# Isolating top contributions in the production of the 750 GeV diphoton excess

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# The 750GeV diphoton excess: who introduces it?

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Recently, both ATLAS and CMS collaborations report an excess at 750GeV in the diphoton invariant mass spectrum at 13TeV LHC. If it is a new (pseudo)scalar produced via loop induced gluon-gluon fusion process, it is important to know what is the particle in the loop. In this work, we investigate the possibility of determine the fraction of the contribution from the standard model top-quark in the loop.

## I. INTRODUCTION

An excess in diphoton invariant mass spectrum is reported by both ATLAS and CMS collaborations at 13TeV LHC [1, 2]. Although more data is needed to make definite conclusion, it is probably a hint of a new resonance at 750GeV with 45GeV width. In a few weeks, more than a hundred papers appear online to explain the excess [3–149]. A new (pseudo)scalar which is produced via the gluon-gluon fusion (ggF) channel at the LHC is one of the most popular candidate of this excess. In a former work, we discuss the possibility of distinguishing the $q\bar{q}$ and $b\bar{b}$ initial state production channel from the ggF [114]. We showed that we can know whether the ggF process is the dominant production mode in the near future. If ggF is the dominant production mode, it is important to know where is this loop induced effective operator from. Is there a significant contribution from exotic colored particle in the loop? Although exotic colored particles contribute to the production of the scalar resonance in most of the models currently, it is not clear whether such contribution is necessary. The contribution from the top-quark loop could be enough and there is not top-pair resonance signal at hadron colliders. So the constraint from searching heavy resonance in top-quark pair final state is useless here.

In this work, we try to answer this question. If the excess is confirmed by data in the future, we suggest the experimentalists look for the $t\bar{t}\gamma\gamma$ signal at the LHC Run-II, which can be used to measure the top-quark contribution in the loop. The reasons are explained in detail in Sec. II. In Sec. III, we study the LHC phenomenology of this signal. A simple simulation for a 100TeV $pp$ collider is also shown there. Both of the CP-even ($\phi_H$) and CP-odd ($\phi_A$) scalars are considered. Our conclusions are summarized in Sec. IV.

## II. THE SIGNAL

We limit our discussion on a 750 GeV (pseudo)scalar resonance $\phi_H$ ($\phi_A$) produced at the LHC via effective operator[1]

$$\frac{\alpha_s c_\phi}{12\pi v}\phi_H G^a_{\mu\nu}G^{a,\mu\nu} \quad \left(\frac{\alpha_s c_\phi}{12\pi v}\phi_A G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right). \tag{1}$$

Such a loop-induced effective operator could be generated through a SM top-quark loop or some colored NP particles. If the operator is from top-quark loop, it is well known that the amplitude square could be written as

$$\begin{aligned}\left|\mathcal{M}\left(gg\to\phi_H\right)\right|^2 =& \frac{\alpha_s^2 c_t^2 G_F M_{\phi_H}^4}{96\sqrt{2}\pi^2}\left|\frac{m_t^2}{M_{\phi_H}^2}\left[2+\left(1-\frac{4m_t^2}{M_{\phi_H}^2}\right)\right.\right.\\ &\left.\left.\times f\left(\frac{m_t^2}{M_{\phi_H}^2}\right)\right]\right|^2,\\ \left|\mathcal{M}\left(gg\to\phi_A\right)\right|^2 =& \frac{\alpha_s^2 c_t^2 G_F M_{\phi_A}^4}{96\sqrt{2}\pi^2}\left|\frac{m_t^2}{M_{\phi_A}^2} f\left(\frac{m_t^2}{M_{\phi_A}^2}\right)\right|^2,\end{aligned} \tag{2}$$

where

$$f(x) \equiv \begin{cases} 2\arcsin^2\left(\dfrac{1}{2\sqrt{x}}\right), & x > \frac{1}{4}, \\ -\frac{1}{2}\left[\log\left(\dfrac{1+\sqrt{1-4x}}{1-\sqrt{1-4x}} - i\pi\right)\right]^2, & x < \frac{1}{4}. \end{cases} \tag{3}$$

