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We analyze the process $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-\ell^+\ell^-$ ($\ell = e, \mu, \tau$-leptons) considering several non-standard contributions in order to search for new physics beyond the standard model. We are able to test compositeness up to the TeV mass scale at LEP II and CLIC energies.

I. INTRODUCTION

The reaction $e^+e^- \to \gamma\gamma$ is one of the cleanest ways to look for deviations of the standard QED behavior. Recent measurements[1] of this reaction showed good agreement with the QED prediction, but anomalous effects may show up at higher energies. Nevertheless, the reaction $e^+e^- \to \gamma\gamma$ is able to test just the electron coupling to photons, but it does not yield any information about the interactions of μ's and τ's.

The effects of lepton substructure can manifest themselves in a different way for each kind of lepton, and the process $\gamma\gamma \to \ell^+\ell^-$ also acquires importance to unravel deviations from QED. This process is embodied in the two-photon reaction $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-\ell^+\ell^-$. We should not forget the usual advantage of two-photon processes due to an enhancement by a factor $\ln^2(s/4m_e^2)$, which is large for high energy e^+e^- colliders. Moreover, some cross sections of non-standard subprocesses $\gamma\gamma \to \ell^+\ell^-$ are proportional to the lepton mass, and the suppression of order α^2 in the total cross section is compensated through the observation of a heavy lepton. It is clear that an anomalous contribution whose cross section is proportional to the lepton mass will hardly be observed in $e^+e^- \to \gamma\gamma$. The above aspects make the study of the reaction $e^+e^- \to e^+e^-\ell^+\ell^-$ at least a complementary tool to discover new physics beyond the Standard Model at very high energy colliders.

In this work we study several anomalous contributions to the subprocess $\gamma\gamma \to \ell^+\ell^-$ ($\ell = e, \mu, \tau$). The interactions that contribute to this electromagnetic process will be introduced through effective Lagrangians involving operators of different dimensions, and the full cross-section $e^+e^- \to e^+e^-\ell^+\ell^-$ will be computed in the equivalent-photon approximation [2]. It is important to notice that we can isolate experimentally the two–photon contribution by tagging the e^+e^- leptons at small angles, with respect the incident directions, in coincidence with the lepton pair produced at wide angles [3].

There are many reasons to consider anomalous contributions to the reaction

$e^+e^- \to e^+e^-\ell^+\ell^-$. One of the simplest scenarios we can think of is the existence of compositeness, *i.e.* fermions and/or bosons may be composite and, at short distances, this would imply deviations from QED. Some other possibilities include the existence of new particles that may appear as intermediate state in the subprocess $\gamma\gamma \to \ell^+\ell^-$. For example, such intermediate state could be a spin zero composite. Actually the Standard Model contains at least one scalar boson remnant from the gauge symmetry breaking, and the possibility of this (or any other) scalar boson being composite has been considered by several authors [4]. In the scenario of composite models we cannot discard the possibility of a composite gauge boson, as well as contact interactions respecting U(1) electromagnetic gauge invariance.

The content of our paper is distributed as follows. Section II contains the description of the effective Lagrangians that we have considered and the cross sections for the subprocess $\gamma\gamma \to \ell^+\ell^-$. We discuss our results in Section III, and conclude in Section IV.

II. EFFECTIVE LAGRANGIANS CONTRIBUTING TO $\gamma\gamma \to \ell^+\ell^-$

One way to search for new physics is to work with effective Lagrangians, and to study their contributions to the subprocess $\gamma\gamma \to \ell^+\ell^-$. In the following we list all the effective couplings between leptons and photons that we have considered, as well as their respective contributions to the subprocess cross section.

The effective Lagrangian describing the coupling of an excited lepton to a photon and a standard lepton is given by a dimension five operator [5]

$$\mathcal{L}_* = \frac{1}{2}\bar{\psi}_*\sigma_{\mu\nu}F^{\mu\nu}(g_*^S - ig_*^P\gamma_5)\psi \ + \ h.c. \ , \tag{1}$$

where the coupling constants $g_*^{S,P}$ are $O(1/\Lambda)$, with Λ being the scale of compositeness and ψ (ψ_*) being the fermionic field associated to the (excited) lepton.

