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SEARCH FOR A CHARGED-LEPTON SPECIFIC FORCE IN ELECTRON-POSITRON COLLISIONS*

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ABSTRACT

We have used e^+e^- collisions at 29 GeV to search in the reactions $e^+e^- \rightarrow e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$ for a charged-lepton specific force — a hypothetical force which would be associated only with charged leptons. No evidence was found. The limits of the search are described in terms of the mass and coupling strength of a particle which might carry such a force.

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In speculations on unknown forces which might act on elementary fermions, it is usual to assume that any force which acts on leptons will also act on quarks. This is a straightforward extension of the properties of the electroweak and gravitational forces. However, in searches for an unknown force it is important to consider the possibility that the force might only be associated with charged-leptons,[1] invalidating searches and limits which depend on processes involving quarks or neutrinos. In our thinking we suppose the charged-lepton specific force is carried by a neutral boson called λ with mass m_λ. Some limits[1] on the existence and properties of the λ can be derived from related limits pertaining to axions and Higgs particles, providing the latter limits are derived from purely leptonic processes. When m_λ is larger than several tens of MeV/c^2 previous limits[1] come from measurements of $g_e - 2$, $g_\mu - 2$, $e^+e^- \to e^+e^-$, and $e^+e^- \to \mu^+\mu^-$. In this paper we describe a new search for the λ using the process in Fig. 1a

$$\begin{aligned} &e^+ + e^- \to e^+ + e^- + \lambda \\ &\lambda \to e^+ + e^- \text{ or } \lambda \to \mu^+ + \mu^- \end{aligned} \tag{1}$$

where λ is a real particle.

We use electron-positron collision events obtained by the Mark II detector[2] at the PEP storage ring. The total energy is 29 GeV and the total luminosity is 205 pb^{-1}. The principle production mechanism for the reaction in Eq. 1 is similar to the virtual Compton scattering process, where one final e^+ or e^- remains close to the beamline. The other e^- or e^+ and the λ are produced at larger angles. This topology corresponds to a pole in the cross section, yielding a large cross section for λ production. In the parameter region of this search, the lifetime of the λ would be too short to permit detection of a secondary vertex. Therefore, the event signatures are

$$e^+ + e^- \rightarrow e^\pm + e^+ + e^- + x_{miss} \tag{2a}$$

$$e^+ + e^- \rightarrow e^\pm + \mu^+ + \mu^- + x_{miss} \tag{2b}$$

where x_{miss} represents a missing particle of zero mass whose direction of motion is close to the beamline.

The general event selection criteria were:

(i) 3 charged particles detected, each with momentum $p \geq 1.$ GeV/c;

(ii) No isolated[3] photon with energy above 0.2 GeV;

(iii) At least 2 identified leptons and no identified hadron;

(iv) The particle identifications must be consistent with the event containing an e^+e^- pair or a $\mu^+\mu^-$ pair.

We found 794 events satisfying criteria i – iv.

The precision of the momentum and angle measurements of the Mark II detector does not permit a precise determination of the missing mass; the error is of the order of 1 GeV/c^2. Therefore, a set of kinematic criteria were used to select events approximately fitting Eq. 2.

(v) The total energy of the 3 charged particles is $E_{tot} \geq 15.$ GeV;

(vi) The magnitude of the momentum transverse to the beam line is $P_t \leq 1.$ GeV/c;

(vii) The magnitude of the momentum parallel to the beam line is $|P_{long}| > 1.$ GeV/c.

These criteria reduce the number of events to 138. We then applied a criteria to eliminate eee events with very small mass e^+e^- pairs.

$(viii)$ All e^+e^- pairs in the event have $m_{ee} \geq 70$ MeV/c^2.

This left 65 eee events and 36 $e\mu\mu$ events.

The spectra of the e^+e^- and $\mu^+\mu^-$ pair masses, m_{ee} and $m_{\mu\mu}$, are given in Fig. 2. There are two entries in Fig. 2a for each eee event, and one or two entries in Fig. 2b for each $e\mu\mu$ event (depending on whether one or two muons are clearly identified and on the sign of the charges of the identified muons). The existence of a λ would show up as a bunching of events in Fig. 2. To our disappointment there is no bunching of events. Therefore, our remaining task is to set limits on the mass and coupling strength of the hypothetical λ.