Here we introduce $c_t$ to describe the contribution to $c_\phi$ from the top-quark loop. We have

$$c_\phi = c_t + c_{NP}, \tag{4}$$

where $c_{NP}$ is the contribution to $c_\phi$ from the exotic colored particles[2]. Our aim is investigating the size of $c_{NP}$ and $c_t$. The $pp\to\phi\to t\bar{t}$ is one of the possible channel. However, there are some disadvantages of this channel. First, the result of this channel depends on

$$\frac{\mathrm{Br}\left(\phi\to\gamma\gamma\right)}{\mathrm{Br}\left(\phi\to t\bar{t}\right)}, \tag{5}$$

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[1] If the particles in the loop is from new physics (NP) at cutoff scale $\Lambda$, from the point of the effective field theory view, the interaction should be expanded in according to the order of $1/\Lambda$ but not $1/v$ where $v$ is the scale of the electroweak spontaneously symmetry breaking (ESSB). Here we absorb the cutoff scale $\Lambda$ into $c_\phi$ for formally simplicity.

[2] We will use $\phi$ when the result works for both $\phi_H$ and $\phi_A$ for short. People can discuss non-renormalizable interactions between $\phi$ and the SM top-quark. However, the existence of them means NP effective in the production.

which is highly model dependent. Even when we fix the production mechanism, it still depend on the details in the $\phi$ decay. Such a dependence will make the conclusion weaker. Second, it has been well known that the "peak" in the $t\bar{t}$ invariant mass spectrum from this process is suffered by the interference effect with the SM top-pair production [150–154]. This interference effect will smear the "peak" and make the discovery of the signal very difficult at the LHC, especially for the $\phi$ which is heavier than 700GeV. These reasons make the $pp \to \phi \to t\bar{t}$ not be a good channel to investigate the contribution of the top-quark in the $\phi$ production. The $pp \to t\bar{t}\phi \to t\bar{t}t\bar{t}$ channel is helpful to solve the second problem [155, 156]. But it still highly depends on the details of the decay of the resonance. Because of the large SM backgrounds, at least ∼1fb (∼4fb) $t\bar{t}t\bar{t}$ cross section is needed to exclude (discover) a 750GeV (pseudo)scalar which decays to $t\bar{t}$ with 95% ($\sim 5\sigma$) confidence level (C.L.) at 14TeV LHC with 3000fb$^{-1}$ integrated luminosity. The advantage of this channel is that it is $c_{NP}$-independent and thus can be used to measure the absolute value of $c_t$.

To avoid these disadvantages, we notice that if the SM top-quark contribute to the ggF production, there must be the $pp \to t\bar{t}\phi \to t\bar{t}\gamma\gamma$ process. The $\mathrm{Br}\left(\phi \to \gamma\gamma\right)$ dependence is cancelled when we take the ratio

$$\frac{\sigma\left(pp \to t\bar{t}\phi \to t\bar{t}\gamma\gamma\right)}{\sigma\left(pp \to \phi \to \gamma\gamma\right)} \propto \left|\frac{c_t}{c_t + c_{NP}}\right|^2. \tag{6}$$

This ratio only depends on $c_{NP}/c_t$, which tells us that if $c_{NP} = 0$, the $t\bar{t}\gamma\gamma$ signal event number is uniquely determined by the diphoton signal strength, and is a perfect observable to measure the size of the contribution from the top-quark loop. Then the relative $t\bar{t}\gamma\gamma$ signal strength $\mu$, which is the ratio between the $\sigma\left(pp \to t\bar{t}\phi \to t\bar{t}\gamma\gamma\right)$ and the cross section $\sigma\left(pp \to t\bar{t}\phi \to t\bar{t}\gamma\gamma\right)_0$ from the rescaling of the inclusive diphoton signal strength with $c_{NP} = 0$ assumption, is just

$$\left|1 + \frac{c_{NP}}{c_t}\right|^{-2}. \tag{7}$$

It will be shown that the result is not too sensitive to the parity of the resonance. Thus this signal is a very important model-independent way to investigate the contribution to the 750GeV resonance production from the NP.

