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Diphoton Production at Hadron Colliders and New Contact Interactions *

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Abstract

We explore the capability of the Tevatron and LHC to place limits on the possible existence of flavor-independent $q\bar{q}\gamma\gamma$ contact interactions which can lead to an excess of diphoton events with large invariant masses. Assuming no departure from the Standard Model is observed, we show that the Tevatron will eventually be able to place a lower bound of 0.5-0.6 TeV on the scale associated with this new contact interaction. At the LHC, scales as large as 3-6 TeV may be probed with suitable detector cuts and an integrated luminosity of $100 fb^{-1}$.

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Although the Standard Model(SM) appears to be as healthy as ever[1], it is generally believed that new physics must exist to address all of the questions the SM leaves unanswered and which can explain the values of the various input parameters (*e.g.*, fermion masses and mixing angles). Although there are many suggestions in the literature, no one truly knows the form this new physics might take or how it may first manifest itself. Instead of the direct production of new particles, physics beyond the SM may first appear as deviations in observables away from SM expectations, such as in the rates for rare processes or in precision electroweak tests. Another possibility is that deviations in cross sections of order unity may be observed once sufficiently high energy scales are probed. This kind of new physics can generally be parameterized via a finite set of non-renormalizable contact interactions, an approach which is quite popular in the literature[2]. In fact, limits already exist from a number of experiments on the scales associated with contact interactions of various types[3].

In this paper we will explore the capability of both the Tevatron and the CERN Large Hadron Collider(LHC) to probe the existence of flavor-independent(apart from electric charge), $q\bar{q}\gamma\gamma$ contact interactions of dimension-8. Searches for such operators, with the quarks replaced by electrons, have already been performed at TRISTAN and LEP [4] and have resulted in a lower bound of approximately 139 GeV on the associated mass scale. As we will see below, the Tevatron(LHC) will easily be able to push the scale in the corresponding $q\bar{q}$ situation above 0.5-0.6(2.8-5.3) TeV. As we will see below, unlike Higgs bosons or other possible $\gamma\gamma$ resonances, this new contact interaction will manifest itself only as a smooth modification of the various $\gamma\gamma$ distributions.

To be definitive, we will follow the notation employed by [5] as well as by the ALEPH Collaboration[4] and assume that these new interactions are parity conserving. (We will return to the cases where such interactions may be chiral below.) In this case we can parameterize the $q\bar{q}\gamma\gamma$ contact interaction as

$$\mathcal{L} = \frac{2ie^2}{\Lambda^4} Q_q^2 F^{\mu\sigma} F_\sigma^\nu \bar{q} \gamma_\mu \partial_\nu q \,, \tag{1}$$

where e is the usual electromagnetic coupling, Q_q is the quark charge, and Λ is the associated mass scale. The most obvious manifestation of this new operator is to modify the conventional Born-level partonic $q\bar{q} \to \gamma\gamma$ differential cross section so that it now takes the form

$$\frac{d\hat{\sigma}}{dz} = Q_q^4 \frac{2\pi\alpha^2}{3\hat{s}} \left[\frac{1+z^2}{1-z^2} \pm 2\frac{\hat{s}^2}{4\Lambda_\pm^4}(1+z^2) + \left(\frac{\hat{s}^2}{4\Lambda_\pm^4}\right)^2 (1-z^4) \right] , \tag{2}$$

where $\hat{s},\ z$ are the partonic center of mass energy and the cosine of center of mass scattering angle, θ^*, respectively. Note that we have written $\Lambda_\pm$ in place of Λ in the equation above to indicate that the limits we obtain below will depend upon whether the new operator constructively or destructively interferes with the SM contribution. In our discussion, we focus on the case of constructive interference but will give results for both cases below.

There are two major effects due to finite Λ: (i) Clearly, once $\hat{s}$ becomes comparable to Λ^2, the parton-level differential cross section becomes less peaked in the forward and backward directions implying that the photon pair will generally be more central and will occur with higher average p_t's. (ii) When integrated over parton distributions the resulting cross section will lead to an increased rate for photon pairs with large $\gamma\gamma$ invariant masses. From these two observations we see that the best hope for isolating finite Λ contributions is to look for excess diphotons with high, balanced p_t's in the central detector region with large pair masses.

