LHC prospects in searches for neutral scalars in \( pp \to \gamma\gamma + \text{jet} \): SM Higgs boson, radion, sgoldstino

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Abstract

At hadron colliders the \( \gamma\gamma + \text{jet} \) channel provides larger signal-to-background ratio in comparison with inclusive \( \gamma\gamma \) channel in hunting for scalars uncharged under the SM gauge group. At NLO in QCD perturbation theory we evaluate selfconsistently the signal significance for the SM Higgs boson production in \( \gamma\gamma + \text{jet} \) channel at LHC. Three-body final state kinematics allows for refined cuts. The adjustment of these cuts increases the signal significance upto the level of inclusive channel. Applying a justified simple rescaling procedure to the results obtained for SM Higgs boson, we estimate the LHC prospects in searches for radion and sgoldstino in \( \gamma\gamma + \text{jet} \) channel. We have found that this channel is comparable with \( \gamma\gamma \) channel in searches for new physics and deserves further detailed investigations.

1 Introduction

With a lack of deeper understanding of strong interactions, search for signal events in hadron collisions is somewhat ambiguous due to the uncertainties in the prediction of the cross section of background processes. In case of large number of background events the theoretical uncertainties in QCD predictions can result in swamping the signal. Thus at hadron colliders among various channels of the same signal significance the most favorable are those with large signal-to-background ratio.

In this paper we study the LHC prospects in searches for Standard Model (SM) Higgs boson, radion and sgoldstino in \( \gamma\gamma + \text{jet} \) channel. In comparison with inclusive \( \gamma\gamma \) channel, which has almost the same signal significance, \( \gamma\gamma + \text{jet} \) channel exhibits larger signal-to-background ratio and, consequently, stronger possibility to have control over QCD background. Though the signal cross section is smaller in the channel with a high energy jet than in the inclusive channel, rich 3-body kinematics in the final state affords an opportunity to reduce the background significantly.

The \( \gamma\gamma + \text{jet} \) channel has been extensively investigated as a channel where SM Higgs boson with mass in the range 100 – 140 GeV should be discovered at LHC.

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At the leading order in perturbation theory the signal significance was estimated in Ref. [1]. The obtained results suggested that $\gamma\gamma + \text{jet}$ channel is comparable with $\gamma\gamma$ channel in searches for SM Higgs boson: the signal significances differ slightly, while the signal-to-background ratio is several times larger for $\gamma\gamma + \text{jet}$ channel.

This observation aroused the interest in phenomenology of this channel and several thorough investigations have been performed. In particular, the NLO corrections to the cross sections of the dominant signal subprocesses have been evaluated in Ref. [2] in the limit of the infinite mass of $t$-quark, $M_t \to \infty$. Similar to the inclusive channel, QCD corrections double the Higgs production. The next natural step was done in Ref. [3, 4], where cross sections of main QCD background subprocesses were calculated at NLO and their variations with cuts have been studied. Finally, the photon smooth isolation procedure [5], which is required to get rid of photons from fragmentation, was included in the analysis of the NLO QCD background.

In this work we accumulate all relevant NLO results to calculate self-consistently the NLO signal significance for SM Higgs boson production in $pp \to H(H \to \gamma\gamma) + \text{jet}$ channel. Along with light $u, d, s$ quarks contribution we take into account also antiquark and heavy quark contribution missed in paper [1] that raise the signal cross section by $6 - 7\%$ while background — by about $25\%$. We have found that for cuts selected as in Ref. [1] the signal significance remains almost intact with increasing order of perturbation theory. Thus LO results for signal significance are stable with respect to QCD corrections. We estimate the uncertainties of our results for the signal significance to be not larger than $10\%$, if unknown higher order QCD corrections are disregarded. Let us stress that our estimates are performed in a selfconsistent way with respect to QCD perturbative calculus.

Then we play with varying cuts and observe that their refinement allows as much as $30\%$ rise in the signal significance, provided that at LHC the very forward hadron calorimeters will operate properly.

The discovery of SM Higgs boson is a major goal of LHC. To this end many channels have been scrutinized closely. One can exploit these results to get for free accurate estimates of LHC sensitivity to new physics which manifestation mimics SM Higgs boson production. Indeed, any scalar uncharged under SM gauge group couples to the SM fields exactly in the same way as SM Higgs boson. The only distinguishing features are values of the corresponding coupling constants, hence the production rate of the new scalar in the same channel as SM Higgs boson production can be estimated by making use of a simple rescaling procedure. Since the background is the same, this yields the accurate estimate of the signal significance for the production of this new scalar particle.