## III. PHENOMENOLOGY

To predict the $t\bar{t}\gamma\gamma$ signal strength, we first fit the diphoton excess. In this work, we take the data from the ATLAS collaboration as example. We generate parton level events using MadGraph5 [157] with CT14llo parton distribution function (PDF) [158]. For ggF process, $pp \to \phi + \mathrm{n}j$ events are generated to n=1. The MLM matching scheme is used to avoid the double counting in

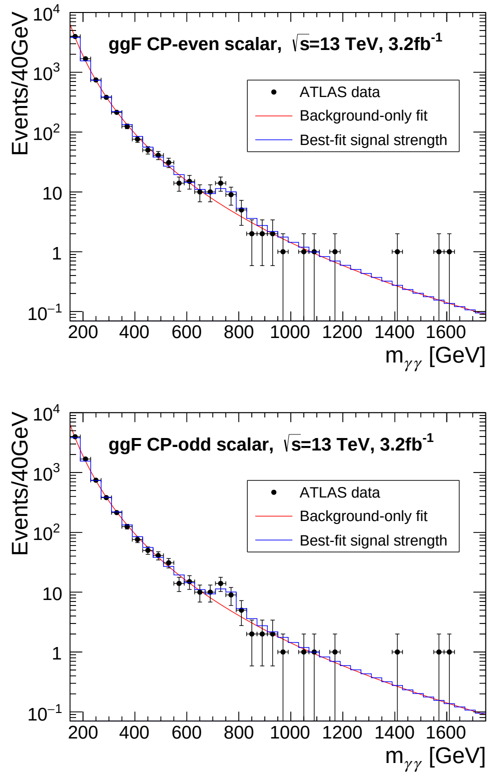


FIG. 1. The best-fit result of the LHC Run-II diphoton excess with the ggF production mode [114].

the parton showering. All parton level events are showered using PYTHIA6.4 with Tune Z2 parameter assignment [159, 160]. We use DELPHES3 to mimic the detector effects [161, 162]. The $b$-tagging efficiency (and the charm and light jets mis-tagging rates) is tuned to be consistent with the result shown in Ref. [163]. People could find more details of this fitting in [114]. We reshow the result in FIG. 1. With this result, the unfolded signal cross section[3]

$$\begin{aligned} \sigma\left(pp \to \phi_H + X\right)\mathrm{Br}\left(\phi \to \gamma\gamma\right) &= 12.3\text{fb}, \\ \sigma\left(pp \to \phi_A + X\right)\mathrm{Br}\left(\phi \to \gamma\gamma\right) &= 13.4\text{fb}. \end{aligned} \tag{8}$$

We calculate the 750GeV SM Higgs-like scalar ggF cross section at 13TeV LHC to next-to-leading order (NLO) QCD level using MCFM7.0 [164] with CT10 PDF [165]. The renormalization ($\mu_R$) and factorization ($\mu_F$) scales are both set to be $m_\phi/2 = 375$GeV. The inclusive production cross section is 565fb for $\phi_H$. For $\phi_A$, the NLO QCD

[3] This result depends on the cut acceptance from the Monte Carlo (MC) simulation, which will not be exactly. For example, if the photon identification rate from DELPHES is not perfectly the same to the real case, it will be part of the systematic error of the unfolding. However, most of these errors will be partially cancelled when we take the ratio between the inclusive cross sections since they also appear in the $t\bar{t}\phi$ MC simulation.