We shall also consider a spin zero composite boson which may have anomalously large couplings to the photons, contrarily to what is expected for the Higgs boson in

the Standard Model. The lowest order effective Lagrangian describing the couplings of a scalar and pseudoscalar boson to fermions and photons can be written as,

$$\mathcal{L}_\phi = \frac{m}{\Lambda_f}\bar{\psi}\psi\phi_S + \frac{1}{4}g_S F_{\mu\nu}F^{\mu\nu}\phi_S + i\frac{m}{\Lambda_f}\bar{\psi}\gamma_5\psi\phi_P + \frac{1}{4}g_P F_{\mu\nu}\tilde{F}^{\mu\nu}\phi_P \ , \tag{2}$$

where $\phi_{S(P)}$ are the scalar (pseudoscalar) fields and $g_{S,P}$ are $O(1/\Lambda_{S,P})$.

In this work, we also study a spin one neutral composite particle (Z) exhibiting an anomalous $Z\gamma\gamma$ coupling [6]. The effective Lagrangian describing this coupling is assumed to be

$$\mathcal{L}_Z = \frac{1}{4}g_z Z_\mu(\partial^\mu\tilde{F}_{\alpha\beta})F^{\alpha\beta} \ , \tag{3}$$

where g_Z is $O(1/\Lambda^2)$. The coupling of the Z to the fermions is assumed to be the Standard Model one.

It is also possible to construct several effective Lagrangians containing contact terms involving photons and leptons which are gauge invariant and differ in their dimensions. The lowest order effective Lagrangians, describing these contact interactions, contain operators of dimension 6, 7 and 8:

$$\mathcal{L}_6 = i\bar{\psi}\gamma_\mu(\overleftrightarrow{D}_\nu\,\psi)(g_6F^{\mu\nu} + \tilde{g}_6\tilde{F}^{\mu\nu}) \ , \tag{4}$$

$$\mathcal{L}_7 = \frac{1}{4}g_7^S\bar{\psi}\psi F_{\mu\nu}F^{\mu\nu} + \frac{i}{4}g_7^P\bar{\psi}\gamma_5\psi F_{\mu\nu}\tilde{F}^{\mu\nu} \ , \tag{5}$$

$$\mathcal{L}_8 = \frac{1}{4}\bar{\psi}\gamma^\mu(g_8^V - \gamma_5 g_8^A)\psi(\partial_\mu\tilde{F}^{\alpha\beta})F_{\alpha\beta} \ , \tag{6}$$

where the coupling constants g_i are $O(1/\Lambda^{(i-4)})$, D_μ is the QED covariant derivative and $\tilde{F}_{\mu\nu}$ is the dual of the electromagnetic tensor ($\tilde{F}^{\alpha\beta} = \epsilon^{\alpha\beta\mu\nu}F_{\mu\nu}$). These kind of interactions have been discussed by several authors in different contexts and, in particular, they were studied in the reaction $e^+e^- \to \gamma\gamma$ at LEP energies [7]. Some of the above Lagrangians may result in large contributions to the anomalous magnetic moment of leptons [8]. However, an appropriate choice of the coupling constants may cope with this problem and it was considered in the numerical calculations.

The above effective Lagrangians give rise to additional contributions to the subprocess $\gamma\gamma \to \ell^+\ell^-$. For the sake of completeness we list the subprocess cross sections obtained using the above interactions [9]. The excited lepton contribution to the process $\gamma\gamma \to \ell^+\ell^-$ is:

$$\hat{\sigma}_*(\hat{s}) = \hat{\sigma}_{QED}(\hat{s}) + \pi\alpha^2\xi_*\Big\{ (2-\delta) + \frac{1}{2}(1-\delta)^2 \ln\Big(\frac{\delta+1}{\delta-1}\Big) + \Big(\frac{\xi_*\hat{s}}{4}\Big)\Big[A_0 + A_1(\delta-1)^2 \ln\Big(\frac{\delta+1}{\delta-1}\Big)\Big]\Big\} , \qquad (7)$$

where we have defined

$$\xi_* = \frac{1}{e^2}[(g_*^S)^2 + (g_*^P)^2] , \qquad \delta = 1 + \frac{2M_*^2}{\hat{s}} ,$$

$$A_0 = \frac{-2}{3(\delta+1)}[6\delta^3 - 12\delta^2 - \delta + 5] , \qquad A_1 = \frac{1}{\delta}[2\delta^2 - 2\delta - 1] ,$$

with M_* being the lepton mass and $\hat{\sigma}_{QED}(\hat{s})$ being the QED standard contribution:

$$\hat{\sigma}_{QED}(\hat{s}) = \frac{4\pi\alpha^2\beta}{\hat{s}}\Big[\frac{3-\beta^4}{2\beta}\ln\Big(\frac{1+\beta}{1-\beta}\Big) - 2 + \beta^2\Big] , \qquad (8)$$

where β is the CMS velocity of the final state lepton of mass M ($\beta^2 = 1 - \frac{4M^2}{\hat{s}}$).