This method is applicable to many models, in particular, to any models with extended Higgs sector. In this paper we consider two examples of the appropriate models. The first example is provided by models with warped extra spatial dimensions, where new scalar particle $\phi$, radion, emerges in the low-energy spectrum. It is
associated with moduli, which vacuum expectation value $\Lambda_\phi$ suppresses radion coupling to the SM fields. We estimate the LHC sensitivity to $\Lambda_\phi$ in $\gamma\gamma + jet$ channel for the models with radion mass of $100 - 140$ GeV. The second example is given by supersymmetric extensions of the SM with low-energy spontaneous supersymmetry breaking, where sgoldstinos gain masses of the order of electroweak scale. Their couplings to the SM fields are determined by the scale $\sqrt{F}$ of the supersymmetry breaking and corresponding soft supersymmetry breaking terms. We estimate the LHC sensitivity to $\sqrt{F}$ in $\gamma\gamma + jet$ channel for models with sgoldstino mass of $100 - 300$ GeV and soft supersymmetry breaking terms within $100 - 500$ GeV. Both examples suggest that discovery potential of $\gamma\gamma + jet$ channel in searches for new physics is comparable to prospects of the inclusive channel. Note in passing that radion production and sgoldstino production in inclusive channel have been estimated for the first time \cite{6, 7} by making use of the rescaling procedure similar to the one we apply in this work.

The rest of the paper is organized as follows. In section II we evaluate at NLO in perturbation theory the signal significance for SM Higgs boson production at LHC in $pp \rightarrow \gamma\gamma + jet$ channel. There we study the dependence of the significance on variations of the selected cuts and outline the optimal set of cuts. Section III is devoted to estimates of LHC prospects in searches for new physics in this channel. Namely, we consider multidimensional models with radion of $100 - 140$ GeV and supersymmetric models with sgoldstinos of $100 - 300$ GeV. Section IV contains discussion and conclusions.

## 2 Higgs boson

We begin with studying LHC prospects in searches for SM Higgs boson in $\gamma\gamma + jet$ channel. Since NLO $K$-factors for main signal and background processes have been calculated recently \cite{2, 4}, we embrace them to improve the estimate \cite{1} of the signal significance by taking into account all relevant NLO corrections. In the next sections we extend this result and estimate the LHC potential in searches for radion and sgoldstino in this channel.

In calculations of the SM Higgs boson production at LHC we use the CompHEP package \cite{8} with implemented $Hgg$, $Hggg$, and $H\gamma\gamma$ effective point-like couplings. The coupling constants entering these vertices have been obtained by matching the corresponding partial widths, evaluated by means of CompHEP package, with NLO results of HDECAY \cite{9}. This method is justified because the analysis \cite{2} reveals that NLO corrections to QCD subprocesses of $pp \rightarrow H(H \rightarrow \gamma\gamma) + jet$ can be reproduced by almost the same $K$-factor as for the inclusive channel. Subprocesses with $WWH$ and $ZZH$ vertices are considered only at tree level of perturbation theory. Although they give a substantial contribution (about 20%) to the signal cross section, we do
not expect any considerable deviation of total NLO results for signal significance, since QCD corrections to SM Higgs boson production via W, Z-fusion are rather modest, $5 - 10\%$ [10].

Evaluating the rates of both signal and background processes, we adopt CTEQ6M approximation to NLO parton distribution functions, and for main QCD subprocesses we set renormalization scale to $Q^2 = M_{\gamma\gamma}^2 + (p_T^{\text{jet}})^2$, where $M_{\gamma\gamma}$ is invariant mass of the photon pair and $p_T^{\text{jet}}$ is transverse momentum of the hadronic jet. For the subprocesses with $W$- or $Z$-bosons we set $Q^2 = M_V^2$.

The NLO result for the background cross section was calculated in Ref. [4], so to obtain the NLO approximation to the signal significance we use almost the same set of cuts: $p_T > 40\,\text{GeV}$, $|\eta| < 2.5$ for both photons and jet with $\eta$ being pseudorapidity, $R_{\gamma\gamma} > 0.4$, $R_{\gamma\text{jet}} > 1.5$ (here $R_{ij} = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ is a separation between two particles $i$ and $j$ in azimuth-angle–rapidity plane); the isolation parameters are taken to be $R = 1$, $\epsilon = 0.5$, see Ref. [5], [4] for details.

