Search for Higgs boson and other neutral scalar particles in association with high energy jet at LHC

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Abstract

At NLO in QCD perturbation theory we evaluate selfconsistently the signal significance for the SM Higgs boson production in $\gamma\gamma + jet$ channel at LHC. The adjustment of 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 $\gamma\gamma + jet$ 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

Present talk bases on the work [1] in which we study the LHC prospects in searches for Standard Model (SM) Higgs boson, radion and sgold-

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stino in $\gamma\gamma + jet$ channel. In comparison with inclusive $\gamma\gamma$ channel, which has almost the same signal significance, $\gamma\gamma + jet$ 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 $\gamma\gamma + jet$ 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. At the leading order in perturbation theory the signal significance was estimated in Refs. [2]. The obtained results suggested that $\gamma\gamma + jet$ 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 $\gamma\gamma + jet$ 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. [3] in the limit of the infinite mass of t-quark, $M_t \to \infty$. The next natural step was done in Ref. [4, 5], where cross sections of main QCD background subprocesses were calculated at NLO.

In this work we accumulate all relevant NLO results to calculate selfconsistently the NLO signal significance for SM Higgs boson production in $pp \to H(H \to \gamma\gamma) + jet$ channel. Along with light u, d, s quarks contribution we take into account also heavy quarks and antiquarks contribution missed in papers [2]. We have found that for cuts selected as in Ref. [2] the signal significance remains almost intact with increasing order of perturbation theory.

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, interaction lagrangian of any scalar uncharged under SM gauge group with SM fields contains in the lowest order in field, generally, terms of the same structure as in the case of 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 this paper we consider two examples of the appropriate models: model with warped spartial extra dimensions and SUSY model with sgoldstinos. Note in passing that radion and sgoldstino production in inclusive channel have been estimated for the first time [7, 8] 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 2 we evaluate at NLO in perturbation theory the signal significance for SM Higgs boson production at LHC in $pp \to \gamma\gamma + jet$ channel. There we study the dependence of the significance on variations of the selected cuts and outline the optimal set of cuts. Section 3 is devoted to estimates of LHC prospects in searches for new physics in this channel. Namely, we consider models with radion of $100 - 140$ GeV and supersymmetric models with sgoldstinos of $100 - 300$ GeV. Section 4 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 [3, 5], we embrace them to improve the estimate [2] of the signal significance by taking into account all relevant NLO corrections.

In calculations of the SM Higgs boson production at LHC we use the CompHEP package [9] 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 [10]. 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, $5-10\%$ [11].

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 $Q^2 = M_{\gamma\gamma}^2 + (p_T^{jet})^2$, where $M_{\gamma\gamma}$ is invariant mass of the photon pair and p_T^{jet} is transverse momentum of the hadronic jet. For the subprocesses with W- or Z-bosons involved we set $Q^2 = M_V^2$.

The NLO result for the background cross section was calculated in Ref. [5], so to obtain the NLO approximation to the signal significance we use almost the same set of cuts: $p_T > 40$ GeV, $|\eta| < 2.5$ for both photons and jet with η being pseudorapidity, $R_{\gamma\gamma} > 0.4$, $R_{\gamma jet} > 1.5$ (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. [6], [5] for details.

The NLO results for the total signal and background cross sections are presented in Table 1. The background events have been

M_H, GeV	100	110	120	130	140
total signal cross section, σ_S, fb	5.06	6.76	8.06	8.34	7.25
background cross section, σ_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.

collected in a bin $M_H \pm 1.4 \cdot \sigma(M_{\gamma\gamma})$, where $\sigma(M_{\gamma\gamma})$ is the mass resolution of ATLAS detector [12]. 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 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. One can see, that in the viable mass range, 115 GeV$< M_H <$140 GeV,

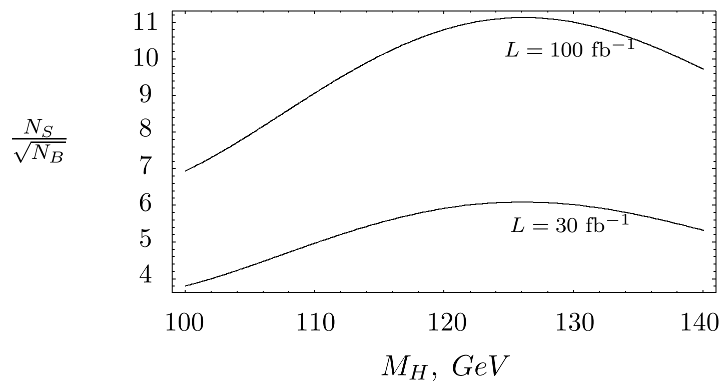

Figure 1: Signal significance $\frac{N_S}{\sqrt{N_B}}$ of the Higgs boson production in $pp \to \gamma\gamma + jet$.

it will be possible to discover SM Higgs boson in $pp \to \gamma\gamma + jet$ channel even with low luminosity of 30 fb^{-1} (the first year of LHC operating).