Taking into account the couplings of the (pseudo) scalar, the cross section, in the limit $\hat{s} \gg m^2$, is given by

$$\hat{\sigma}_\phi(\hat{s}) = \hat{\sigma}_{QED}(\hat{s}) - 4\pi\alpha^2 m^2\Big\{\xi_S \frac{\hat{s} - M_S^2}{(\hat{s}-M_S^2)^2 + M_S^2\Gamma_S^2}\Big[\ln\frac{\hat{s}}{m^2} - 1\Big] + \frac{1}{2}\xi_P \frac{\hat{s} - M_P^2}{(\hat{s}-M_P^2)^2 + M_P^2\Gamma_P^2}\ln\frac{\hat{s}}{m^2}\Big\} + \frac{\pi\alpha^2 m^2}{4}\Big\{\xi_S^2 \frac{\hat{s}^2}{(\hat{s}-M_S^2)^2 + M_S^2\Gamma_S^2} + \xi_P^2\frac{\hat{s}^2}{(\hat{s}-M_P^2)^2 + M_P^2\Gamma_P^2}\Big\} , \qquad (9)$$

where

$$\xi_{S(P)} = \frac{g_{S(P)}}{e^2\Lambda_f}$$

and $M_{S(P)}$ and $\Gamma_{S(P)}$ are the mass and width of the scalar (pseudoscalar). The total widths $\Gamma_{S(P)}$ has been computed assuming that the main decay mode of the spin zero boson is into two photons, resulting in:

$$\Gamma_{S(P)} \simeq \Gamma(\phi_{S(P)} \to \gamma\gamma) = \frac{1}{16}\frac{M_{S(P)}^3}{\Lambda_{S(P)}^2} . \qquad (10)$$

We should notice that $\hat{\sigma}_\phi$ is proportional to the lepton mass, and, therefore, the observation of this kind of event in $e^+e^- \to \gamma\gamma$ is unlikely due to the smallness of the electron mass.

The contribution of the Z to the cross section of the subprocess $\gamma\gamma \to \ell^+\ell^-$ is

$$\hat{\sigma}_Z(\hat{s}) = \hat{\sigma}_{QED}(\hat{s}) + \frac{\pi\alpha^2}{4}\frac{m^2}{M_Z^4}\xi_Z^2\hat{s}^2 , \qquad (11)$$

where

$$\xi_Z = \frac{g g_Z}{4e^2\cos\theta_W} .$$

It is interesting to notice that Eq.(11) does not exhibit the Z pole since it is forbidden by Yang's theorem [10]. Another interesting feature of this extra contribution is that it is proportional to the square of the lepton mass.

The cross sections for the subprocess $\gamma\gamma \to \ell^+\ell^-$ when we take into account the contribution of the operators of dimension 6, 7 and 8 are:

$$\hat{\sigma}_6(\hat{s}) = \hat{\sigma}_{QED}(\hat{s}) + \pi\alpha^2\xi_6\hat{s}\left(\frac{8}{3} + \frac{1}{5}\xi_6\hat{s}^2\right) , \qquad (12)$$

$$\hat{\sigma}_7(\hat{s}) = \hat{\sigma}_{QED}(\hat{s}) + \frac{\pi\alpha^2}{4}\xi_7\hat{s}^2 , \qquad (13)$$

$$\hat{\sigma}_8(\hat{s}) = \hat{\sigma}_{QED}(\hat{s}) + \frac{\pi\alpha^2}{4}\xi_8 m^2\hat{s}^2 , \qquad (14)$$

where,

$$\xi_6 = \frac{(g_6)^2 + (\tilde{g}_6)^2}{e^2} , \qquad \xi_7 = \frac{(g_7^S)^2 + (g_7^P)^2}{e^4} , \qquad \xi_8 = \frac{(g_8^A)^2}{e^4} . \qquad (15)$$

The effects of higher dimensional operators are weakened by the presence of larger powers of $1/\Lambda$ in the cross section. It is interesting to note that the helicity nature of the interaction Eq.(6) causes the appearance of the mass dependence in Eq.(14).

