The top threshold effect in the $\gamma\gamma$ production at the LHC

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We compute the top quark threshold contributions to the $\gamma\gamma$ production at the LHC. These contributions become significant when the invariant mass of the photon pair, $M_{\gamma\gamma}$, just exceeds two times the mass of the top quark and induce some features in the $M_{\gamma\gamma}$ distribution, a hint of which is already visible in the recent data. We determine the magnitude of this threshold effect and investigate kinematic cuts which may enhance its significance.

I. INTRODUCTION

The $\gamma\gamma$ pair production in proton-proton colliders such as the LHC plays a very important role in the search for new physics. Recently this channel has attracted considerable attention due to a potential hint of new physics [1–3]. Hence it is important to determine the background, i.e., the Standard Model (SM) contribution to this channel as reliably as possible. The background generally shows a smooth behaviour with respect to the invariant mass of the photon pair ($M_{\gamma\gamma}$), as indicated, for example, by the background-only fit obtained by the ATLAS collaboration [1]. However, at the threshold of production of a new particle, this smooth feature can get disturbed. In this letter, we shall primarily look at the top quark threshold effect that appears about $M_{\gamma\gamma} \sim 350$ GeV, a kinematic region not far off from the region where the hint of new physics was observed.

The $\gamma\gamma$ pair production at the LHC gets contribution from several parton level sub-processes, including the quark anti-quark annihilation ($q\bar{q} \rightarrow \gamma\gamma$) at the leading order (LO), the quark-gluon scattering ($gg \rightarrow q\bar{q}\gamma\gamma$) at the next-to-leading order (NLO) in QCD and the gluon process ($gg \rightarrow \gamma\gamma$) at the next-to-next-to-leading order (NNLO) in QCD [4–6]. The top threshold effect appears in the gluon fusion process that occurs through the fermion loop diagrams, like the one shown in Fig. 1 (the box diagram). It arises from the destructive interference between the top loop diagrams containing on-shell top quarks and other diagrams containing light quark loops. Once $M_{\gamma\gamma}$ exceeds two times the mass of the top quark, $m_t \approx 173$ GeV, the gluon fusion process gets contribution from on-shell tops in the box loop, creating a dip in the invariant mass distribution [4–7].

The precise nature of the threshold effect can be seen explicitly in Fig. 4 of [7]. It shows the ratio of the cross sections of the gluon fusion process computed with $m_t = 173$ GeV to that obtained by setting $m_t = \infty$ at the 14 TeV LHC. In other words, it shows the correction due to the top loop to the gluon fusion process. This ratio is found to be equal to unity for $M_{\gamma\gamma} < 200$ GeV. As $M_{\gamma\gamma}$ increases, the ratio starts to decrease and shows a sudden dip at about $M_{\gamma\gamma} = 2m_t$. After the dip, it rises smoothly and eventually saturates to a value of approximately 1.75 for $M_{\gamma\gamma} \approx 1600$ GeV. Note, however, there is nothing special about the top quark or about this process, similar dips are also predicted at the threshold of each new particle in the light by light scattering [9].

Though this threshold effect exists, a priori it is not clear whether it can be observed since the gluon fusion gives a sub-dominant contribution to the two photon production [4, 10–15]. As mentioned, the leading order contributions arise from the quark anti-quark annihilation process. Fortunately, the NLO as well as NNLO contributions are relatively large for the $\gamma\gamma$ pair production [15]. The gluon fusion process, although higher order in strong coupling in comparison to the quark anti-quark annihilation process, is not negligible and gives a significant contribution [5, 6, 15]. This may be further enhanced by imposing some kinematical cuts. An even higher order contribution to this, classified as NNNLO, has also been computed [6]. It is found to be small but not negligible.

It is intriguing that the ATLAS data [1] already show a hint of a dip at $M_{\gamma\gamma} \approx 2m_t$, exactly where it is expected. However, more data is required to conclude whether this is a statistical fluctuation or not. In this letter, we compute the $pp \rightarrow \gamma\gamma$ production process at NLO QCD and the $gg \rightarrow \gamma\gamma$ process to determine whether the top quark threshold effect can be observed at the 13 TeV LHC. Motivated by the hint in the data, here we mostly follow the ATLAS analysis for kinematic cuts. But we also explore additional cuts that may enhance the threshold contribution.

