Looking for a light Higgs boson in the overlooked channel

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The final state obtained when a Higgs boson decays to a photon and a $Z$ boson has been mostly overlooked in current searches for a light Higgs boson. However, when the $Z$ boson decays leptonically, all final state particles in this channel can be measured, allowing for accurate reconstructions of the Higgs mass and angular correlations. We determine the sensitivity of the Large Hadron Collider (LHC) running at center of mass energies of 8 and 14 TeV to Standard Model (SM) Higgs bosons with masses in the 120 – 130 GeV range. For the 8 TeV LHC, sensitivity to several times the the SM cross section times branching ratio may be obtained with 20 inverse femtobarns of integrated luminosity, while for the 14 TeV LHC, the SM rate is probed with about 100 inverse femtobarns of integrated luminosity.

\textbf{Introduction} – The search for the Higgs boson is entering a critical phase. Data collected at the LHC rules out the SM Higgs boson for a wide range of masses and may suggest a Higgs boson with mass near 125 \text{ GeV} \cite{1,2}. Searches for a light SM Higgs in the still-relevant mass window rely primarily on the $\gamma\gamma$ channel, though the $WW^*\rightarrow 2\ell2\nu$ channel and the golden channel, $ZZ^*\rightarrow 4\ell$, are also important.

So far very little attention has been given to the $Z\gamma\rightarrow \ell\ell\gamma$ channel\textsuperscript{3}, although its event rate is comparable to that of the golden channel for a light SM Higgs boson. Nevertheless, this channel has the advantage that all final state particles can be measured well, which carries several important implications: 1) the Higgs mass could be measured from the total invariant mass spectrum, 2) the spin of a putative signal can be determined by studying angular correlations \cite{4}, and 3) the separation of signal from background can be facilitated by employing full kinematic information, potentially allowing searches with enhanced sensitivities. For the golden channel in $ZZ^*\rightarrow 4\ell$ the above questions have been studied extensively \cite{5,7}, but we are not aware of any detailed studies for the $Z\gamma\gamma$ channel.

Measurements of all four Higgs decay modes into electroweak bosons are in fact very important in determining the electroweak quantum numbers of a putative Higgs signal \cite{8}. Furthermore, an electroweak singlet scalar could easily have a branching fraction to the $Z\gamma\gamma$ mode that is orders of magnitude larger than the SM expectation \cite{9} which provides an important additional incentive for studying this channel.

\textbf{Kinematics} – The kinematics of $Z\gamma\rightarrow \ell\ell\gamma$ is described by three angles, $\Theta$, $\theta$, and $\phi$, where $\Theta$ may be taken to be the angle describing the production of the $Z$ boson in the center of mass frame, and $\theta$ and $\phi$ are the angles that describe the decay of the $Z$ to leptons, as defined in more detail in \cite{7}. To accommodate events with jet radiation in the final state, we use the momentum of the $Z\gamma$ system in the lab frame, rather than the beam axis, to define $\Theta$.

The dominant irreducible background to the Higgs signal arises from initial state radiation (ISR) and final state radiation (FSR) from Drell-Yan production of a $Z$ boson; the diagram describing this process is shown in Fig. 1(a) and (b). The invariant mass of the $Z\gamma$ system from FSR events is close to the $Z$ boson mass, so this background is removed efficiently by imposing $m_{\ell\ell\gamma}>100$ GeV, and we can focus on the ISR diagram and the corresponding $u$-channel diagram for the rest of this analysis.

The signal and background cross sections were computed using the helicity basis in \cite{10}. We now discuss some qualitative features of these differential cross sections, in particular the $\Theta$ dependence of the signal and background processes.

In the signal case, angular distributions follow from the fact that the Higgs is a scalar particle, and hence only the decay angle $\theta$ has a nontrivial distribution:

\begin{equation}
\frac{1}{N} \frac{d\sigma}{d\cos \Theta d\cos \theta d\phi} = (1 + \cos^2 \theta),
\end{equation}

For the background distributions, the non-vanishing helicity combinations are $(\lambda_1, \lambda_2) = (\pm, \mp), (0, \pm)$, and $(\pm, \pm)$. The production angular distribution exhibits a collinear singularity at $\cos \Theta = \pm 1$, which is seen by examining the $t$-channel propagator in Fig. 1(a),

\begin{equation}
\frac{1}{(k_q - p_\gamma)^2} = \frac{1}{-2E_q E_\gamma (1 - \cos \Theta)},
\end{equation}

while the $u$-channel propagator gives the collinear singularity at $\cos \Theta = -1$. Thus the production angular distribution for the background process is peaked at...
The cos Θ distribution in Fig. 2 therefore implies that the
sensitivity can be gained from the cos Θ distribution.

