamber system, and Fig. 1(b) corresponds to the data taken with this system.

Experimental backgrounds arise from two types of processes: 1) those with a large angle jet together with other particles produced at angles outside the detector acceptance, and 2) the processes $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$. The two-photon annihilation reactions, $e^+e^- \rightarrow e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$, $e^+e^-\tau^+\tau^-$, or $e^+e^-q\bar{q}$, with unobserved beam particles escaping in the beam pipe, can produce the first type of background. However, the transverse momentum of the observed jet in these processes must be balanced by that of the unobserved particles. If efficient particle detection extends to within a small angle $\theta_{\rm veto}$ from the beam axis, then $P_\perp$ is kinematically limited by $P_\perp \leq (\sqrt{s} - {\rm E}^{\rm jet}) \sin\theta_{\rm veto}$, where ${\rm E}^{\rm jet}$ is the energy of the detected jet. A search region in $P_\perp$ was chosen well removed from the above backgrounds. The first sample of 144 pb^{-1} had $\theta_{\rm veto} \approx 10°$ with the search region chosen as $P_\perp \geq 5$ GeV/c. The second data sample of 94 pb^{-1} had $\theta_{\rm veto} = 5°$, expanding the search region to include $P_\perp \geq 3$ GeV/c. The peak around 3 GeV/c seen in Fig. 1(a) can be explained by the two-photon annihilation backgrounds and is not present in the data sample taken with the additional small angle veto requirement, as shown in Fig. 1(b).

The second type of background is expected from the reactions $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$ where one tau decays into a jet and the other tau decays into either i) a particle with very low momentum ($\leq$ 20 MeV/c) which stays inside the beam pipe, or ii) a particle traveling opposite to the parent tau direction. In each case one or more neutrinos carry away most of the associated tau energy. This background has been calculated by a Monte Carlo simulation. The program of Berends, Kleiss, and Jadach[8] was used to calculate the prediction for $\tau^+\tau^-(\gamma)$

to order α^3. The tau decays were simulated as accurately as possible including all the known decay modes. The events were then passed through the MAC detector simulation program and subjected to the selection criteria used for real data. It was found that 7.0 events were expected in the first data sample and 6.2 events in the second data sample, where the numbers of observed events were 7 and 4 respectively. The calculated distributions of these tau events are shown as the dashed curves in Fig. 1. Figure 2 shows the invariant mass distribution for the observed events as well as the expected distribution for tau decays. The high mass tail of the calculated tau distribution results from events in which one of the taus produces a backwards decay particle. The observed events are seen to be completely consistent with the tau decay hypothesis. These events also have the characteristic low multiplicity of tau decays, specifically no events were found with five or more charged particles.

Upper limits at the 90% confidence level for monojet production have been calculated from the combined data samples by subtracting the calculated tau backgrounds. The detection efficiencies used in the calculation were determined for the detector and trigger configurations for each data sample assuming the two different monojet production models described below. In order to combine the data samples, an effective detection efficiency was obtained by taking an average of these efficiencies weighted by the integrated luminosity of each data sample.

An interpretation of this cross section limit may be made in terms of virtual Z^0 production and decay. The total cross section $e^+e^- \to m_1 m_2$ may be written:

$$\sigma_{m_1 m_2} = \frac{G_F M_Z \Gamma_Z s}{\sqrt{2}((s - M_Z{}^2)^2 + M_Z^2 \Gamma_Z^2)}(1 - 4\sin^2\theta_W + 8\sin^4\theta_W) \cdot BR_{m_1 m_2}$$

where G_F is the Fermi coupling constant, M_Z=92 GeV/c^2 and Γ_Z=3.0 GeV are the Z^0 mass and width, and $BR_{m_1m_2}$ is the Z^0 branching ratio of the decay responsible for the monojet events.

The upper limit for the branching ratio $BR_{m_1m_2}$ has been calculated for two cases:

1) m_1=0.2 GeV/c^2 and m_2 variable, and

2) m_1=m_2 variable.