Unfortunately, the $q\bar{q} \to \gamma\gamma$ tree-level process is not the only one which produces diphotons satisfying the above criteria. The issue of diphoton production at hadron colliders has been discussed for many years[6], mostly within the context of searches for Higgs bosons in the intermediate mass region, and a full next-to-leading(NLO) order SM calculation now exists[8]. In the Higgs search scenario, one is looking for a very narrow peak in the diphoton mass distribution for which there are extremely large misidentification induced backgrounds from QCD. In the case of contact interactions, however, the deviation from SM expectations occurs over a rather wide range of diphoton pair masses. The authors of Ref.[8] have provided an excellent summary of the various sources which lead to diphoton pairs and we will generally follow their discussion. The most obvious additional source of diphotons arises from the process $gg \to \gamma\gamma$ which is induced by box diagrams. Although relatively small in rate at the Tevatron, the increased gg luminosity as one goes to LHC energies (combined with the fact that $q\bar{q}$ annihilation is now a 'sea-times-valence' process) implies that $gg \to \gamma\gamma$ is extremely important there. We include the $gg-$induced diphotons in our calculations by employing 5 active quark flavors in the gg-induced box diagram for partonic center of mass energies, $\hat{s}$, below $4m_t^2$, 6 active flavors for $\hat{s} >> 4m_t^2$, and smoothly interpolate between these two cases. In order to include the potential effects of loop corrections to the rate for the $gg \to \gamma\gamma$ we have scaled the results obtained by this procedure by an approximate 'K-factor' of 1.3(1.5) at the Tevatron(LHC). (In numerical calculations, we assume $m_t^{phys} = 170$ GeV in agreement with precision electroweak measurements and the recent evidence for top production at the Tevatron reported by the CDF Collaboration[1].) A similar 'K-factor' is also employed in the $q\bar{q} \to \gamma\gamma$ calculation; we use the results of Ref.[7]. While this procedure gives only an approximate result to the full NLO calculation, it is sufficient for our purposes as the effects of the new contact interaction are quite large as they modify the tree level cross section.

Additional 'background' diphotons arise from three other sources. For $2 \to 2$ processes, one can have either (i) single photon production through $gq \to \gamma q$ and $q\bar{q} \to g\gamma$ followed by the fragmentation $g, q \to \gamma$, or (ii) a conventional $2 \to 2$ process with *both* final state q, g partons fragmenting to photons. Although these processes appear to be suppressed by powers of α_s, these are off-set by large logs. Numerically, in our analysis these fragmentation contributions are calculated at the leading-log level using the results in Refs.[8, 9]. For $2 \to 3$ processes, (*iii*) double bremsstrahlung production of diphotons is possible, *e.g.*, $gq \to q\gamma\gamma$ or $q\bar{q} \to g\gamma\gamma$. All of these 'backgrounds' are relatively easy to drastically reduce or completely eliminate at both the Tevatron and the LHC by the series of cuts we employ below. We first select diphotons with large invariant masses that are both central and have high transverse momenta ($|\eta_\gamma| < 1,\ 2.5$ and $p_t^\gamma > 15,\ 100$ GeV at the Tevatron and LHC respectively). We next demand that any additional hadronic activity in these events be widely separated (*i.e.*, isolated) from the photons and have only small associated jet energies ($E_j^{cut} < 5,\ 20$ GeV at the Tevatron and LHC). As a last requirement we demand that both photons are close to being back to back with nearly balancing p_t's, *i.e.*, $p_t^1/(p_t^1 + p_t^2) < 0.7$, with $p_t^1 \geq p_t^2$ as required by the ATLAS Higgs search analysis[10]. It is easy to see how these cuts will greatly reduce the backgrounds from the sources (*i*)-(*iii*). In process (*i*), the additional γ produced from the fragmentation essentially follows the fragmenting parton's direction but is generally softer than the primary photon in the opposite hemisphere and is contained within a jet which has, on average, a relatively large energy. Under these circumstances, it is very difficult for the two photons to be isolated and have their p_t's balance; it is also harder for the softer photon to pass the minimum p_t cut and combine with the primary photon to pass the invariant pair mass requirements. Process (*ii*) has an even more difficult time satisfying these cuts since the photons are both softer than their parent partons, are embedded in jets, and need to have similar fragmentation energies to balance p_t's. We find in practice that the combination of the cuts above reduces the backgrounds from the sum of sources (*i*) and (*ii*) by at least a factor $> 15-20$ for both the Tevatron and LHC for the diphoton pair masses of interest to us in our discussion below. In fact, for the machine luminosities we consider, these cuts essentially eliminate (*ii*) as a diphoton background source. For the $2 \rightarrow 3$ processes (*iii*), most of the phase space is dominated by the infrared and co-linear regions. Since *both* γ's must be hard and isolated with essentially matching p_t's, the cuts above are designed to remove this background source almost completely.