The NLO results for the cross sections of the main signal subprocesses and the background are presented in Table 1. The background events have been collected in $M_{\gamma\gamma} \pm 1.4 \cdot \sigma(M_{\gamma\gamma})$ interval, where $\sigma(M_{\gamma\gamma})$ is the mass resolution of ATLAS detector [11].

| $M_H$, GeV | 100 | 110 | 120 | 130 | 140 |
|-------------|-----|-----|-----|-----|-----|
| $gg \to g\gamma\gamma$, fb | 2.72 | 3.65 | 4.47 | 4.66 | 4.05 |
| $qg \to q\gamma\gamma$, fb | 0.68 | 0.89 | 1.07 | 1.10 | 0.95 |
| $q\bar{q} \to g\gamma\gamma$, fb | 0.38 | 0.49 | 0.59 | 0.60 | 0.52 |
| $W$-, $Z$-contributions, fb | 1.23 | 1.67 | 1.86 | 1.91 | 1.68 |
| total signal cross section, $\sigma_S$, fb | 5.06 | 6.76 | 8.06 | 8.34 | 7.25 |
| background cross section, $\sigma_B$, fb | 53.2 | 55.6 | 56 | 57.3 | 55.6 |
| $N_S/N_B$ | 0.10 | 0.12 | 0.14 | 0.15 | 0.13 |

Table 1: Summary of main signal and background cross sections. The background photons have been collected within $M_{\gamma\gamma} \pm 1.4 \cdot \sigma(M_{\gamma\gamma})$ interval, where $\sigma(M_{\gamma\gamma})$ is the mass resolution of ATLAS detector [11].

Mass range $100 - 115$ GeV is already experimentally excluded for SM Higgs boson, but we will use these points in the next section to carry out similar estimates for LHC sensitivity to new physics. It is worth to note that in this estimates we do

\footnote{Along with light $u$, $d$, $s$ quarks contribution we take into account also antiquark and heavy quark contribution missed in paper [11] that raise the signal cross section by $6 - 7\%$ while background — by about $25\%$.}
not take into account the efficiency of photon and jet registrations in future LHC detectors.

The signal significance for ATLAS detector is plotted in Fig. 1 as a function of

\[
\frac{N_S}{\sqrt{N_B}}
\]

Figure 1: Signal significance \( \frac{N_S}{\sqrt{N_B}} \) of the Higgs boson production in \( pp \rightarrow \gamma\gamma + \text{jet} \) channel with integrated luminosities of 30 fb\(^{-1}\) and 100 fb\(^{-1}\).

Higgs mass for two values of the integrated luminosity: 30 fb\(^{-1}\) and 100 fb\(^{-1}\). One can see, that in the viable mass range, 115 GeV < \( M_H \) < 140 GeV, it will be possible to discover SM Higgs boson in \( pp \rightarrow \gamma\gamma + \text{jet} \) channel even with low luminosity of 30 fb\(^{-1}\) (the first year of LHC operating).

Comparing two channels, \( pp \rightarrow H(H \rightarrow \gamma\gamma) + \text{jet} \) and \( pp \rightarrow H \rightarrow \gamma\gamma \), we find that ratio of the signal significances for these channels (our results for the first channel and results, presented in [13] for the second channel) is about 0.8 – 0.9, while the signal-to-background ratio is higher by a factor of 2 – 3 for the channel with a high energy jet. Hence, we confirm that \( \gamma\gamma + \text{jet} \) channel is competitive with the inclusive channel in hunting for SM Higgs boson.

Let us discuss the accuracy of the presented results. The main uncertainty is related to still unknown NNLO QCD corrections, or, in our setup, to the strong dependence of the NLO results on the renormalization scale. Indeed, it was shown in Refs. [2] and [4], that for the renormalization scale parameterized as \( Q^2 = x \cdot (M_{\gamma\gamma}^2 + (p_T^{\text{jet}})^2) \) the dominant QCD signal and background cross sections decrease by about 50% and 10 – 30%, respectively, with \( x \) changing from 0.5 to 2. With a lack of understanding of the structure of QCD perturbation series, any reliable quantitative estimate of this uncertainty seems improper.