production cross section at 13TeV LHC is roughly 705fb [166]. The top-pair associated production cross section of the SM Higgs-like scalar is calculated using MCFM7.0 to leading order (LO) with MSTW2008LO PDF [167] and $\mu_R = \mu_F = (2m_t + m_\phi)/2 = 548.2$GeV, which is shown to have a $K$-factor $\sim 1$ [168]. The total cross section $\sigma(pp \to t\bar{t}\phi_H)$ is 2.4fb at 13TeV LHC, 3.25fb at 14TeV LHC, and 1.00pb at 100TeV $pp$ collider. The total cross section $\sigma(pp \to t\bar{t}\phi_A)$ is 3.5fb at 13TeV LHC, 4.7fb at 14TeV LHC, and 1.49pb at 100TeV $pp$ collider. Thus we have

$$\begin{aligned}\sigma(pp \to t\bar{t}\phi_H \to t\bar{t}\gamma\gamma) &= \sigma(pp \to t\bar{t}\phi_H)\,\mathrm{Br}(\phi_H \to \gamma\gamma)\\ &= \frac{\sigma(pp \to t\bar{t}\phi_H)}{\sigma(pp \to \phi_H + X)}\sigma(pp \to \phi_H + X)\\ &\quad\times \mathrm{Br}(\phi_H \to \gamma\gamma)\\ &= 52.3 \times 10^{-3}\mathrm{fb},\\ \sigma(pp \to t\bar{t}\phi_A \to t\bar{t}\gamma\gamma) &= 66.1 \times 10^{-3}\mathrm{fb} \end{aligned} \tag{9}$$

at 13TeV LHC,

$$\begin{aligned}\sigma(pp \to t\bar{t}\phi_H \to t\bar{t}\gamma\gamma) &= 70.6 \times 10^{-3}\mathrm{fb},\\ \sigma(pp \to t\bar{t}\phi_A \to t\bar{t}\gamma\gamma) &= 88.7 \times 10^{-3}\mathrm{fb}\end{aligned} \tag{10}$$

at 14TeV LHC, and

$$\begin{aligned}\sigma(pp \to t\bar{t}\phi_H \to t\bar{t}\gamma\gamma) &= 21.8\mathrm{fb},\\ \sigma(pp \to t\bar{t}\phi_A \to t\bar{t}\gamma\gamma) &= 28.1\mathrm{fb}\end{aligned} \tag{11}$$

at 100TeV $pp$ collider.

In this work, we check both the dileptonic and semi-leptonic decay modes of the top-quark pair in the $t\bar{t}\gamma\gamma$ events. We add some preselection cuts on the reconstructed objects as follows:

- **Photon:** The transverse energy of the leading (subleading) photon should be larger than 40 (30) GeV. The pseudo-rapidity of the photons should satisfy

  $$|\eta^\gamma| < 1.37, \text{ or } 1.52 < |\eta^\gamma| < 2.37. \tag{12}$$

  We add the isolation cut for the photon. The ratio between the summation of the transverse momentum of the tracks in a $\Delta R = 0.4$ cone region around the reconstructed photon and the transverse energy of the photon should be smaller than 0.022 (tight selection).

- **Electron:** Electron in the pseudo-rapidity region

  $$|\eta^e| < 1.37, \text{ or } 1.52 < |\eta^e| < 2.47 \tag{13}$$

  is reconstructed if its transverse momentum is larger than 25GeV. The ratio between the summation of the transverse momentum of the tracks in a $\Delta R = 0.2$ cone region around the reconstructed electron and the transverse momentum of the electron should be smaller than 0.1. Electrons which are within $\Delta R < 0.4$ of any reconstructed jet are removed from the event.

- **Muon:** Muon should satisfy

  $$|\eta^\mu| < 2.5, \; p_{\mathrm{T}}^\mu > 25\mathrm{GeV}. \tag{14}$$

  The ratio between the summation of the transverse momentum of the tracks in a $\Delta R = 0.2$ cone region around the reconstructed electron and the transverse momentum of the electron should be smaller than 0.1. Muons which are within $\Delta R < 0.4$ of any reconstructed jet are removed from the event to reduce the background from muons from heavy flavor decays .