\[ 1 \frac{d\sigma}{N' d\cos \Theta d\cos \theta d\phi} = \]
\[ (g_L^2 + g_R^2) (g_R^2 + g_L^2) G_1 + (g_L^2 - g_R^2) (g_R^2 - g_L^2) G_2, \]

with
\[ G_1 = \left[ (m_{12}^2 + \hat{s}^2)(3 + \cos 2\theta)(4 \csc^2 \Theta - 2) \right. \]
\[ + 8m_{12}^2 \hat{s} \sin^2 \theta (2 + \cos 2\phi) \]
\[ + 8m_{12}\sqrt{\hat{s}} (m_{12}^2 + \hat{s}) \cot \Theta \sin 2\theta \cos \phi \right], \]
\[ G_2 = 16 \csc \Theta \left[ (m_{12}^2 + \hat{s}^2) \cos \theta \cot \Theta \right. \]
\[ + \left. m_{12}\sqrt{\hat{s}} (m_{12}^2 + \hat{s}) \sin \theta \cos \phi \right], \]
where \( g_{L(R)} \) and \( g_{R(L)} \) are the Z couplings to left- and
right-handed quarks (leptons).

In Fig. 2 we show the distributions in cos Θ, φ, and
\( \cos \theta \) for a 125 GeV Higgs boson and a background pro-
cess \( dd \to Z\gamma \) at \( \sqrt{s} = 125 \) GeV at the parton level.
These are modified after including the effects of parton
distribution functions (PDF) and detector acceptance
and isolation cuts. In particular, we note that \( \cos \Theta \) is
directly connected to the photon \( p_T \) through
\[ \cos \Theta = \sqrt{1 - 4p_T^2\hat{s}/(\hat{s} - m_Z^2)^2}. \]

The smearing results in the broadening of the lineshape
in the total invariant mass of the Z\gamma system, \( m_{\ell\ell\gamma} \), for
the signal events. Therefore, before performing more
detailed analyses, we perform an invariant mass cut; demand-
ing that the invariant mass of the Z\gamma system be
within 5 GeV of the mean invariant mass of the Z\gamma sys-
tem in signal events. It is worth emphasizing that since
subsequent analyses will effectively reduce the range of
invariant mass considered, the specific details of this ini-
tial cut does not have a strong effect on the final value
of \( S/\sqrt{B} \) obtained. Note that this cut also effectively re-
moves the background coming from FSR radiation that
is characterized by \( m_{\ell\ell\gamma} \sim M_Z \).

To determine the expected number of signal events at
the 14 TeV LHC, we obtain the inclusive Higgs produc-
tion cross section from [17]. For the 8 TeV LHC, we
use the values given in [18]. The branching fraction for
\( h \to Z\gamma \) is found using HDECAY [19], while we use the
PDG value (6.73\%) for the branching fraction for a Z
decaying to leptons [20]. The background cross section
is found by using MCFM [21, 22] with FSR photon radi-

FIG. 2: Signal (red, solid) and background (blue, dashed) distributions in cos Θ, φ and cos θ, with \( \sqrt{s} = m_h = 125 \) GeV.
The signal and background cross sections, as well as the significance after an optimal cut on the discriminant in Eq. (8) in the invariant mass only analysis at the 8 TeV LHC. In the parenthesis we also show the corresponding values for all events passing the $p_T$ and geometric acceptance cuts and which are within an invariant mass window of 10 GeV centered on the Higgs mass, as described in the text.

| Higgs Mass | Signal (fb) | Backg. (fb) | $S/\sqrt{B}$ (20 fb$^{-1}$) |
|------------|-------------|-------------|-----------------------------|
| 120 GeV    | 0.38 (0.45) | 32. (110)  | 0.30 (0.19)                  |
| 125 GeV    | 0.61 (0.74) | 30. (100)  | 0.50 (0.33)                  |
| 130 GeV    | 0.66 (0.86) | 23. (89.)  | 0.62 (0.41)                  |

| Higgs Mass | Signal (fb) | Backg. (fb) | $S/\sqrt{B}$ (100 fb$^{-1}$) |
|------------|-------------|-------------|-------------------------------|
| 120 GeV    | 0.83 (1.0)  | 36. (180)  | 1.2 (0.78)                    |
| 125 GeV    | 1.3 (1.6)   | 37. (160)  | 2.0 (1.3)                     |
| 130 GeV    | 1.7 (2.1)   | 40. (140)  | 2.7 (1.8)                     |

TABLE II: Same as Tab. I for the 14 TeV LHC, with a luminosity of 100 fb$^{-1}$. 

FIG. 3: Exclusion limits at the 95% confidence level on the Higgs production rate times branching fraction to $Z\gamma$ at the 8 TeV LHC with an integrated luminosity of 20 fb$^{-1}$. The green (yellow) band is the 1(2) $\sigma$ contour. The solid red line corresponds to the SM expectation.