Another source of uncertainty is associated with the local approximation to \( ggH \) coupling (valid in large \( M_t \) limit). Namely, gluons and Higgs boson are assumed to
be on shell. Actually, this is not the case: one (two) gluon(s) entering LO (NLO) diagrams can be off shell. However, for $M_H < M_t$ the local approximation works well enough (with accuracy higher than a few percent, see Refs. [14], [15]).

In our estimates we adopt the results for the background processes [4] obtained by making use of the photon isolation procedure [5]. This procedure is aimed at rejecting photons from fragmentation. For the inclusive $pp \to H \to \gamma\gamma$ channel it was demonstrated in Ref. [13], that with reasonable choice of the isolation parameters the signal significance increases but mostly due to reduction of the background. In our calculations we do not apply this procedure to single out the signal events and estimate the corresponding corrections to be less than $5 - 10\%$.

Thus, without unknown QCD-corrections, we conclude that in total the uncertainty of our results for the signal significance does not exceed $10\%$. The obtained results and their accuracy ensure that SM Higgs boson of mass within $115 - 140$ GeV will be definitely observed in $pp \to \gamma\gamma + jet$ channel at LHC even with low integrated luminosity of $30$ fb$^{-1}$.

Finally let us study the dependence of the signal significance on the cuts. We do not pretend on a completeness or on a high accuracy in this study, the purpose is to catch the general tendency and outline the optimal set of cuts. To this end we consider only dominant QCD-subprocesses, thus neglecting $W$-boson and $Z$-boson contributions. Also we simplify the evaluation as follows. The LO results for a new set of cuts are obtained by making use of CompHEP package. The NLO corrections are included as $K$-factors of the same values as for the old set of cuts.

To begin with, we include the additional cut on the energy of scattering partons in their c.m.s., $\sqrt{\hat{s}}$, since this cut enables one to reduce the background significantly [1]. The results presented in Table 2 show that signal significance $N_S/\sqrt{N_B}$ always degrades when cuts on $\sqrt{\hat{s}}$ are introduced. On the other hand the signal-to-background ratio increases from $0.09 - 0.11$ (without any cut on $\sqrt{\hat{s}}$) to $0.2 - 0.25$

| $M_H$, GeV | 100 | 110 | 120 | 130 | 140 |
|------------|-----|-----|-----|-----|-----|
| $\sqrt{\hat{s}} > 250$ GeV | 5.3 | 0.07 | 6.8 | 0.09 | 8.3 | 0.11 | 8.5 | 0.11 | 7.5 | 0.10 |
| $\sqrt{\hat{s}} > 300$ GeV | 5.3 | 0.12 | 6.7 | 0.15 | 8.0 | 0.15 | 8.1 | 0.15 | 7.1 | 0.12 |
| $\sqrt{\hat{s}} > 350$ GeV | 5.3 | 0.16 | 6.7 | 0.19 | 7.8 | 0.20 | 7.8 | 0.19 | 6.7 | 0.15 |

Table 2: Dependence of the signal significance $N_S/\sqrt{N_B}$ and signal-to-background ratio $N_S/N_B$ on the additional cut on $\sqrt{\hat{s}}$ at the integrated luminosity of 100 fb$^{-1}$. The rest of the selection cuts is the same as in Table 1. The contributions from $W$- and $Z$-bosons have been omitted.
(for $\sqrt{s} > 350$ GeV). Hence, additional cut on $\sqrt{s}$ leads to considerable growth of the signal-to-background ratio at a price of slight decrease in signal significance.

Then we estimate $N_S/\sqrt{N_B}$ for various cuts on $p_T^\gamma$ (see Table 3). The reason

| $M_H$, GeV | 100 | 110 | 120 | 130 | 140 |
|------------|-----|-----|-----|-----|-----|
| $p_T^\gamma > 40$ GeV | 5.3 | 0.07 | 6.8 | 0.09 | 8.3 | 0.11 | 8.5 | 0.11 | 7.5 | 0.10 |
| $p_T^\gamma > 30$ GeV | 6.5 | 0.07 | 8.2 | 0.09 | 9.5 | 0.11 | 9.4 | 0.11 | 8.0 | 0.10 |
| $p_T^\gamma > 20$ GeV | 6.9 | 0.06 | 8.4 | 0.08 | 9.6 | 0.10 | 9.5 | 0.10 | 8.0 | 0.09 |