Case 1 has mass conditions suitable for the Glashow-Manohar model[4] as a monojet source, namely production of Higgs particles $e^+e^- \to \chi^0\lambda^0$ followed by $\chi^0 \to \tau^+\tau^-$ or $c\bar{c}$ decay. The scalar Higgs particle λ^0 has a long lifetime because of its small mass and does not interact in the detector. The mass of the λ^0 was assumed to be 0.2 GeV/c^2 and the mass of the χ^0 was varied from 4 to 10 GeV/c^2, a range compatible with the CERN monojet events. The production angular distribution for this case is $d\sigma/d\Omega \propto \sin^2\theta$ and the χ^0 was assumed to decay preferentially into $\tau^+\tau^-$ or $c\bar{c}$ giving a jet detection efficiency of about 60%. If no mixing of the Higgs particles is assumed, the Z^0 decay rate into a Higgs particle pair is well defined and the expected branching ratio for $Z^0 \to \chi^0\lambda^0$ is given by:[9]

$$BR_{\chi^0\lambda^0} = \frac{G_F M_Z^3}{24\sqrt{2}\pi\Gamma_Z} \cdot [1 - \frac{2}{s}(m_\chi^2 + m_\lambda^2) + \frac{1}{s^2}(m_\chi^2 - m_\lambda^2)^2]^{\frac{3}{2}}$$

where m_χ and m_λ are the χ^0 and λ^0 masses respectively.

Case 2 is applicable to the case of Z^0 decay into a neutral heavy lepton pair ($N\bar{N}$). In order to produce a monojet, one neutral heavy lepton is assumed to decay into three neutrinos with a branching ratio on the order of 10% while the other is assumed to decay into a jet.[10] The model of Gronau *et al.*[11] was used for the neutral heavy lepton decay simulations and the mass of the neutral heavy lepton was varied from 2 to 10 GeV/c^2. The production angular distribution in this case is $d\sigma/d\Omega \propto (1+\cos^2\theta)$ and the jet detection efficiency is about 50%. The expected branching ratio for $Z^0 \rightarrow N\bar{N}$ followed by $N \rightarrow \nu\nu\bar{\nu}$ is given by:

$$BR_{N\bar{N}} = \frac{G_F M_Z^3}{24\sqrt{2}\pi\Gamma_Z}\cdot 2(1-\frac{4m_N^2}{s})^{\frac{1}{2}}\cdot(1-\frac{m_N^2}{s})\cdot 2BR_{\nu\nu\bar{\nu}}\cdot(1-BR_{\nu\nu\bar{\nu}})$$

where m_N is the mass of the neutral heavy lepton.

Figure 3 shows the 90% confidence level upper limit for the monojet cross section and Z^0 branching ratio as a function of the mass for the two cases described above. The calculated branching ratios for each of these two cases are also shown in Fig. 3 and are about 3% for case 1 and about 1% for case 2 if $BR_{\nu\nu\bar{\nu}}$ is taken to be 0.1. The theoretical distributions for the jet invariant mass are shown in Fig. 2 for the case of a 4 GeV/c^2 parent mass. It can be seen that both models predict significantly more events with jet invariant mass above 2 GeV/c^2 than are observed. For parent masses greater than 4 GeV/c^2 the discrepancy becomes considerably larger. The above limits are valid only if the particles assumed to be responsible for the jets have lifetimes less than about 10^{-11} sec, due to the vertex constraints on the reconstructed tracks.

On the basis of the above limits, the hypothesis that the UA1 monojet events are due to Z^0 decays into light Higgs particles is ruled out even if mixing angle effects of Higgs particles reduce the cross section by as much as a factor of 5. The hypothesis that the CERN events are due to Z^0 decays into neutral heavy leptons is ruled out for a branching ratio into monojets as small as about 0.5% for Z^0 decays into masses up to approximately 10 GeV/c^2. The results for the Higgs case are more sensitive than recent results from similar searches reported by the HRS[12] and Mark II[13] Collaborations. Limits for monojets arising from neutral heavy leptons have not been reported previously.