III. NUMERICAL RESULTS

The total cross section for the process $e^+e^- \rightarrow e^+e^-\ell^+\ell^-$ is related to the subprocess cross section ($\hat{\sigma}_{\gamma\gamma\rightarrow\ell^+\ell^-}(\hat{s})$) through [11],

$$\sigma(s) = \int_{\tau_{min}}^{1} d\tau \frac{dL}{d\tau} \hat{\sigma}_{\gamma\gamma\rightarrow\ell^+\ell^-}(\hat{s}) \; , \qquad (16)$$

where

$$\frac{dL}{d\tau} = \frac{\alpha^2}{4\pi} \log^2\left(\frac{s}{4m^2}\right) \frac{1}{\tau} \left[(2+\tau)^2 \log\left(\frac{1}{\tau}\right) - 2(1-\tau)(3-\tau)\right] \qquad (17)$$

with $\tau = \hat{s}/s$, and $\hat{s}$ is the CMS energy of the of photon-photon system, and m is the electron mass.

In the following we present the results of the numerical evaluation of the cross section $e^+e^- \rightarrow e^+e^-\ell^+\ell^-$ taking into account the contributions coming from the effective interactions discussed in the previous section.

Our goal is to observe effects of new physics beyond the Standard Model, which are characterized by a large mass scale (Λ). In order to do so, we look at processes with large subprocess CMS energy ($\hat{s}$) since the standard QED contribution falls very fast with the increase of $\hat{s}$, while any non-standard process, described by a non-renormalizable effective lagrangian, show an anomalous behavior at some high energy scale. Therefore, we introduce a cut in $\hat{s}$ (or, equivalently, in τ) when computing the total cross section (Eq.(16)). The higher is $\hat{s}_{min}$, the larger is the difference between the cross section of QED and the ones containing anomalous contributions. If we demand the production of at least 1000 muons and 2500 taus/year coming from QED, we obtain the following values of $\hat{s}_{min}$: 1) 35 and 60 GeV for tau and muon pair production at LEP II, and 2) 275 and 450 GeV for tau and muon production at CLIC.

As remarked above, the cross section of the anomalous contribution grows with the energy, and at energies of the order of the compositeness scale this growing should be controlled by a form-factor determined through the dynamics of the theory responsible by the composite state. Since we do not have any *a priori* knowledge of the underlying

composite theory we saturate the anomalous contribution to the subprocess cross sections, *i.e.* $\sigma(\hat{s}) = \sigma(\Lambda^2)$ for $\sqrt{\hat{s}} \geq \Lambda$.

In order to estimate the excess of anomalous events over the QED background, we evaluate the quantity,

$$\Delta = \frac{\sigma_{TOT} - \sigma_{QED}}{\sigma_{QED}} \times 100\% \; , \qquad (18)$$

where the total cross section (σ_{TOT}) is obtained, for each anomalous contribution of Sec. II, introducing the subprocess cross sections ($\hat{\sigma}$) into Eq.(16) and taking into account the appropriated cuts, whereas σ_{QED} stands for the total cross section due only to QED. We demand, as a criterion to identify non-standard contributions to lepton pair production, a value of Δ larger than 10% with at least 100 events/year above the QED background.

Let us start by analyzing the effect of excited leptons in the $\mu^+\mu^-$ production. In order to overcome the bounds on compositeness, coming from the experimental limit of the anomalous magnetic moment of the electron [8], one must have $|g_*^S| = |g_*^P|$. In particular, we assumed that $g_*^S = g_*^P = \sqrt{4\pi}/\Lambda$ in Eq.(7), where the factor $\sqrt{4\pi}$ is the *ad hoc* normalization condition used in experimental bounds for Λ.

Figure (1) contains the numerical results for Δ (Eq.(18)), as a function of the excited lepton mass (M_*), for several values of Λ and for muon-pair production at LEP II and CLIC. For the excited lepton contribution, there is no significant difference between μ or τ pair production for the chosen values of the cut (s_{min}). Requiring that Δ is larger than 10% with 100 anomalous events/year and $\Lambda = 1$ TeV, we verify that at LEP II it is possible to test the existence of an excited lepton with mass up to 100 GeV, while at CLIC with $\Lambda = 5$ TeV, we can probe excited lepton masses of 3 TeV. In Fig. (2) we present the values of Δ as a function of Λ which shows that compositeness scales of O(10 TeV) can be investigated at CLIC.