Comparing two channels, $pp \to H(H \to \gamma\gamma) + jet$ and $pp \to H \to \gamma\gamma$, 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 $\gamma\gamma + jet$ channel is competitive with the inclusive channel in hunting for SM Higgs boson. Without unknown

QCD-corrections, we estimate the total uncertainty of our results for the signal significance does not exceed 10%.

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 [2]. The results presented in Table 2 show that signal significance $N_S/\sqrt{N_B}$ always degrades when cuts on

M_H, GeV	120		130		140	
	$\frac{N_S}{\sqrt{N_B}}$	$\frac{N_S}{N_B}$	$\frac{N_S}{\sqrt{N_B}}$	$\frac{N_S}{N_B}$	$\frac{N_S}{\sqrt{N_B}}$	$\frac{N_S}{N_B}$
no cut on $\sqrt{\hat{s}}$	8.3	0.11	8.5	0.11	7.5	0.10
$\sqrt{\hat{s}} > 350$ GeV	7.2	0.24	7.6	0.23	6.5	0.18

Table 2: Dependence of signal significance $N_S/\sqrt{N_B}$ on the additional cut on $\sqrt{\hat{s}}$.

$\sqrt{\hat{s}}$ 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 $0.2 - 0.25$ (for $\sqrt{\hat{s}} > 350$ GeV).

Then we estimate $N_S/\sqrt{N_B}$ for various cuts on p_T^γ (see Table 3). One can see, that its adjustment yields $10-15\%$ increase in the signal significance.

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

M_H, GeV	120		130		140	
	$\frac{N_S}{\sqrt{N_B}}$	$\frac{N_S}{N_B}$	$\frac{N_S}{\sqrt{N_B}}$	$\frac{N_S}{N_B}$	$\frac{N_S}{\sqrt{N_B}}$	$\frac{N_S}{N_B}$
$p_T^{\gamma} > 40$ GeV	8.3	0.11	8.5	0.11	7.5	0.10
$p_T^{\gamma_2} > 20$ GeV	9.6	0.10	9.5	0.10	8.0	0.09

Table 3: Signal significance $N_S/\sqrt{N_B}$ at various cuts on p_T^{γ} for one of photons.

M_H, GeV	120		130		140	
	$\frac{N_S}{\sqrt{N_B}}$	$\frac{N_S}{N_B}$	$\frac{N_S}{\sqrt{N_B}}$	$\frac{N_S}{N_B}$	$\frac{N_S}{\sqrt{N_B}}$	$\frac{N_S}{N_B}$
$\|\eta_{jet}\| < 2.5$	8.3	0.11	8.5	0.11	7.5	0.10
$\|\eta_{jet}\| < 4$	9.7	0.12	10.1	0.13	8.9	0.11

Table 4: Signal significance $N_S/\sqrt{N_B}$ at various cuts on η_{jet}.

calorimeter allows $10-15\%$ raise in signal significance.

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, $pp \to H(H \to \gamma\gamma) + jet$ 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. 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 σ_X for $pp \to X(X \to \gamma\gamma) + jet$ process can be obtained by means of rescaling

$$\sigma_X = \sigma_H \cdot \left(\frac{A_{Xgg}}{A_{Hgg}}\right)^2 \cdot \frac{Br(X \to \gamma\gamma)}{Br(H \to \gamma\gamma)} ,$$

where A_{Hgg} and A_{Xgg} are effective coupling constants entering Hgg and Xgg vertices, respectively, and σ_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, σ_X estimated in this way implies the same set of cuts as σ_H. Below we consider two different extensions of the SM with new scalars.

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 [17] results in its coupling to the SM fields

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

where Λ_ϕ is a vacuum expectation value of the module and $T^\mu_\mu(SM)$ is the trace of SM energy-momentum tensor.