In presenting our numerical results, we follow the approach employed by the CDF Collaboration in presenting their high p_t diphoton data[11], *i.e.*, we integrate the invariant diphoton mass distribution above a given fixed minimum value of the diphoton mass, $M_{\gamma\gamma}^{min}$, subsequent to making all the other cuts discussed above. In order to get a feel for the event rates involved, we scale this integrated cross section by a luminosity appropriate to the Tevatron or the LHC, *i.e.*, $20pb^{-1}$ and $100fb^{-1}$, respectively. The results from this procedure are shown in Figs. 1 and 2. Fig. 1a compares the SM diphoton cross section as a function of $M_{\gamma\gamma}^{min}$ with the constructive interference scenario for various values of the Λ parameter. It is clear that present data from the Tevatron[11] is already probing values of Λ of order 400 GeV. (In fact, CDF observes a possible excess of diphotons at large values of $M_{\gamma\gamma}^{min}$ consistent with values of Λ not far from 400 GeV. Of course, this is most likely a statistical fluctuation.)

Assuming that no event excesses are observed, we can ask for the limits that can be placed on $\Lambda_\pm$ as the Tevatron integrated luminosity is increased. To do this we perform a Monte Carlo study, first dividing the $M_{\gamma\gamma}^{min}$ range above 100 GeV into nine steps of 50 GeV. Almost all of the sensitivity to finite Λ will lie in this range since for smaller values of $M_{\gamma\gamma}^{min}$ the cross section looks too much like the SM while for larger values of $M_{\gamma\gamma}^{min}$ the event rate is too small to be useful even for integrated luminosities well in excess of $1fb^{-1}$. We generate events using the SM as input and then try to fit the resulting $M_{\gamma\gamma}^{min}$ distribution by a $\Lambda_\pm$-dependent fitting function. ¿From this, bounds on Λ are directly obtainable via a χ^2 analysis.

In the first approach, we assume that the normalization of the cross section for small values of $M_{\gamma\gamma}^{min}$ using experimental data will remove essentially all of the systematic errors so that only statistical errors are put into the fitting procedure. In this case, for a luminosity of $100(250,\ 500,\ 1000,\ 2000)pb^{-1}$ we obtain the bounds $\Lambda_+ > 487(535,\ 575,\ 622,\ 671)$ GeV and $\Lambda_- > 384(465,\ 520,\ 577,\ 635)$ GeV, respectively, at 95% CL. Note that the constraints we obtain on Λ_- are generally weaker than those for Λ_+ although the two bounds begin to numerically converge at larger integrated luminosities. If we also allow for an *additional* overall systematic error of $15-20\%$ due to other uncertainties not accounted for by the normalization at small $M_{\gamma\gamma}^{min}$ values, we find that our Λ_+ limits are degraded by at most a factor of $\simeq 10\%$ while the corresponding ones for Λ_- are somewhat more significantly reduced, often by as much as 20%. Fig. 1b shows a sample case from this Monte Carlo analysis wherein an integrated luminosity of 500 pb^{-1} and only statistical errors are assumed; the generated data together with the curves associated with the two 95% CL bounds and the best fit, corresponding to $\Lambda_- = 1128$ GeV, are displayed explicitly.

At the LHC, we find the results presented in Figs. 2a-c. Fig. 2a clearly shows, for the default values of the cuts described above and an integrated luminosity of $100fb^{-1}$, that values of Λ greater than 2 TeV will be easily probed. If we strengthen our canonical $\gamma\gamma$ selection cuts, *i.e.*, $|\eta_\gamma| < 1$ and $p_t^\gamma > 200$ GeV, we see in Fig. 2b that we are left with reduced statistics but significantly improved sensitivity. If we follow the same Monte Carlo approach as above, we obtain very strong limits on $\Lambda_\pm$. We take the $M_{\gamma\gamma}^{min}$ range above 250 GeV and divide it into ten steps and generate data as above fitting to a $\Lambda_\pm$-dependent distribution; we assume that the only errors are statistical in this first pass as in the analysis above. (The best fit value for the canonical cuts is found to be $\Lambda_+ = 5.17$ TeV.) From this we obtain the 95% CL bounds of $\Lambda_+ > 2.83$ TeV and $\Lambda_- > 2.88$ TeV; the best fit and the corresponding limit curves are shown in Fig. 2c. If we increase the integrated luminosity to

$200 fb^{-1}$, the limits increase to $\Lambda_+ > 3.09$ TeV and $\Lambda_- > 3.14$ TeV. If, instead, we strengthen the cuts, as described above, we find these limits for a $100 fb^{-1}$ integrated luminosity are improved to 5.27 TeV and 5.37 TeV, respectively. If, in addition, we also simultaneously increasing the luminosity we find instead the limits of 5.77 TeV and 5.86 TeV, respectively. (These limits may be improved slightly by extending the fit region outwards by another 500 GeV particularly in the higher luminosity case.)