The existence of a spin zero composite scalar may be one of the most interesting process to be investigated through $\gamma\gamma$ fusion, because its coupling to $\gamma\gamma$ may deviate substantially from the standard model prediction for the Higgs boson. As described in Sec. II, we assume the coupling of the spin zero boson to the fermions to be proportional to m/Λ_f, where m is the fermion mass. Apparently, if $\Lambda_f \geq 250$ GeV, the Weinberg-Salam symmetry breaking scale, we have a suppression of the process $\gamma\gamma \to \phi_{S(P)} \to \ell^+\ell^-$ when compared to the standard Higgs boson production. Nevertheless, this suppression is counterbalanced by the large coupling of the scalar (or pseudoscalar) to the photons, which is strongly suppressed in the Standard Model. When Λ_f is equal to the Weinberg-Salam symmetry breaking scale the anomalous process involving the composite scalar boson is several orders of magnitude larger than the one with the fundamental Higgs boson.

In order to estimate the signal to background ratio for the composite scalar (pseudoscalar), we computed Δ integrating over a bin of 2 GeV around the scalar peak. Furthermore, we present the results for the production of τ pairs since the cross section is proportional to the lepton mass squared and the signal to background ratio is large only for tau-pair production. In Fig.(3.a) we show Δ as a function of Λ $(= \Lambda_f)$ for scalar masses $M_S = 75$, 100 and 150 GeV, and at CLIC energies. Notice that for a small composite scale there is a large contribution from the anomalous event, and increasing the statistics we can test scales of the order of few TeV (the contribution of the pseudoscalar is similar to the scalar one). For a scalar boson of mass $M_S = 100$ GeV we can reach a Λ scale of 750 GeV at the CLIC when we require at least 100 anomalous events per year above the QED background and $\Delta \geq 10\%$.

We can also think of a scenario in which the coupling scalar-fermions is given by the Standard Model one (*i.e.* $\Lambda_f = v = 246$ GeV). We can evaluate Δ using the narrow resonance approximation to integrate over the bin around the Breit-Wigner peak. Assuming that σ_{QED} and $dL/d\tau$ are slowly varying functions of τ in the range of integration, we can take them as a constant to obtain

$$\Delta \simeq \frac{1}{8\alpha^2}\left(\frac{m}{\Lambda_f}\right)^2 \frac{M_S}{2[\text{GeV}]} \frac{1}{\ln(M_S^2/m^2) - 1} . \qquad (19)$$

An interesting feature of the last expression is that Δ does not depend neither on the machine (LEP II or CLIC), nor on the scale characterizing the (pseudo)scalar-

photons coupling $(\Lambda_{S(P)})$. In this case, we obtain $\Delta \sim 100\%$ for $M_S \simeq 100$ GeV and $\tau^+\tau^-$ production. It is interesting to notice that, in this scenario, the reach in M_S is limited only by statistics, *i.e.* by the total number of events.

It is important to stress that a measurement of the invariant mass distribution is necessary only for the spin zero composite, and this task can be performed by measuring the spectator e^+e^- pair. If an excess of taus, peaked at some invariant mass, is found in a preliminary analysis, then we may look for other complementary signals, *e.g.* pairs of bottom quarks or photons, which will be produced in a large amount and yield another determination of the composite scalar mass.

Figure (3.b) contains the results for the production of tau-pairs for CLIC energy including the effect of a composite spin one neutral particle. Due to the dependence of the cross section with the square of the lepton mass this process will have a considerable signal over the QED background only for τ-lepton production. However, even in this case we may test values of Λ not larger than $O(10^2$ GeV). Despite the discouraging result we believe that any other experiment to discover such kind of interaction $(Z\gamma\gamma)$ at larger mass scales will be quite difficult to perform.

The analyse of processes generated by contact terms, which are suppressed by large powers of $(1/\Lambda)$, indicates that these interactions can be tested only at very small mass scales, hardly larger than 1 TeV. Notice that only the dimension 6 operator has interference with QED, and the dimension 8 contribution has a cross section similar to one coming from the exchange of a spin one composite. The results for the dimension 6 and 7 interactions are shown in Figs. (4) for LEP II and CLIC energies, and for muon and tau production. The dimension 8 operator gives a negligible signal.