Observation of this phenomenon is interesting by itself but it may also be useful to understand the relative magnitudes of different contributions. Theoretically, these have significant uncertainties due to the unknown higher order contributions. Furthermore, if the effect can be observed with sufficient accuracy, it may also provide another measurement of the top quark mass.

II. COMPUTATIONS AND RESULTS

We compute both the $gg \rightarrow \gamma\gamma$ process and the NLO $pp \rightarrow \gamma\gamma(j)$ process at the 13 TeV LHC in the MadGraph5_AMC@NLO [16] environment with NN23LO1 parton density functions (PDFs) [17] and PYTHIA6 [18] for...
parton showers (PS). Throughout our analysis, we only consider photons with transverse energy, $E_T > 25$ GeV. For $M_{\gamma\gamma} \geq 200$ GeV, the cross section for the gluon fusion is about 270 fb. It reduces to about 115 fb once we impose the following additional cuts defined in Eq. (1) on the two $E_T\gamma$ ordered photons,

$$E_{T1} > 0.4M_{\gamma\gamma}, \ E_{T2} > 0.3M_{\gamma\gamma}.$$ (1)

We show the invariant mass distribution obtained from the $gg \rightarrow \gamma\gamma$ process in Fig. 2. For this plot, we have first generated 100,000 events with $M_{\gamma\gamma} \geq 200$ GeV in the gluon fusion channel alone and then applied the cuts defined in Eq. (1) on these events to clearly demonstrate the threshold effect. The red line in the top panel is a smooth fit of the binned events. (Bottom plot) The difference between the simulated events and the smooth fit. A clear dip is seen at $M_{\gamma\gamma} \approx 2m_t$.

which is consistent with the result seen in Fig. 3. We point out that the dip is rather broad and spreads over several bins. Hence the significance of the cumulative effect is higher than the one sigma value quoted above. As we shall argue below, the threshold effect will be seen at the LHC once sufficient data becomes available.

### A. A new cut on the $\gamma\gamma$ system

We next explore the possibility of enhancing the significance of the dip by imposing different kinematical cuts that are less restrictive on the gluon fusion channel. In particular, when we relax the $M_{\gamma\gamma}$ dependent cuts of Eq. (1), the number of events in the bin corresponding to $M_{\gamma\gamma} = 340$ GeV increase by a factor of roughly four (see Fig. 4). Hence we expect a 2 sigma detection of the dip in this bin, again in rough agreement with the simulation result shown in Fig. 4 (top plot). However, without the $M_{\gamma\gamma}$ dependent $E_T$ cuts, though the gluon fusion cross section increases to about 270 fb for $M_{\gamma\gamma} \geq 200$ GeV, the corresponding cross section of the NLO $pp \rightarrow \gamma\gamma(j)$ process becomes much larger, about 2.8 pb (i.e., the gluon fusion contribution becomes even less than 10% of the NLO $pp \rightarrow \gamma\gamma(j)$ process).

We next define a variable $C$ related to the centrality of the

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1 Note that the fit is not very precise at the low values of $M_{\gamma\gamma}$ ($\sim 200$ GeV), but this happens because of the limitations of the simple form of the fitting function in Eq. (2).
\[ C = \frac{\vec{P}_{\gamma_1} + \vec{P}_{\gamma_2}}{M_{\gamma\gamma}} \]  

where \( \vec{P}_{\gamma_1} \) and \( \vec{P}_{\gamma_2} \) denote the 3-momenta of the outgoing photons in the lab frame. Clearly, when the lab frame coincides with the center of mass frame of the two outgoing photons \( C = 0 \). Now, if we demand \( C \) to be smaller than or equal to some fixed number \( C_0 \) (say), depending on the choice of \( C_0 \) such a cut could affect the \( gg \) or \( gq \) initiated processes more than the \( gg \) initiated one. (This is possible because the valence quark PDFs peak at very different values of \( x \) in comparison to those of the sea quarks and gluons.)