In models with radion there are only two free parameters [1]: radion mass m_ϕ and Λ_ϕ (current experimental bounds [18] are $M_\phi >$ 120 GeV at $\Lambda_\phi = 1$ TeV). The results for the models with radion are presented in Fig. 2. Any models with parameters in the region below

[1] In a number of models higgs-radion mixing can arise, but in this paper we ignore this possibility.

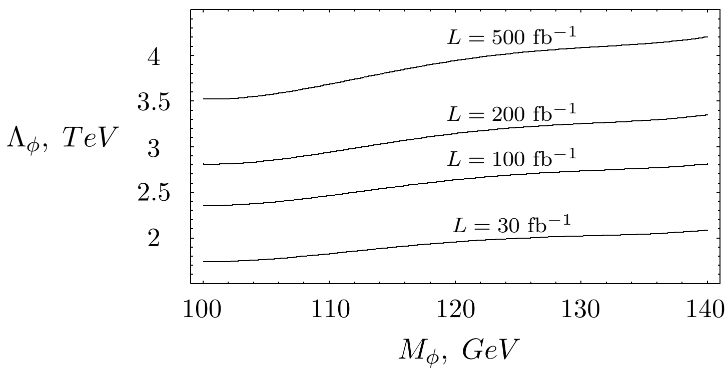

Figure 2: Signal significance (5σ-level) for the radion production.

plotted lines will be discovered at LHC (ATLAS detector only) at the confidence level better than 5σ if corresponding integrated luminosities are collected.

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 and could be produced at LHC.

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 [8].

Sgoldstino width is generally saturated by decay into gluons, so two-photon branching ratio remains intact for $M_S \simeq 100 - 300$ GeV and $pp \to \gamma\gamma + jet$ 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. 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.

The results for the two models are presented in Figs. 3 and 4. The solid lines indicate the scales of supersymmetry breaking $\sqrt{F}$

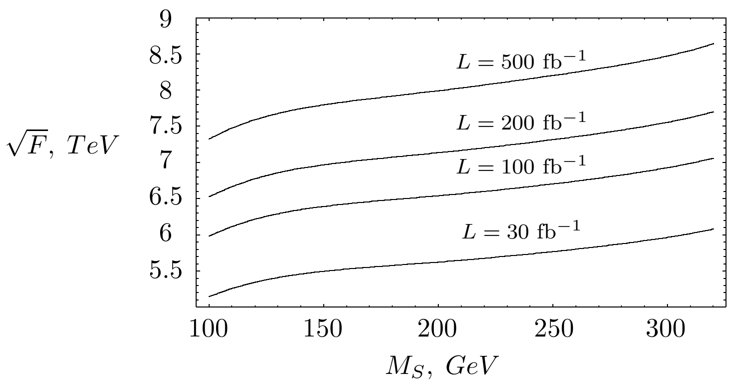

Figure 3: 5σ-level for sgoldstino production (Model I) in $pp \to \gamma\gamma + jet$.

which will be tested at 5σ-level in searches for sgoldstino in $pp \to \gamma\gamma + jet$ channel at LHC (ATLAS detector only) with various integrated luminosities.

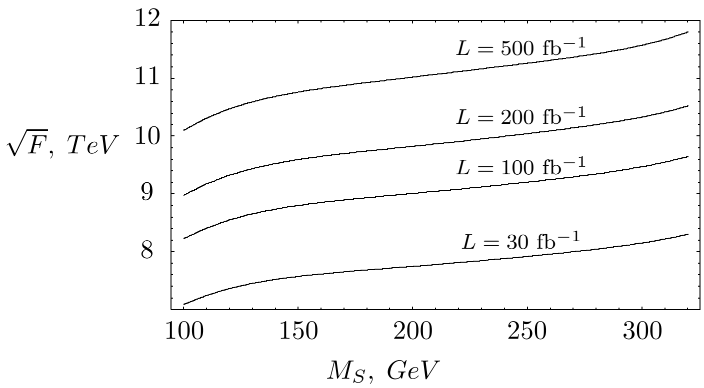

Figure 4: 5σ-level for sgoldstino production (Model II) in $pp \to \gamma\gamma + jet$.

4 Discussion and Conclusions

In this work we have explored the capability of LHC in searches for SM Higgs boson, sgoldstino and radion in $pp \to \gamma\gamma + jet$ channel. The NLO effects in both the signal and the background cross sections were taken into account in a 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 $pp \to \gamma\gamma + jet$ and $pp \to \gamma\gamma$ 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 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 $pp \to \gamma\gamma + jet$ channel is very promising in searches for new physics.

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

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