IV. CONCLUSIONS

In this work we discussed how photon-photon processes in electron-positron collisions may open a window for investigating new physics beyond the Standard Model. Nonstandard contributions to the QED subprocess $\gamma\gamma \to \ell^+\ell^-$ were studied through the introduction of effective Lagrangians involving new interactions between fermions and photons. We studied the effects of existence of excited leptons, scalar and vector composite bosons as well as some contact interactions. In spite of the collision energy being lower for two-photon processes, we can analyze events involving heavy fermions which enhances the detection abilities of interactions that couple with the fermion mass, which cannot be accessed in the direct channel $e^+e^- \to \gamma\gamma$. Moreover, the analysis of two-photon processes allow us to study anomalous interactions, like $\mu\mu\gamma\gamma$ and $\tau\tau\gamma\gamma$, which have not been tested yet.

The basic signal for the non-standard effects consists of the observation of an anomalous lepton pair production. In the cases where the cross sections depend on the mass of the leptons we should look for tau pairs in the final state in order to increase the signal to background ratio. In the case of a spin zero composite, this particle appears in the s channel and to reconstruct its signal and mass we must measure the final state lepton-pair invariant mass. However, in this case there are complementary signals that we can look for, *e.g.* heavy quark or photon pairs, which can be used to establish the existence of this composite particle. These topics are currently under study.

Notice that the anomalous effects that we discussed will also appear when we study asymmetries originated by spin effects [12], with some of the non-standard contributions giving very peculiar angular distributions. This method may yield better constraints in the scale Λ, despite the fact that such measurements are very hard to perform.

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FIGURES

FIG. 1. Δ as a function of the excited lepton mass (M_*) for the production of $\mu^+\mu^-$. (a) LEP II: $\Lambda = 0.5$ (dashed line), 1.0 (dotted line), 1.5 (dot-dashed line) TeV, and $\Lambda = M_*$ (solid line). (b) CLIC: $\Lambda = 1.0$ (dashed line), 3.0 (dotted line), 5.0 (dot-dashed line) TeV, and $\Lambda = M_*$ (solid line).

FIG. 2. Δ as a function of Λ for the excited lepton contribution for the production of $\mu^+\mu^-$. (a) LEP II: $M_* = 300$ (dotted line), 500 (solid line), and 800 (dashed line) GeV. (b) CLIC: $M_* = 500$ (dotted line), 1000 (solid line), and 1500 (dashed line) GeV.

FIG. 3. Δ as a function of Λ for the production of $\tau^+\tau^-$ at CLIC. (a) Contribution of the composite scalar boson ($\Lambda = \Lambda_f$) integrated in a bin of 2 GeV for $M_S = 75$ (dotted line), 100 (solid line), and 150 (dashed line) GeV. (b) Contribution of the composite vector boson ($M_Z = 92$ GeV).

FIG. 4. Δ as a function of Λ for the production of $\mu^+\mu^-$ (solid line) and $\tau^+\tau^-$ (dashed line) for the contribution of dimension 6 operator at LEP II (a) and CLIC (b), and of dimension 7 operator at LEP II (c) and CLIC (d).