In Fig. 5, we show the ratio of the cross-sections of two subprocesses, the gluon fusion and the NLO QCD \( pp \rightarrow \gamma\gamma \) for different values of \( C_0 \).

From Fig. 5 we see that the contribution of \( gg \rightarrow \gamma\gamma \) is about 20\% of the contribution of the NLO \( pp \rightarrow \gamma\gamma(j) \) process for \( C_0 \) between 0.5 to 1. However, with decreasing \( C_0 \), the total number of events also decreases substantially and so, we need to optimize the value of \( C_0 \). For Fig. 4 (bottom plot), we choose \( C_0 = 2 \), which is a reasonable compromise. In this figure, the upper plot is obtained without any cut on \( C \) [i.e., \( C_0 \rightarrow \infty \) and also without the ATLAS \( M_{\gamma\gamma} \) dependent cuts defined in Eq. (1)] whereas the lower plot is obtained with \( C_0 = 2 \). From this it is clear that the cut on \( C \) enhances the significance of the threshold effect. Note, here we have focused only on the bin at \( M_{\gamma\gamma} = 340 \text{ GeV} \). But, as mentioned before, the dip spreads over several bins. Hence, if we include these nearby bins too in our estimations, the combined significance of the dip is much higher than a two sigma effect at this luminosity. Hence the effect will be seen in the near future since the chosen luminosity is within the reach of the LHC.

Finally, before we conclude, we note that there could be another source of top threshold effect in the photon pair production channel. Just as the gluon splitting creates \( cc \) and \( bb \) pairs that contribute in the sea quark density of a proton, once the top threshold is crossed, one could also imagine \( t\bar{t} \) pairs appearing in the sea (i.e. a ‘\( t\)-PDF’). Hence, additional threshold effects would arise due to the processes \( t\bar{t} \rightarrow \gamma\gamma \) and \( tg \rightarrow t\gamma \). If, naively, one assumes that the ‘\( t\)-PDF’ at a scale \( Q \) is roughly given by the \( b\)-PDF at the scale \( Qm_t/m_t \), the contributions of these processes turn out to be much smaller than the effect considered here. It is not easy to quantify this argument, as the behaviour of this density function near the top threshold won’t be captured properly. However, since the top quark is much heavier than the \( b \)-quark, it is reasonable to assume that these processes are unlikely to produce any observable features with the present luminosity, though they might be important for precision studies.
FIG. 5. The effects of the cut $C \leq C_0$ [see Eq. (3)] on the gluon fusion and the NLO $pp \to \gamma\gamma(j)$ processes obtained without the cuts defined in Eq. (1). The cross sections are obtained for $M_{\gamma\gamma} \geq 200$ GeV.

III. SUMMARY AND CONCLUSIONS

In this letter we have investigated the top quark threshold effect in the two photon channel at the LHC. This effect arises in the loop mediated $gg \to \gamma\gamma$ subprocess due to the destructive interference between top loop diagrams containing on-shell top quarks and other light quark loop diagrams. It appears as a dip in the invariant mass distribution of the photon pair near two times the mass of the top quark.

Though a hint of this effect can already be seen from the present ATLAS data, observing this dip with a large statistical significance would require more data. Within the SM, the gluon fusion process is overshadowed by the NLO (QCD) $pp \to \gamma\gamma(j)$ process that has a larger cross-section. However, here, we have argued that this can be mitigated to some extent by judicious choices of kinematical cuts. We have demonstrated this by defining a new cut on the gamma gamma system. Though it is beyond the scope of this letter, it might be possible to make the threshold effect even more prominent with sophisticated techniques like multivariate analysis etc.

It will be very interesting to observe this SM effect more accurately at the LHC. However, there are other motivations to look into this in detail. It can provide us another way to probe the top-mass experimentally. Not only this, threshold effects can also tell us about some beyond the SM fermions indirectly. Since this effect arises from the interference effects, any heavy fermion that can run in the loop of the $gg \to \gamma\gamma$ process would lead to such a threshold effect. Hence, observation (or non-observation) of any such effect in the gamma gamma spectrum could let us infer about new heavy coloured fermions carrying non-zero electromagnetic charge in a model independent manner.

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