Table 3: Signal significance $N_S/\sqrt{N_B}$ signal-to-background ratio $N_S/N_B$ at various cuts on $p_T^\gamma$ for one of photons with the integrated luminosity of 100 fb$^{-1}$. The other selection cuts are the same as ones in the Table 1. The contributions from $W$- and $Z$-bosons have been omitted.

is that the standard set of cuts usually adopted for ATLAS and CMS detectors in numerical simulations of the SM Higgs boson production, $p_T^\gamma > 40$ GeV, $p_T^\gamma > 25$ GeV, differs from our set. One can see, that adjustment of this cut yields $10–15\%$ increase in the signal significance (at a price of a slight decrease in the signal-to-background ratio).

At last we vary cuts on $|\eta_{jet}|$, as motivated by the expected ability of hadronic calorimeter to cover the broad range of pseudorapidity, $|\eta| < 4–5$. The results presented in Table 4 suggest that very forward calorimeter allows $10–15\%$ raise in signal significance.

| $M_H$, GeV | 100 | 110 | 120 | 130 | 140 |
|------------|-----|-----|-----|-----|-----|
| $|\eta_{jet}| < 2.5$ | 5.3 | 0.07 | 6.8 | 0.09 | 8.3 | 0.11 | 8.5 | 0.11 | 7.5 | 0.10 |
| $|\eta_{jet}| < 4$ | 6.0 | 0.08 | 7.9 | 0.10 | 9.7 | 0.12 | 10.1 | 0.13 | 8.9 | 0.11 |

Table 4: Signal significance $N_S/\sqrt{N_B}$ signal-to-background ratio $N_S/N_B$ at various cuts on $\eta_{jet}$ with the integrated luminosity of 100 fb$^{-1}$. The other selection cuts are the same as in Table 1. The contributions from $W$- and $Z$-bosons have been omitted.

In total one can expect, that at least $10–30\%$ increase in the signal significance is anticipated at optimal choice of cuts. Reverting to the comparison of $\gamma\gamma$ channel to $\gamma\gamma + jet$ channel we conclude that the latter exhibits practically the same signal significance as former and $2–2.5$ times larger signal-to-background ratio. Consequently, $pp \rightarrow H(H \rightarrow \gamma\gamma) + jet$ process can be treated even as a promising alternative to the inclusive production.
3 Other (pseudo)scalars

Let us describe how to extend the analysis presented in the previous section to the production of non-SM (pseudo)scalars. By making use of the results obtained for SM Higgs boson we will estimate the sensitivity of LHC in channel \( pp \rightarrow \gamma\gamma + \text{jet} \) to the multidimensional models with radions and supersymmetric models with sgoldstinos.

The obvious procedure is a simple rescaling. Indeed, any scalar \( X \) uncharged under SM gauge group interacts with SM massless gauge bosons via nonrenormalizable couplings and the simplest among them are of the same structure as for SM Higgs boson. The very values of the corresponding coupling constants are the only difference. Hence, if the gluon fusion mechanism dominates new-scalar particle production, the signal cross section \( \sigma_X \) for \( pp \rightarrow X(X \rightarrow \gamma\gamma) + \text{jet} \) process can be obtained by means of rescaling

\[
\sigma_X = \sigma_H \cdot \left( \frac{A_{Xgg}}{A_{Hgg}} \right)^2 \cdot \frac{\text{Br}(X \rightarrow \gamma\gamma)}{\text{Br}(H \rightarrow \gamma\gamma)},
\]

where \( A_{Hgg} \) and \( A_{Xgg} \) are effective coupling constants entering \( Hgg \) and \( Xgg \) vertices, respectively, and \( \sigma_H \) contains only contributions from partonic diagrams with \( ggH \) and \( gggH \) vertices to the Higgs boson production. It is straightforward to generalize this rescaling to the models with non-negligible \( Xqq \) couplings. Certainly, \( \sigma_X \) estimated in this way implies the same set of cuts as \( \sigma_H \).