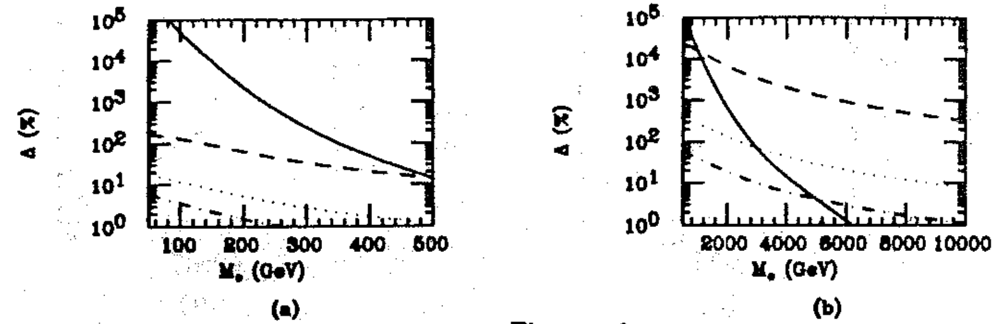

Figure 1

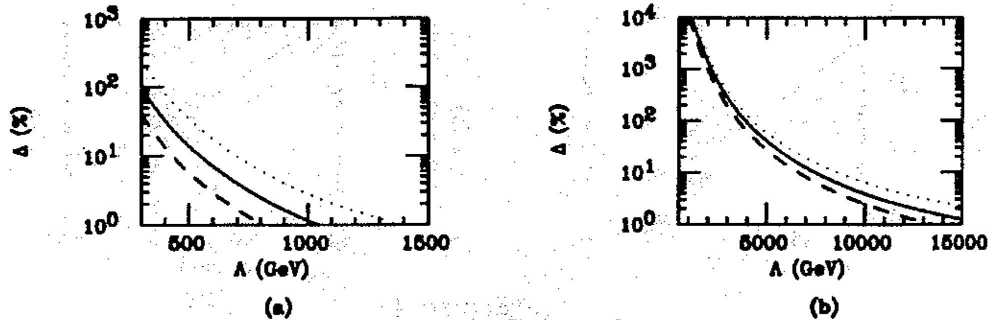

Figure 2

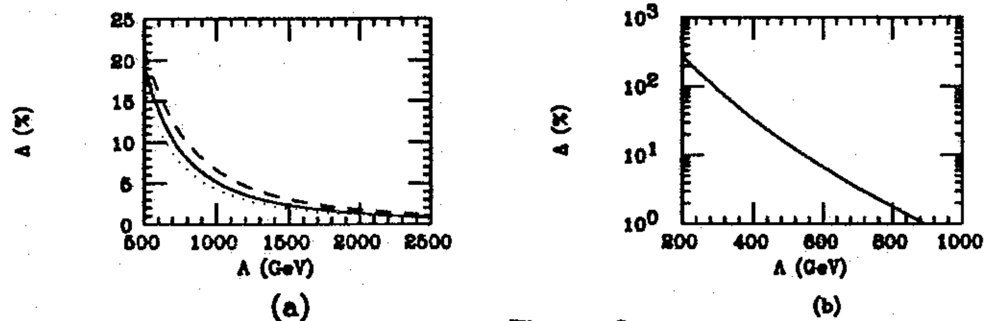

Figure 3

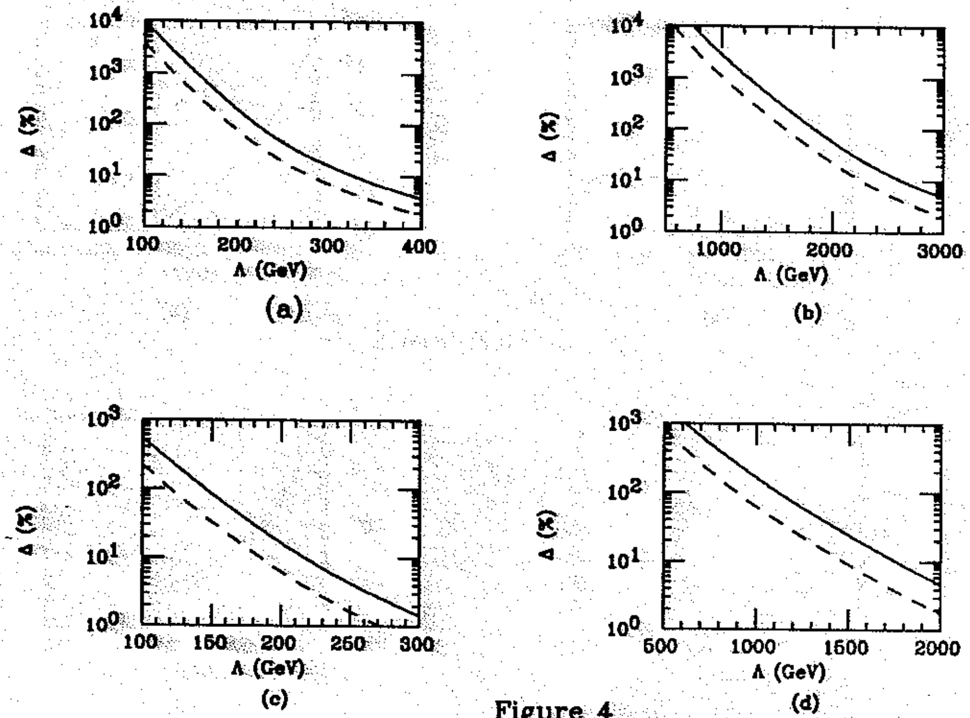

Figure 4