We perform three analyses, two of which are multivariate. The multivariate discriminants we use are based on the matrix element of the signal and background processes. In the context of a maximum likelihood analysis such a discriminant was used in the discovery of the single top production in [23]. For simplicity we use a cut-based approach to determining our sensitivity using these multivariate discriminants.

We construct a discriminant using the fully differential cross sections computed for the signal and background processes to quantify the relative probability of a particular event being signal-like or background-like. We then determine an optimal cut on the discriminant to maximize the value for $S/\sqrt{B}$. In one analysis, we include PDF weights for the leading initial state for signal or background events ($gg$ or $q\bar{q}$ respectively). In the second multivariate analysis, we do not include a weight from PDFs. Labelling the signal and background differential cross sections by $s(\Omega)$ and $b(\Omega)$, respectively, we consider the quantity

$$D(\Omega) = \frac{s(\Omega)}{s(\Omega) + b(\Omega)} = \left(1 + \frac{s(\Omega)}{b(\Omega)}\right)^{-1}.$$  

(8)

Here, $\Omega = \{x_1, x_2, s, m_{l\ell}, \Theta, \theta, \phi\}$ is the complete set of kinematic observables characterizing each event. When evaluating $D$ on a sample of pure signal events the distribution is peaked toward 1 while it is peaked toward 0 for a pure background sample. For each Higgs mass, a cut on $D$ is determined by maximizing $S/\sqrt{B}$ of the events passing the cut. One advantage of using the multivariate discriminant in a cut-based approach is that the relative normalization of the signal and background cross sections does not affect the final significance computed using $S/\sqrt{B}$. The drawback, on the other hand, is that we lose those events not passing the cut, which would not be the case if the signal and background matrix elements were used to construct the likelihood directly.

Our multivariate discriminants use the parton-level differential cross section except for the Higgs propagator, as for the Higgs masses considered the Higgs width is much narrower than the experimental resolution. In principle, one can deal with this issue by using transfer functions for the lepton momenta. We take the simpler approach of weighting each event with a Gaussian invariant mass distribution that is centered at the average invariant mass for signal events. The width used in this Gaussian weighting is found by scanning (in 20 MeV increments) over potential values, from 100 MeV to 5 GeV, and selecting the value which maximizes the sensitivity of the analysis. The third analysis uses the same Gaussian invariant mass weight, but no other kinematic information about the events. While one would expect a loss of sensitivity, this approach has the advantage of being less sensitive to higher order corrections that could modify the angular distributions that enter the multivariate analyses.

We find the best values for $S/\sqrt{B}$ from the analysis in which the full differential cross sections and PDF weights are used. However the sensitivity from this analysis is only $\sim 1\%$ larger than that obtained from the invariant mass only analysis. The smallness of this increase in sensitivity is due to the fact that the relatively hard $p_T$ cut leaves us without much additional sensitivity to $\Theta$, and the other angular variables are not as sensitive, especially given geometric acceptance and finite momentum resolution. We therefore quote results using the invariant mass only analysis, as they should be more robust with respect to systematic uncertainties. In particular, the $m_{l\ell\gamma}$ distribution is unaffected by jet radiation, so that corrections to the jet multiplicity and momentum distribution, which is only simulated to leading order in our analysis, will not reduce the sensitivity.

The signal and background cross sections after the op-
FIG. 4: Exclusion limits at the 95% confidence level on the Higgs production rate times branching fraction to $Z\gamma$ at the 14 TeV LHC with an integrated luminosity of 100 fb$^{-1}$. The green (yellow) band is the (1/2) $\sigma$ contour. The solid red line corresponds to the SM expectation.

with 100 fb$^{-1}$ of integrated luminosity for the 8 TeV LHC in Fig. 3 and for the 14 TeV LHC with 100 fb$^{-1}$ in Fig. 4.

**Conclusions** – We have considered the possibility of searching for a light Higgs boson in its decays to $\ell\ell\gamma$ final states via $Z\gamma$. This branching ratio is known precisely in the SM, and deviations from this rate are unambiguous signals of new physics that couples to the Higgs boson, or could even signal the presence of a Higgs imposter [9].

We have performed a detailed Monte Carlo study for the 8 and 14 TeV LHC. We find that branching ratios for the Higgs decay to $Z\gamma$ of several times the SM rate are probed at 8 TeV with 20 fb$^{-1}$, while the SM rate is probed at the 14 TeV LHC with 100 fb$^{-1}$. For Higgs masses of 125 GeV and above, a measurement of the Higgs branching ratio to $Z\gamma$ is in reach of the 14 TeV LHC. We hope this work inspires experimental efforts in this particular search channel.

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