Below we consider two different extensions of the SM with new scalars. In both cases scalar production is dominated by gluon fusion. For this special type of models the ratio of signal significances of \( pp \rightarrow X(X \rightarrow \gamma\gamma) \) and \( pp \rightarrow X(X \rightarrow \gamma\gamma) + \text{jet} \) channels is model independent: the only relevant parameter governing this ratio is the scalar mass \( M_X \). With the standard set of cuts adopted in hunting for SM Higgs boson in the inclusive channel \[13\] and our set of cuts for \( \gamma\gamma + \text{jet} \) channel the ratio is about \( 0.6 - 0.7 \) for \( M_X = 100 - 140 \text{ GeV} \).

Note in passing that, if subprocesses with exchange of \( W \)-boson or \( Z \)-boson give a comparable contribution to \( X \) production, then: (i) rescaling procedure becomes rather involved, since both renormalizable and nonrenormalizable \( XZZ \) and \( XWW \) couplings are generally allowed, while for SM Higgs boson only renormalizable interactions exist, (ii) the universality of the ratio of significances of two channels breaks down. However, in these models hunting for scalar is more efficient in \( WW^* \) and \( ZZ^* \) decay modes, that is beyond the scope of this paper.

3.1 Radion

In models with warped spatial extra dimensions (see, e.g., Ref. \[16\] and references therein), there is a module, radion, associated with position of a brane. Stabilization
of this module results in its coupling to the SM fields

$$\mathcal{L}_\phi = \frac{\phi}{\Lambda_\phi} T^\mu_{\mu}(SM),$$

where $\Lambda_\phi$ is a vacuum expectation value of the module and $T^\mu_{\mu}(SM)$ is the trace of SM energy-momentum tensor, which consists of ordinary and anomaly contributions. The ordinary term is

$$T^\mu_{\mu}(SM)^{ord} = \sum_f m_f \bar{f} f - 2m_W^2 W^+_\mu W^-_{\mu} - m_Z^2 Z_{\mu} Z_{\mu} + \ldots,$$

where dots denote contributions of SM Higgs boson and higher order terms. For gauge bosons there is also the anomaly contribution:

$$T^\mu_{\mu}(SM)^{anom} = \sum_{\text{all gauge fields}} \frac{\beta_a(g_a)}{2g_a} F^a_{\mu\nu} F^{a\mu\nu},$$

where $\beta_a(g_a)$ are corresponding $\beta$-functions.

The effective couplings of radion to gluons and photons are given by direct contribution from the trace anomaly and contribution from the loop diagrams similar to the diagrams emerging in the case of SM Higgs boson. As a result, $\phi gg$ coupling strongly dominates over $\phi WW$ and $\phi ZZ$ couplings in comparison with the case of SM Higgs boson: contribution of subprocesses with $W$- and $Z$- bosons is less than 2%. Hence our rescaling procedure is justified.

In models with radion there are only two free parameters: radion mass $m_\phi$ and $\Lambda_\phi$ (current experimental bounds are $M_\phi > 120$ GeV at $\Lambda_\phi = 1$ TeV). So we investigate the LHC sensitivity in $pp \to \gamma \gamma + jet$ channel to the scale $\Lambda_\phi$ in models with radion mass $m_\phi = 100 - 140$ GeV by rescaling results obtained for SM Higgs boson, as explained above. The results for the models with radion are presented in Fig. 2 for a set of integrated luminosities. Any models with parameters in the region below plotted lines will be discovered at LHC (ATLAS detector only) at the confidence level better than 5$\sigma$ if corresponding integrated luminosities are collected. One can conclude that it is possible to discover radion with masses of $100 - 140$ GeV in $pp \to \gamma \gamma + jet$ channel, if stabilization scale is not higher than 4 TeV.

### 3.2 Sgoldstino

The models with spontaneous supersymmetry breaking contain goldstino supermultiplet, which includes scalar particles—sgoldstinos—superpartners of goldstino. In a variety of models (see, e.g., Refs. [19], [20]) these particles are relatively light.