- **Jet:** Jets are reconstructed using anti-$k_T$ algorithm with radius parameter $R = 0.4$. They are accepted if

  $$|\eta^j| < 2.5, \; p_{\mathrm{T}}^j > 25\mathrm{GeV}. \tag{15}$$

  In additional, $b$-jets are required to be in

  $$|\eta^b| < 2.4. \tag{16}$$

The signal events are required to have at least one charged lepton, two isolated hard photons and at least one $b$-tagged jet. Then they are separated into same-flavor dilepton events, $e\mu$ events and semi-leptonic events.

Some additional cuts are added for the three different signal events sample. The cuts are generally a combination of the SM top-pair cuts and high invariant mass diphoton cuts [1, 169, 170]. First of all, the invariant mass of the leading and subleading photons $m_{\gamma\gamma}$ must satisfy

$$|m_{\gamma\gamma} - 750\mathrm{GeV}| < 150\mathrm{GeV}. \tag{17}$$

The transverse energy $E_{\mathrm{T}}^{\gamma_1}$ ($E_{\mathrm{T}}^{\gamma_2}$) of the leading (subleading) photon must satisfy

$$\frac{E_{\mathrm{T}}^{\gamma_1}}{m_{\gamma\gamma}} > 0.4 \; \left(\frac{E_{\mathrm{T}}^{\gamma_2}}{m_{\gamma\gamma}} > 0.3\right). \tag{18}$$

- **Same-flavor dilepton events:** Events are required to have either exactly two opposite-sign muons or two opposite-sign electrons. To suppress the backgrounds from the $Z$+jets and heavy flavor decay, the invariant mass of the dilepton system $m_{\ell\ell}$ is required to be

  $$m_{\ell\ell} > 60\mathrm{GeV}, \; |m_{\ell\ell} - m_Z| > 10\mathrm{GeV}. \tag{19}$$

  The missing transverse energy $\not{E}_{\mathrm{T}}$ of the signal events must be larger than 30GeV.

- **Semi-leptonic events:** Events are required to have one and only one charged lepton and at least four jets. The $\not{E}_{\mathrm{T}}$ and the transverse mass $m_{\mathrm{T}}$ of the missing transverse energy and the charged lepton is required to be

  $$\not{E}_{\mathrm{T}} > 40\mathrm{GeV}, \text{ or } m_{\mathrm{T}} > 50\mathrm{GeV} \tag{20}$$

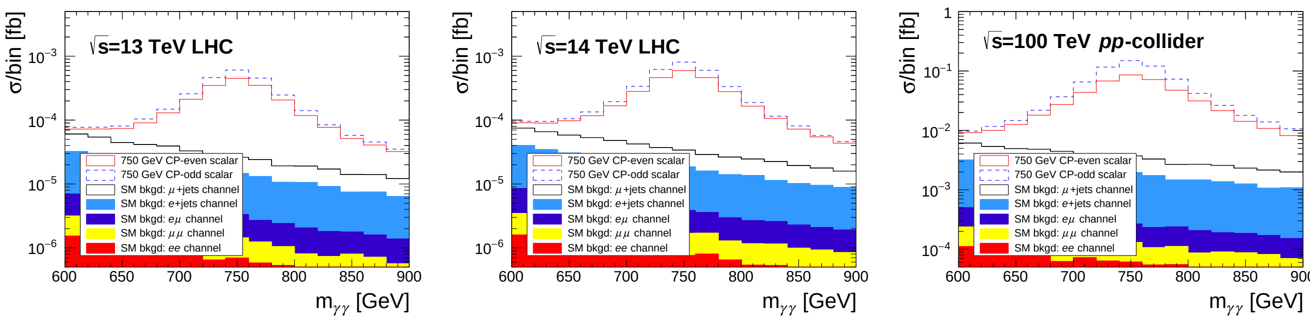


FIG. 2. The diphoton invariant mass distribution of both signal and background events after cuts. The signal strength $\mu$ is set to be 1. The solid red lines and the dashed blue lines are the signals of the scalar and pseudoscalar, respectively.