What happens when we give up the assumption of a parity conserving contact interaction and assume that the quark current is chiral? The result is easily obtained from the considerations of the ALEPH Collaboration[4]. Essentially, assuming either purely left- or right-handed quark currents, the previously obtained values of $\Lambda_\pm$ are reduced by a factor of $2^{1/4} \simeq 1.19$. This is not a sizeable effect numerically so that the ranges of $\Lambda_\pm$ being probed are essentially unaltered.

In this paper, we have explored the capability of the Tevatron and LHC to probe for the existence of flavor-independent contact interactions with the following results:

(i) If new dimension-8 $q\bar{q}\gamma\gamma$ contact interactions, parameterized by a scale $\Lambda_\pm$, exist, they will result in an excess of diphoton events with large invariant masses at hadron colliders. These events will be central and the photons will have large, balancing p_t's. The resulting modifications to the $\gamma\gamma$ cross section for different Λ at the Tevatron and LHC were obtained. Existing constraints on the corresponding e^+e^- operators are rather poor.

(ii) While the new physics we propose only takes place in the $q\bar{q} \to \gamma\gamma$ channel, there are other additional diphoton sources that must be accounted for including the usual $gg \to \gamma\gamma$ box. We have estimated their contributions and included them within the analysis. A large fraction of these additional 'backgrounds' are easily reduced by the cuts we have imposed which simultaneously enriches the highly central, large p_t, large $M_{\gamma\gamma}$ event sample which is most sensitive to the new contact interaction.

(iii) A Monte Carlo analysis was performed for both the Tevatron and LHC to explore the potential constraints on $\Lambda_\pm$ for various integrated luminosities assuming the absence of new physics. The generated data was fit via a χ^2 analysis to the $\Lambda_\pm$-dependent cross section thus obtaining best fit values as well as 95% CL limits under the assumption that the cross section was properly normalized by the data at small values of $M_{\gamma\gamma}$. For the Tevatron with $\mathcal{L} = 500pb^{-1}$, for example, this led to limits in excess of 520 GeV and a best fit value of $\Lambda_- = 1128$ GeV. For the LHC with $\mathcal{L} = 100fb^{-1}$, the limits were found to be sensitive to the choice of cuts and ranged from 2.8 to 5.3 TeV. Although the statistics were reduced by the stronger cuts, this was more than compensated for by the increased sensitivity to the new contact interaction.

Excess diphoton events should be searched for, not only as narrow peaks in $M_{\gamma\gamma}$ signalling the existence of Higgs-like objects, but also in the broad contributions to the tails of distributions. Such searches may yield valuable information on the existence of new physics.

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Figure Captions

Figure 1. (a)Diphoton pair event rate, scaled to an integrated luminosity of $20 pb^{-1}$, as a function of $M_{\gamma\gamma}^{min}$ at the Tevatron subject to the cuts discussed in the text. The solid curve is the QCD prediction, while from top to bottom the dash dotted curves correspond to constructive interference with the SM and a compositeness scale associated with the $q\bar{q}\gamma\gamma$ operator of $\Lambda_+ = 0.2,\ 0.3,\ 0.4,\ 0.5$, and 0.6 TeV respectively. (b) Monte Carlo generated data for an integrated luminosity of 500 pb^{-1} assuming statistical errors only. The two dash dotted curves corresponding to the 95% CL bounds discussed in the text while the solid curve represents the best fit.

Figure 2. Same as Fig. 1, but for the LHC scaling to an integrated lumonosity of $100 fb^{-1}$. From top to bottom the dash dotted curves now correspond to $\Lambda_+ = 0.75,\ 1.0,\ 1.25,\ 1.5,\ 1.75$ and 2.0 TeV respectively. In (a) we require $p_t^\gamma > 100$ GeV and $|\eta_\gamma| < 2.5$, while in (b) we require instead $p_t^\gamma > 200$ GeV and $|\eta_\gamma| < 1.0$. (c) Monte Carlo generated data for an integrated luminosity of 100 fb^{-1} assuming statistical errors only. The two dash dotted curves corresponding to the 95% CL bounds discussed in the text while the solid curve represents the best fit.