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4In a number of models higgs-radion mixing can arise, but in this paper we ignore this possibility.
Figure 2: Signal significance (5σ-level) for the radion production in $pp \rightarrow \gamma\gamma + jet$ reaction with integrated luminosity 30 fb$^{-1}$, 100 fb$^{-1}$ and 200 fb$^{-1}$.

and could be produced at LHC. The part of sgoldstino interaction terms relevant to the study of sgoldstino production in $pp \rightarrow \gamma\gamma + jet$ channel reads [21]

$$L_S = - \sum_{all\ gauge\ fields} \frac{M_\alpha}{2\sqrt{2}F} S \cdot F^\alpha_{\mu\nu} F^{\alpha\mu\nu} - \frac{A^{L}_{ab}}{\sqrt{2}F} y^L_{ab} \cdot S(\epsilon_{ij}l^i_a l^j_b h^i_D + h.c.)$$

$$- \frac{A^{D}_{ab}}{\sqrt{2}F} y^D_{ab} \cdot S(\epsilon_{ij}q^i_a q^j_b h_D^i + h.c.) - \frac{A^{U}_{ab}}{\sqrt{2}F} y^U_{ab} \cdot S(\epsilon_{ij}q^i_a u^j_b h^i_U + h.c.), \quad (1)$$

where $M_\alpha$ are gaugino masses, $A_{ab}$ are soft trilinear coupling constants, $\sqrt{F}$ is the scale of supersymmetry breaking, and $\epsilon_{ij}$ is $2 \times 2$ antisymmetric matrix fixed as $\epsilon_{12} = 1$. The current experimental bounds [22] are $\sqrt{F} > 500 - 200$ GeV at $M_S > 10 - 150$ GeV with MSSM soft mass terms $M_{soft}$ being of order 100 GeV.

Since $Sgg$, $SWW$ and $ZZ$ coupling constants are of the same order, sgoldstino production is saturated by gluon fusion (diagrams with $W, Z$-bosons involve additional weak vertices and corresponding contributions are less than a few percent). Yukawa-type coupling is important for sgoldstino interactions with $t$-quarks, and also for sgoldstino interactions with $b$-quarks, if $\tan \beta$ is sufficiently large. However, sea

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$^5$Here we consider only scalar sgoldstino. It is straightforward to extend the results presented in this section to the production of pseudoscalar sgoldstino as well. The sensitivity of the channel under discussion to coupling constants of pseudoscalar sgoldstino coincides with the sensitivity to the coupling constants of the scalar sgoldstino of the same mass.
b-quarks carry only a small fraction of proton momentum, and their contributions to sgoldstino production can be neglected. Hence one can apply directly the rescaling procedure to estimate LHC prospects in searches for sgoldstino in $pp \rightarrow \gamma\gamma + \text{jet}$ channel.

For the models with sgoldstino we present the estimates of the LHC sensitivity to the scale of supersymmetry breaking $\sqrt{F}$ for the same sets of MSSM soft parameters as ones considered in [7], see Table 5.

| Model | $M_1$  | $M_2$  | $M_3$  | $A$    |
|-------|--------|--------|--------|--------|
| I     | 100 GeV| 300 GeV| 500 GeV| 300 GeV|
| II    | 300 GeV| 300 GeV| 300 GeV| 300 GeV|

Table 5: The values of MSSM soft terms for two supersymmetric models.

For SM Higgs boson $\gamma\gamma$ decay mode is out of interest for $M_H > 140$ GeV, since Higgs width starts to grow rapidly with its mass, thereby diminishing $Br(H \rightarrow \gamma\gamma)$. The similar situation takes place in models with radion. Quite the contrary, sgoldstino width is generally saturated by decay into gluons, so two-photon branching ratio remains intact for $M_S \approx 100 - 300$ GeV, and $pp \rightarrow \gamma\gamma + \text{jet}$ channel (as well as inclusive one) may be employed for searches for sgoldstino not only in the mass range relevant for SM Higgs boson, 115 – 140 GeV, but also in a wider region. While in models with $M_S \lesssim 140$ GeV one can apply the rescaling procedure to obtain the LHC sensitivity to sgoldstino couplings, the opposite case, $M_S \gtrsim 140$ GeV, requires a special study. Indeed, NLO background and $\gamma\gamma$-invariant mass resolution as well as photon isolation procedure have not been thoroughly analyzed for this mass interval. To estimate the LHC prospects in searches for sgoldstino with $M_S \gtrsim 140$ GeV, we adopt the photon energy resolution of ATLAS electromagnetic calorimeter [11] for $\gamma\gamma$-invariant mass resolution. Both cross section of sgoldstino production and background cross section are calculated at LO by making use of CompHEP-sgoldstino package [21]. Finally, these results are corrected by NLO K-factors, which are treated as constants in the whole mass region, 100 – 300 GeV.