TABLE I. The signal and backgrounds cross sections after the cuts at 13 TeV LHC, 14 TeV LHC and 100TeV $pp$ collider. The unit in this table is ab.

| Channel | $e$+jets channel | $\mu$+jets channel | $e\mu$ channel | $ee$ channel | $\mu\mu$ channel |
|---|---|---|---|---|---|
| 13TeV background cross section (ab) | 0.190 | 0.206 | 0.0298 | 0.0110 | 0.0117 |
| 13TeV $\phi_H$ signal cross section (ab) | 0.823 | 0.873 | 0.104 | 0.0374 | 0.0403 |
| 13TeV $\phi_A$ signal cross section (ab) | 1.05 | 1.15 | 0.132 | 0.0465 | 0.0543 |
| 14TeV background cross section (ab) | 0.241 | 0.263 | 0.0363 | 0.0131 | 0.0152 |
| 14TeV $\phi_H$ signal cross section (ab) | 1.11 | 1.16 | 0.137 | 0.0486 | 0.0523 |
| 14TeV $\phi_A$ signal cross section (ab) | 1.39 | 1.55 | 0.172 | 0.0607 | 0.0706 |
| 100TeV background cross section (ab) | 24.5 | 26.0 | 2.35 | 0.956 | 1.03 |
| 100TeV $\phi_H$ signal cross section (ab) | 197 | 194 | 19.0 | 7.65 | 7.06 |
| 100TeV $\phi_A$ signal cross section (ab) | 304 | 324 | 25.4 | 10.3 | 10.9 |

for electron events and

$$\not{E}_{\mathrm{T}} + m_{\mathrm{T}} > 60\mathrm{GeV} \tag{21}$$

for muon events.

- $e\mu$ **events:** Events are required to have a pair of opposite-sign electron and muon. No more cut is added.

All of the results of 100TeV $pp$ collider are get with the simple assumption that the parameters of the detector and the cuts are the same to the LHC.

The irreducible SM background is the $pp \to t\bar{t}\gamma\gamma$ process. There are some reducible SM backgrounds such as

$$\begin{aligned} &pp \to t\bar{t}\gamma j, \\ &pp \to t\bar{t}jj, \\ &pp \to V + \mathrm{jets}. \end{aligned}$$

However, the non-$t\bar{t}+X$ backgrounds would be highly suppressed by the cuts [169, 170]. And the $t\bar{t}jj, t\bar{t}\gamma j$ backgrounds will be suppressed by the mis-identification rate of a (or two) jet(s) to photon. In this preliminary analysis, we will only consider the irreducible SM background $pp \to t\bar{t}\gamma\gamma$ and neglect the irreducible backgrounds. Although the signal cross section is not large, due to the extremely energetic diphoton cut, the background events number is expected to be quite small. The results are shown in TABLE I and FIG. 2. To discover the NP in the production process, we need to exclude the $c_{NP} = 0$ hypothesis which means $\mu = 1$. We separate the invariant mass region into fifteen bins and check the exclusion significance of the signal with strength $\mu$ [171, 172]

$$\mathrm{CL}_b \equiv \sqrt{-2\log\left[\frac{L\left(\mu\left\{s\right\}+\left\{b\right\}|\left\{b\right\}\right)}{L\left(\left\{b\right\}|\left\{b\right\}\right)}\right]}, \tag{22}$$

where $s$ and $b$ are events numbers of the signal and the background, respectively. If the cross sections of the signal and background are $\sigma_s$ and $\sigma_b$ respectively and the luminosity is $\mathcal{L}$, we have

$$s = \sigma_s\mathcal{L}, \quad b = \sigma_b\mathcal{L}. \tag{23}$$

The likelihood function is defined by

$$L\left(\{x\}\,|\,\{n\}\right) \equiv \prod_i \frac{x_i^{n_i}\exp\left(-x_i\right)}{\Gamma\left(n_i+1\right)}. \tag{24}$$