The obvious source of background events to the λ search are the purely electromagnetic processes

$$e^+ + e^- \rightarrow e^+ + e^- + e^+ + e^-,\ e^+ + e^- + \mu^+ + \mu^- \tag{3}$$

with Feynman diagrams such as the one in Fig. 1b. Rather than calculate these as well as any other background processes, we simply fit a function to the observed events, as shown in Fig. 2. This function is then used as the differential cross section for the background to the λ search.

Quantitative evaluation of the sensitivity of this search requires models for the interaction of the λ with leptons. We use two models: (a) the λ is a scalar with coupling $g_{\lambda\ell}\phi_\lambda\bar{v}_\ell u_\ell$ and (b) the λ is a vector particle with coupling $g_{\lambda\ell}\epsilon^\mu_\lambda\bar{v}_\ell\gamma_\mu u_\ell$. We assume the λ-lepton vertex conserves lepton number. For the mass range explored in this paper, the limits for scalar λ are the same as that for pseudoscalar λ, and the limits for axial-vector λ are the same as that for vector λ. This search is only sensitive to the coupling of the λ to electrons, with coupling constant

$\alpha_{\lambda e} = g_{\lambda e}^2/(4\pi)$, since the λ bosons are radiated from electrons. The coupling constants to the other charged leptons may vary, but they only enter into the calculation of the lifetime and the branching ratios of the λ.

The experimentally accepted cross section for λ production is determined using Monte Carlo methods. A Monte Carlo program for $e^+e^- \to e^+e^-\lambda$ was written using the Weizsäcker-Williams equivalent photon approximation[4]. The λ boson is in turn decayed into e^+e^- or $\mu^+\mu^-$ pairs. Events generated by the Monte Carlo program are passed through a detector simulation program and then analyzed by the same program used to analyze the real data.

The 90% confidence limits for $\alpha_{\lambda e}$ versus m_λ are obtained using a Bayesian statistical analysis[5]. For a given value of the λ mass, $m_{\lambda 0}$, the acceptance region is defined as

$$m_{\lambda 0} - \frac{3\sigma_m}{2} < m_\lambda \leq m_{\lambda 0} + \frac{3\sigma_m}{2} \qquad (4)$$

where σ_m is the detector mass resolution as determined using Monte Carlo generated events passed through the detector simulation. The number of mass pairs expected to fall into this region due to background processes is calculated from the functions shown in Fig. 2. The probability of observing N events for b events expected from background sources and n_λ events expected from λ production is based on Poisson statistics:

$$P(N) = \frac{(n_\lambda + b)^N e^{-(n_\lambda + b)}}{N!} \qquad (4)$$

The formula for the confidence limit is then

$$C.L. = \frac{\int_0^{n_\lambda} (s+b)^N e^{-(s+b)} ds}{\int_0^\infty (s+b)^N e^{-(s+b)} ds} \qquad (5)$$

The 90% upper confidence limit on n_λ is that value of n_λ for which $C.L. = 0.90$.

This upper limit on n_λ is related to the lower limit on $\alpha_{\lambda e}$ by

$$\alpha_{\lambda e} = \frac{n_\lambda}{\sigma_\lambda \times L} \tag{6}$$

where L is the luminosity and σ_λ is the equivalent cross section for the number of pairs in the mass acceptance region expected from λ production with $\alpha_{\lambda e} = 1.0$, as shown in Fig. 3.

The 90% lower confidence limits on $\alpha_{\lambda e}$ are determined for two λ branching ratio cases:

$a: \; Br(\lambda \to e^+e^-) \gg Br(\lambda \to \mu^+\mu^-)$

$b: \; Br(\lambda \to \mu^+\mu^-) \gg Br(\lambda \to e^+e^-)$

The case for $\lambda \to \tau^+\tau^-$ is not considered. The resulting limits for both the scalar and vector λ cases are shown in Fig. 4. These limits are the most stringent yet determined for λ masses above 100 MeV/c^2 [1].

REFERENCES

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2. The Mark II detector is described in R. H. Schindler *et al.*, Phys. Rev. **D24**, 78 (1981); G. S. Abrams *et al.*, IEEE Trans. Nucl. Sci. **27**, 59 (1980).