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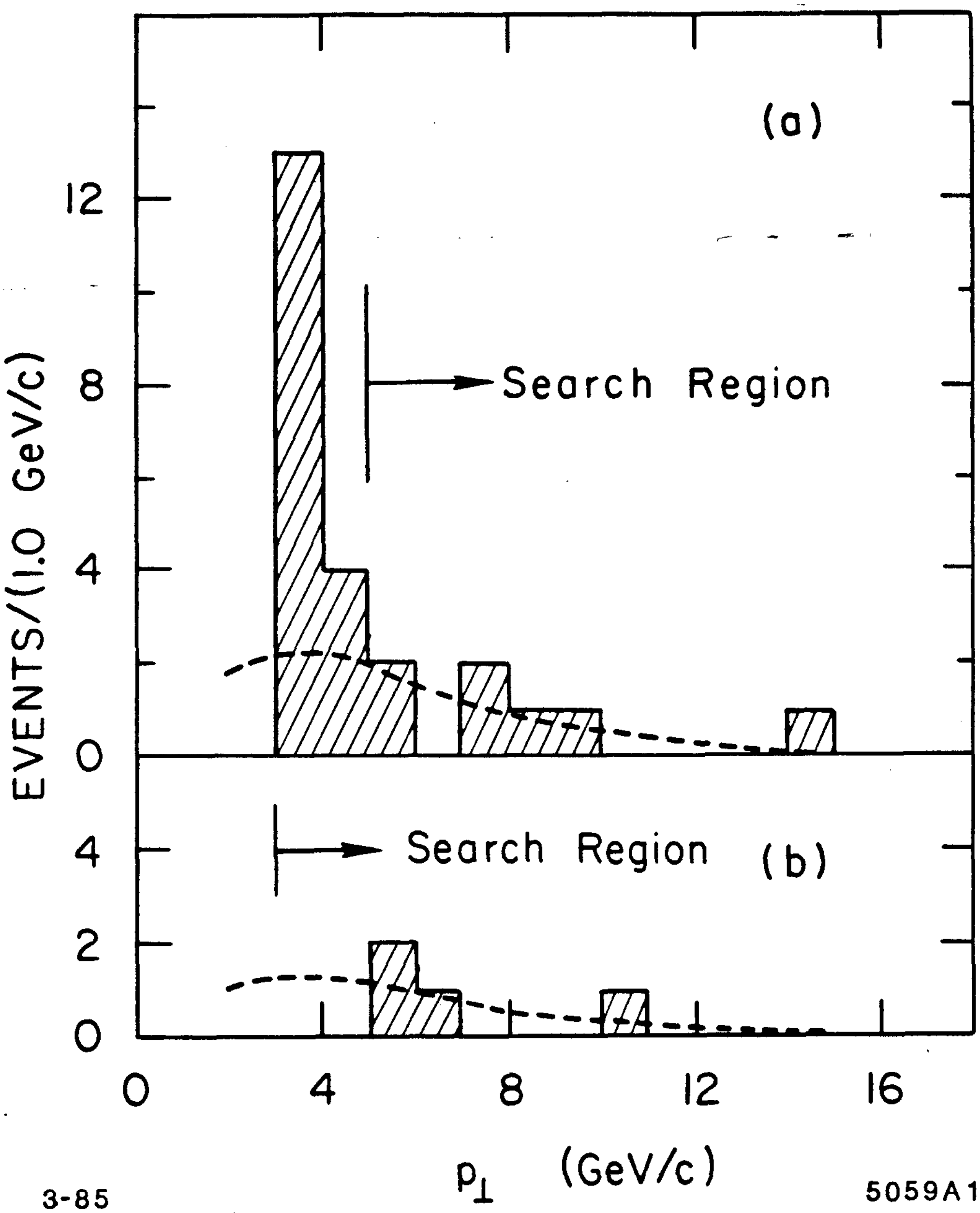
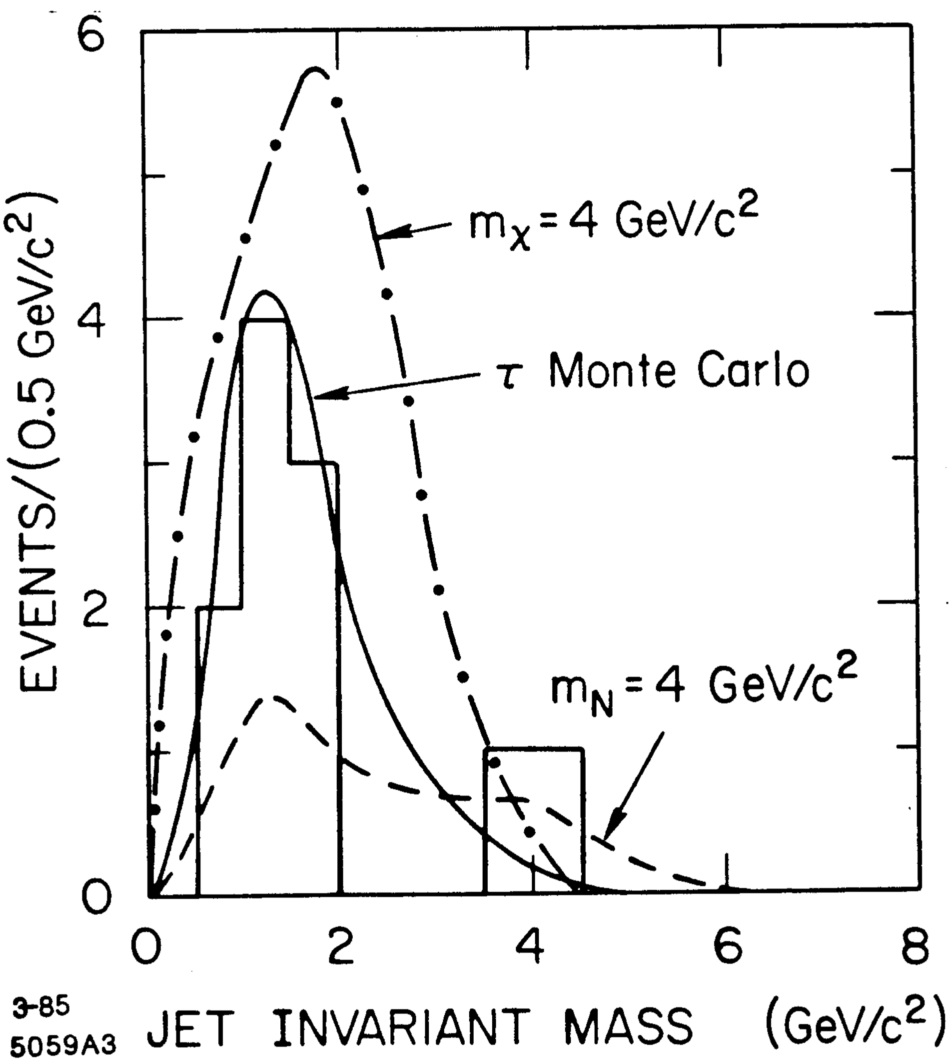
FIGURE CAPTIONS