People can also get the significance of confirming the top-quark loop contribution (excluding $c_t = 0$ hypothesis) which can be defined as

$$\mathrm{CL}_s \equiv \sqrt{-2\log\left[\frac{L\left(\left\{b\right\}|\mu\left\{s\right\}+\left\{b\right\}\right)}{L\left(\mu\left\{s\right\}+\left\{b\right\}|\mu\left\{s\right\}+\left\{b\right\}\right)}\right]}. \tag{25}$$

From FIG. 3, we find that with the full data from the high-luminosity (HL) LHC, a $3\sigma$ C.L. (nearly $5\sigma$ C.L.) exclusion of the $c_{NP} = 0$ ($c_t = 0$) hypothesis can be reached. At 100TeV $pp$ collider, the $3\sigma$ C.L. exclusion of the $c_{NP} = 0$ hypothesis will be reached with 13.8fb$^{-1}$ (8fb$^{-1}$) integrated luminosity for (pseudo)scalar. To

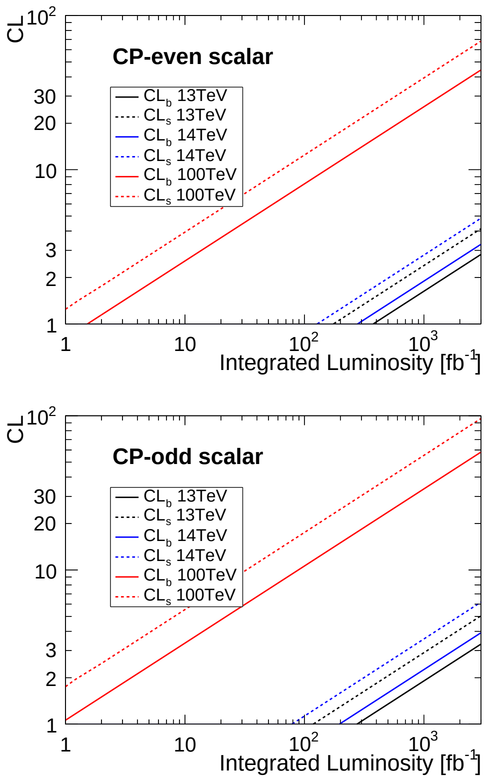


FIG. 3. The significance of exclusion (CL$_b$) and discovery (CL$_s$) of the $c_{NP} = 0$ hypothesis at the LHC and the 100TeV $pp$ collider versus the integrated luminosity.

measure $\mu$ precisely, a 100TeV $pp$ collider is necessary. We define the uncertainty $\delta\mu$ of the signal strength by

$$\sqrt{-2\log\left[\frac{L\left((\mu+\delta\mu)\{s\}+\{b\}\,|\mu\{s\}+\{b\}\right)}{L\left(\mu\{s\}+\{b\}\,|\mu\{s\}+\{b\}\right)}\right]} = 1. \tag{26}$$

At 100TeV $pp$ collider, the signal strength $\mu$ can be measured with about 20% relative uncertainty with 100fb$^{-1}$ integrated luminosity, about 3% relative uncertainty with 3000fb$^{-1}$ integrated luminosity, and less than 1% relative uncertainty with 3ab$^{-1}$ integrated luminosity (see FIG. 4).