3. An isolated photon is a photon which is either (a) greater than 20 cm distant from every charged particle track at the entrance to the liquid argon electromagnetic shower counter, or (b) if within 20 cm of a track has greater energy than that track.

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FIGURE CAPTIONS

Fig. 1. Examples of Feynman diagrams for: a) λ production, b) four lepton background.

Fig. 2. Invariant mass combinations for observed events. The curves are fitted to the points.

Fig. 3. Cross sections with $\alpha_{\lambda e} = 1$ for the number of pairs with an invariant mass within the mass acceptance region for a given m_λ.

Fig. 4. 90% confidence limits on $\alpha_{\lambda e}$ versus m_λ for (a) $Br(\lambda \to e^+e^-) \gg Br(\lambda \to \mu^+\mu^-)$, and (b) $Br(\lambda \to \mu^+\mu^-) \gg Br(\lambda \to e^+e^-)$.

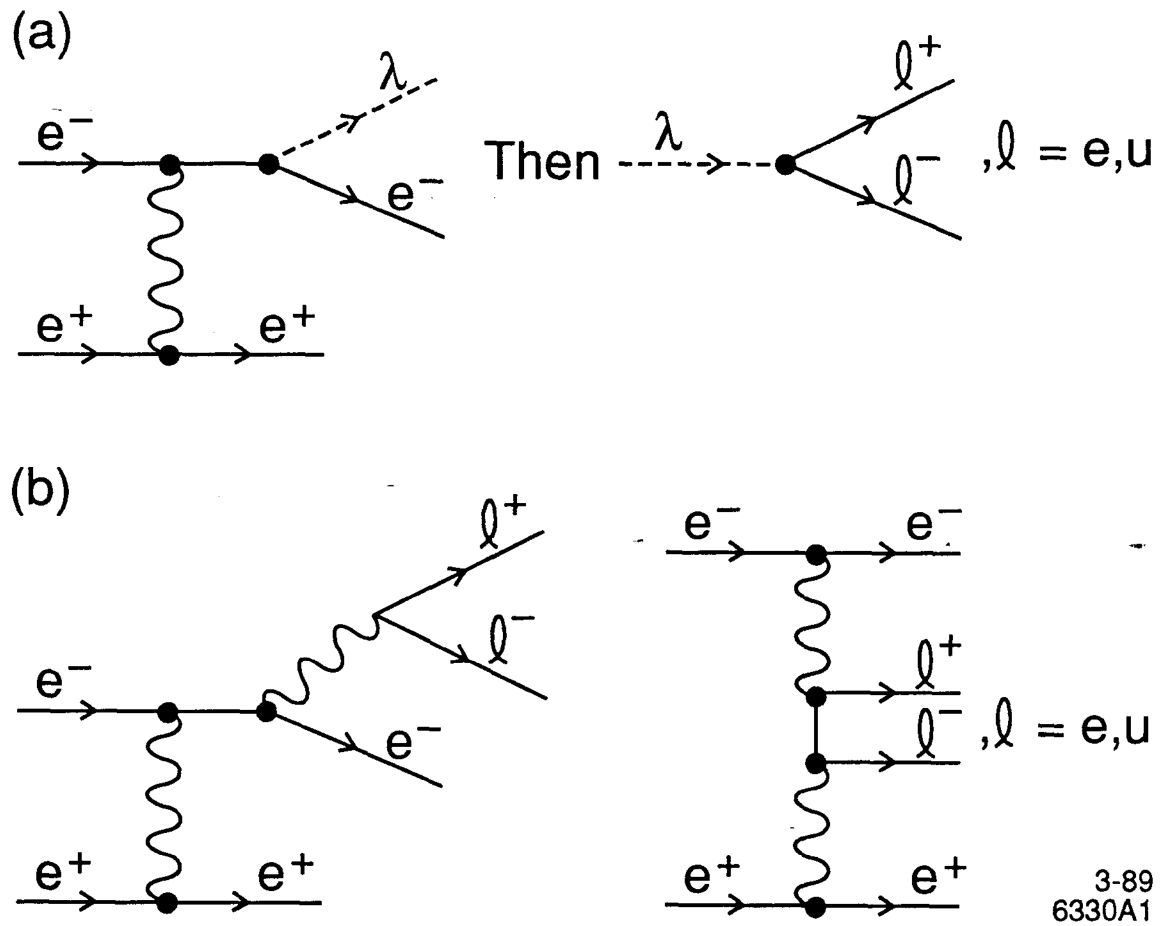


Fig. 1

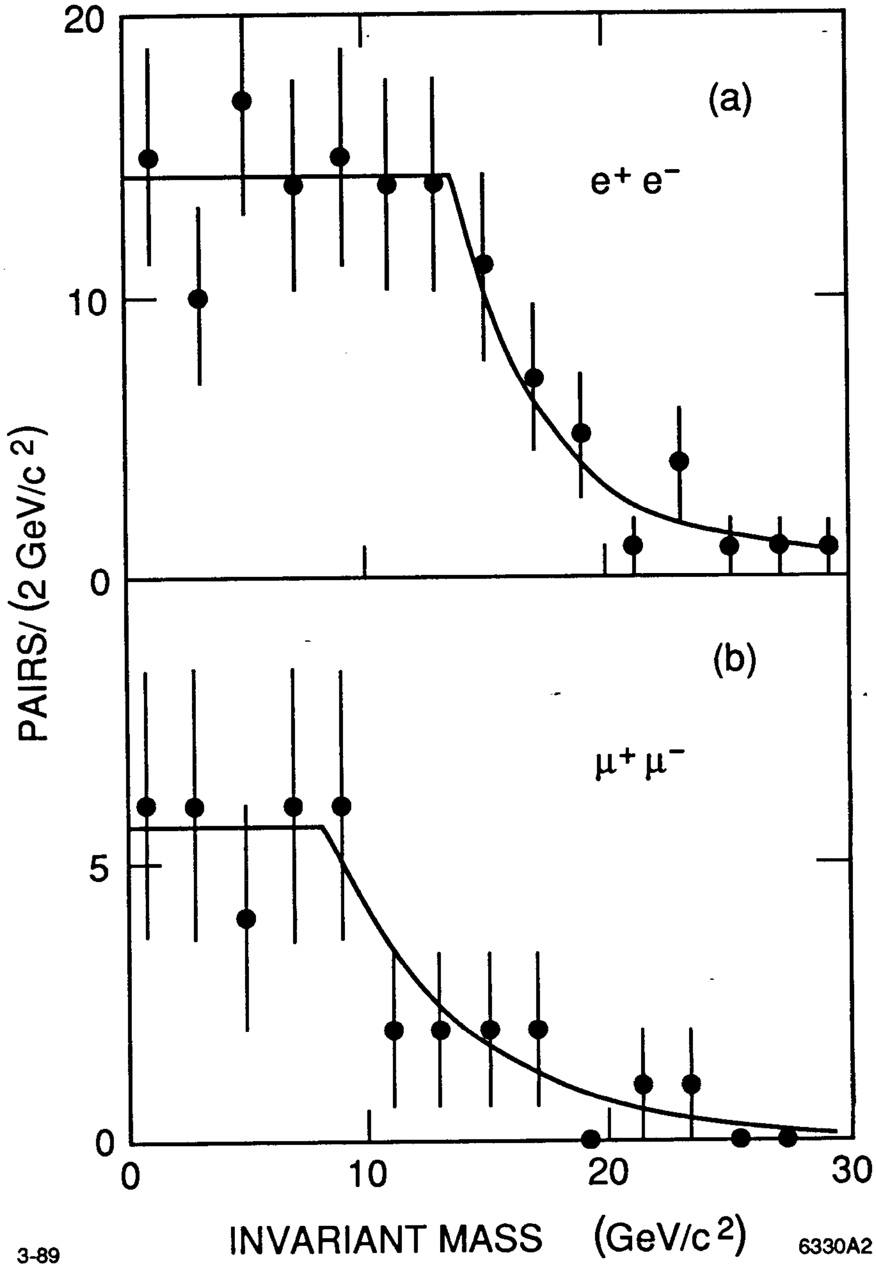
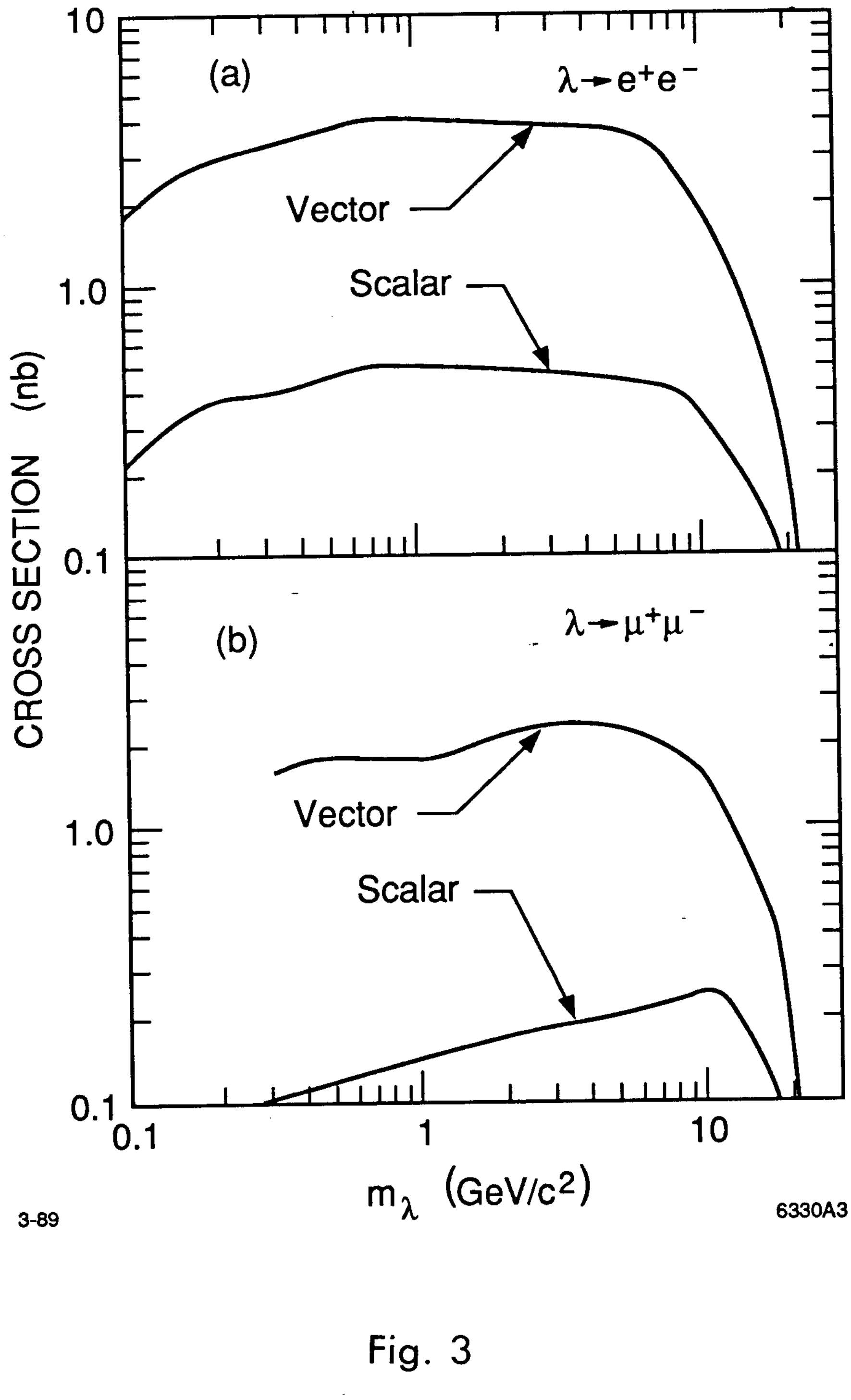