1. (a) The observed $P_\perp$ spectrum for the first data sample of 144 pb^{-1} with $\theta_{veto} = 10°$ and search region $P_\perp > 5.0$ GeV/c^2. (b) The observed $P_\perp$ spectrum for the second data sample of 94 pb^{-1} with $\theta_{veto} = 5°$ and search region $P_\perp > 3.0$ GeV/c^2.
2. The invariant mass distribution of the 11 observed events together with the distribution expected for tau decays (solid line), a 4 GeV/c^2 Higgs (dot-dashed line), and a 4 GeV/c^2 neutral heavy lepton (dashed line).
3. Upper limits at the 90% confidence level for the monojet production cross section and Z^0 decay branching ratio into monojets for the two cases described in the text. The figure also shows the calculated Z^0 decay branching ratio for these two cases.



(a)
Search Region
Search Region
(b)
EVENTS/(1.0 GeV/c)
0
4
8
12
0
2
4
0
4
8
12
16
$p_\perp$ (GeV/c)
3-85
5059A1

Fig. 1



EVENTS/(0.5 GeV/c²)
6
4
2
0
0
2
4
6
8
m_χ = 4 GeV/c²
τ Monte Carlo
m_N = 4 GeV/c²
3-85
5059A3
JET INVARIANT MASS (GeV/c²)