The results for the two models are presented in Figs. 3 and 4. The solid lines indicate the scales of supersymmetry breaking $\sqrt{F}$ which will be tested at 5$\sigma$-level in searches for sgoldstino in $pp \rightarrow \gamma\gamma + \text{jet}$ channel at LHC (ATLAS detector only) with various integrated luminosities. One can see, that the scale of supersymmetry breaking $\sqrt{F}$ will be probed up to 8 – 12 TeV depending on the pattern of MSSM soft terms and sgoldstino mass.
Figure 3: 5σ-level discovery contours for sgoldstino production (Model I) in $pp \rightarrow \gamma\gamma + jet$ channel with various values of integrated luminosity; the set of soft supersymmetry breaking parameters is listed in Table 5.

Figure 4: 5σ-level discovery contours for sgoldstino production (Model II) in $pp \rightarrow \gamma\gamma + jet$ channel with various values of integrated luminosity; the set of soft supersymmetry breaking parameters is listed in Table 5.

4 Discussion and Conclusions

In this work we have explored the capability of LHC in searches for SM Higgs boson, sgoldstino and radion in $pp \rightarrow \gamma\gamma + jet$ channel. The NLO effects in both the signal
and the background cross sections were taken into account in the selfconsistent local approximation for $ggH$ coupling.

We have confirmed that SM Higgs boson of $115 - 140$ GeV will be discovered at LHC in this channel even with low integrated luminosity of $30$ fb$^{-1}$. Comparing the potentials of $pp \rightarrow \gamma \gamma + jet$ and $pp \rightarrow \gamma \gamma$ channels, we have found that the ratio of signal significances of these channels is about $0.8 - 0.9$, while the signal-to-background ratio is larger by a factor of $2 - 3$ for the channel with a high energy jet. The uncertainties of the obtained results are expected to be less than $10\%$, neglecting unknown higher order QCD corrections. It was shown that tuning of cuts on $p_T^\gamma$ and $\eta_{\text{jet}}$ in this channel could yield $10 - 30\%$ enhancement of the signal significance. This suggests that $\gamma \gamma + jet$ channel is highly competitive with the inclusive one. Moreover, with account of larger signal-to-background ratio $\gamma \gamma + jet$ channel seems even more favorable. The definite answer requires further detailed investigations. In particular, one has to take into consideration that $ggH$ effective coupling is nonlocal in this process, since at least one of the gluons is off shell. Likewise we did not take into consideration the registration efficiency of the future LHC detectors.

Starting from the results for SM Higgs boson and adopting the rescaling procedure we have estimated the LHC prospects in searches for new physics in the channel with a high energy jet. For models with warped extra dimensions we have observed that radion with mass of $100 - 140$ GeV could be discovered in $\gamma \gamma + jet$ channel, if stabilization scale $\Lambda_\phi \lesssim 4$ TeV. In models with low-energy supersymmetry and sgoldstino masses of $100 - 300$ GeV the scale of supersymmetry breaking $\sqrt{F}$ could be probed in $\gamma \gamma + jet$ channel up to about $8 - 12$ TeV (depending on the MSSM parameters of soft supersymmetry breaking). These results ensure that $pp \rightarrow \gamma \gamma + jet$ channel is very promising in searches for new physics.

The proposed rescaling procedure can be applied for estimates of LHC sensitivity to various extensions of the SM with new (pseudo)scalars uncharged under the SM gauge group: supersymmetric models, models with extra Higgs bosons, etc. Exhaustive studies of SM Higgs boson production at LHC in various channels afford an opportunity of getting for free very accurate estimates of LHC sensitivities to new physics, and new scalar in $\gamma \gamma + jet$ channel is not the only example.

Generally, an appropriate channel can be useful in searches for new physics in a wider kinematical window, than the window viable for SM Higgs boson. This occurs in models with sgoldstinos: $\gamma \gamma$-decay mode survives for masses larger than $140$ GeV, contrary to the case of SM Higgs boson. To obtain the approximation to the LHC sensitivity, both signal and background NLO K-factors have been extrapolated, so this model still waits for thorough analysis. Another source of uncertainty is related to crude estimates of detector mass resolution for photon pairs with invariant mass larger than $140$ GeV. As we demonstrated this mass range is very important for new physics. These searches will be more efficient with better invariant mass resolution.

To summarize, this work shows that $pp \rightarrow \gamma \gamma + jet$ is very promising in searches
for both SM Higgs boson and new physics and deserves further investigations.

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