20
10
0
5
0
(a)
e+ e−
(b)
μ+ μ−
PAIRS/ (2 GeV/c 2)
0
10
20
30
INVARIANT MASS (GeV/c 2)
3-89
6330A2

Fig. 2



10
(a)
λ→e+e−
Vector
Scalar
1.0
0.1
CROSS SECTION (nb)
(b)
λ→μ+μ−
Vector
Scalar
1.0
0.1
0.1
1
10
mλ (GeV/c2)
3-89
6330A3

Fig. 3

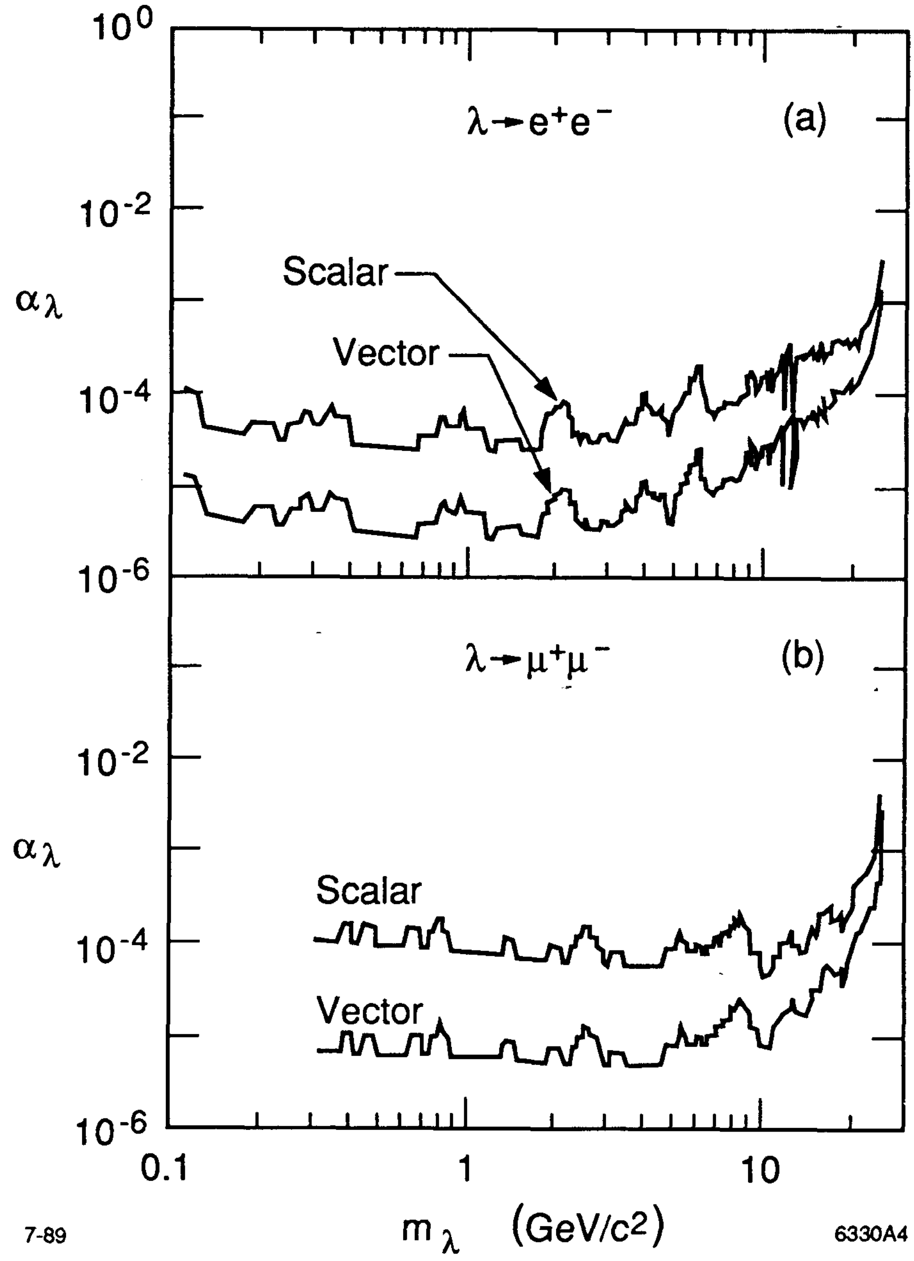

10^0
10^-2
10^-4
10^-6
α_λ
λ→e⁺e⁻
(a)
Scalar
Vector
λ→μ⁺μ⁻
(b)
0.1
1
10
m_λ (GeV/c2)
7-89
6330A4

Fig. 4