## IV. CONCLUSION

Recently, an excess at 750GeV in the diphoton invariant mass distribution is reported by ATLAS and CMS collaboration with the LHC Run-II data. If it is confirmed by the future data, it will be the first particle

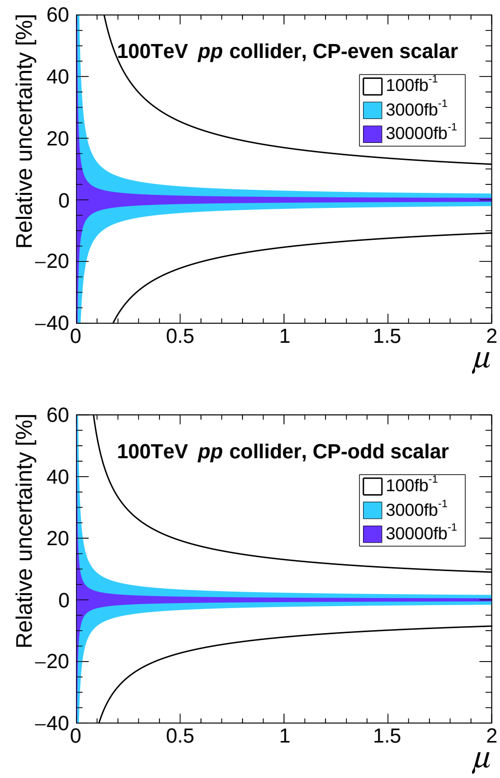


FIG. 4. The relative uncertainty ($\delta\mu/\mu$) of the signal strength at 100TeV $pp$ collider. We only consider statistical uncertainty.

beyond the SM discovered at high energy colliders. And the particle physics SM must be extended. It will be very important to understand the production and the decay properties of the new particle. A ggF produced exotic (pseudo)scalar is one of the most popular explanation of this excess. In this work, we suggest a method to investigate the role of the SM top-quark in the loop-induced effective operator.

If we are lucky, and there are new particles which contribute to the loop-induced effective operator, these particles might be discovered in the searching of heavy colored particles. However, it depends on the mass and the decay modes of the exotic colored particle. Comparing with directly searching for the exotic colored particle, our method can give a definitely answer of the role of the SM top-quark and whether there is exotic contributions to the production of this 750GeV resonance, with either a positive or a null result. We show that with the HL-LHC data, 95% C.L. exclusion of the $c_{NP} = 0$ hypothesis can be reached. It will be a strong hint of the existence of the role of new particles in the production of the 750GeV resonance.

In additional, the contribution from the SM top-quark in the production of the 750GeV resonance can be precisely measured with the 100TeV $pp$ collider in future [173, 174]. With 3ab$^{-1}$ integrated luminosity, the relative uncertainty could be smaller than 1%. This result, with the result from searching $pp \to t\bar{t}\phi \to t\bar{t}t\bar{t}$, can help us understand the properties of the new resonance, especially its production.

Since the (pseudo)scalar couples to the gluon, the $\sigma(pp \to t\bar{t}\phi \to t\bar{t}\gamma\gamma)$ is not exactly 0 when $c_t = 0$. The (pseudo)scalar could be radiated from any gluon in the top-pair process. Such a cross section is in the order of

$$\alpha_s(\mu_R)^2 \times \frac{\alpha_s(\mu_R)^2 c_\phi^2 M_\phi^2}{144\pi^2 v^2} \times \mathrm{Br}(\phi \to \gamma\gamma) \tag{27}$$

while the cross section for $c_t$ induced process is in the order of

$$\alpha_s(\mu_R)^2 \times c_t^2 \times \mathrm{Br}(\phi \to \gamma\gamma). \tag{28}$$

Because they have nearly the same size of the phase space suppression, it is clear that such a tiny production rate can be significant if and only if

$$c_t^2 \sim \frac{\alpha_s(\mu_R)^2 c_\phi^2 M_\phi^2}{144\pi^2 v^2} \tag{29}$$

which means

$$\mu = \frac{c_t^2}{c_\phi^2} \sim \frac{\alpha_s(\mu_R)^2 M_\phi^2}{144\pi^2 v^2} \approx 6 \times 10^{-5}. \tag{30}$$

Thus this contribution is negligible small and not considered in this work.

## V. ACKNOWLEDGMENTS

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