Fig. 2

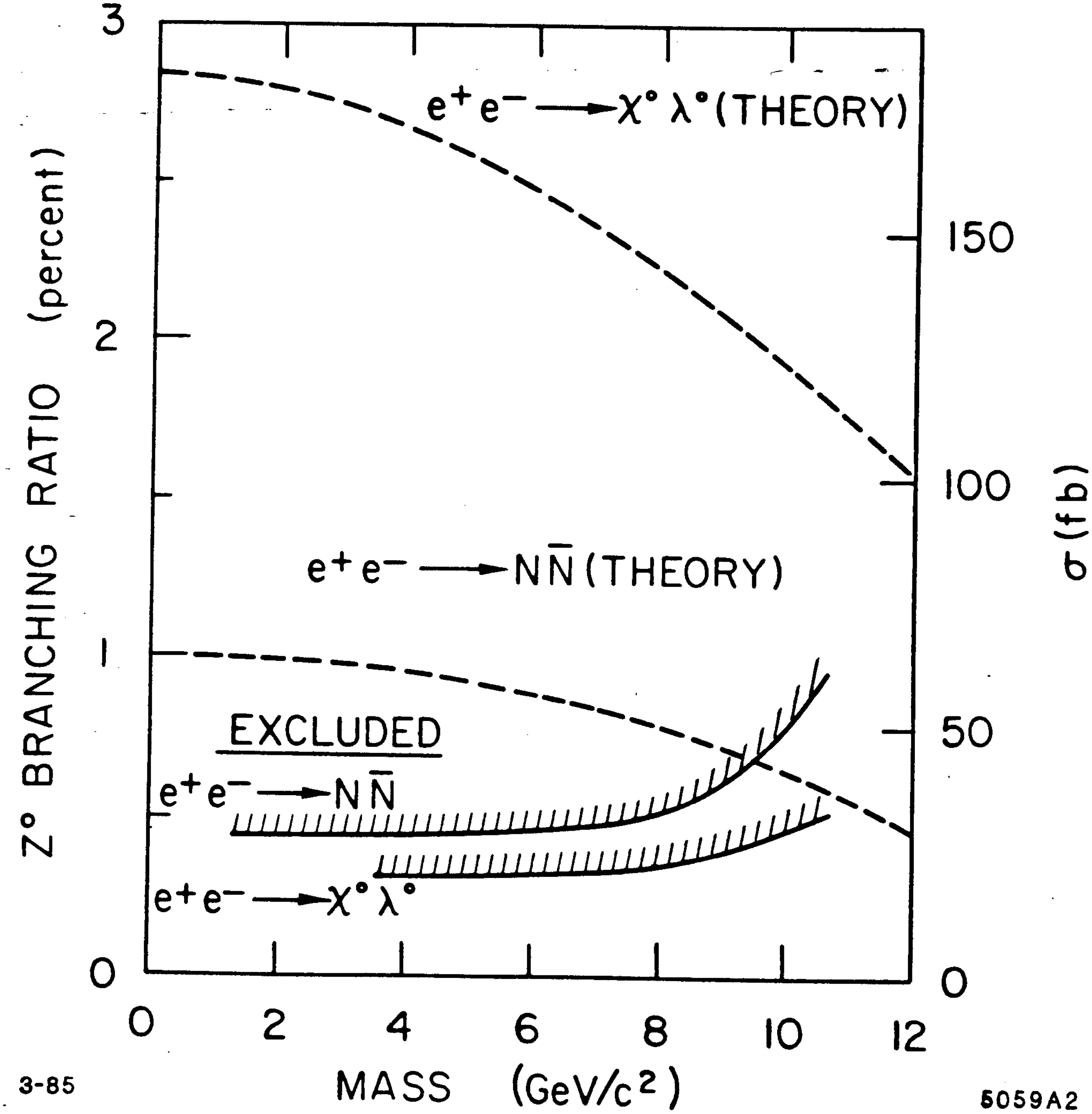

3
2
1
0
150
100
50
0
e+e− ⟶ χ° λ° (THEORY)
e+e− ⟶ N N̄ (THEORY)
EXCLUDED
e+e− ⟶ N N̄
e+e− ⟶ χ° λ°
Z° BRANCHING RATIO (percent)
σ (fb)
0
2
4
6
8
10
12
MASS (GeV/c²)
3-85
5059A2

Fig. 3