CMS Draft Analysis Note

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Search for Higgs boson decays to long-lived scalar particles to SM τ final state with Regions of Interest construction

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Abstract

We present a search for long-lived particles (LLPs) produced in gluon fusion Higgs production mode (ggH), using the novel Regions of Interest strategy. Regions of Interest (ROIs) are formed as a collection of pair-wise track vertices fitted by the V0Fitter in CMSSW. Thus, the analysis focuses on lifetime of LLPs in the tracker region, with concentration on the ggH mode for the highest Higgs production cross-section. Variables of the constructed ROIs become inputs for our Deep Neural Network (DNN) Machine Learning (ML) algorithms, as a main distriminator between the signal and the background. We focus on the τ SM fermion final state. This final state is particulary interesting, given τ final state exclusion limits are frequently omitted in precedent analysis, due to τ fermions' non trivial final state reconstruction. No excess of events over the standard model expectation is observed. The results are interpreted in the context of exotic Higgs decays to a pair of long-lived scalars (S). We set limits on the branching ratio of the Higgs to LLPs, $\mathbf{B}(\mathrm{H}\rightarrow SS)$, as a function of the proper lifetime.

Contents

1 Data and simulated samples

1.1 Data samples

The analysis uses B Parking datasets. Data was collected during 2018 of Run 2and corresponds to an integrated luminosity of 41 fb^{-1}.

Table 1: Datasets used in the analysis:and 2018.

Data sample	Integrated Luminosity (fb^-1)
/ParkingBPH1/Run2018A-05May2019-v1/MINIAOD	0.866
/ParkingBPH2/Run2018A-05May2019-v1/MINIAOD	0.866
/ParkingBPH3/Run2018A-05May2019-v1/MINIAOD	0.866
/ParkingBPH4/Run2018A-05May2019-v1/MINIAOD	0.866
/ParkingBPH5/Run2018A-05May2019-v1/MINIAOD	0.866
/ParkingBPH6/Run2018A-05May2019-v1/MINIAOD	0.866
Total	5.20
/ParkingBPH1/Run2018B-05May2019-v2/MINIAOD	1.083
/ParkingBPH2/Run2018B-05May2019-v2/MINIAOD	1.083
/ParkingBPH3/Run2018B-05May2019-v2/MINIAOD	1.083
/ParkingBPH4/Run2018B-05May2019-v2/MINIAOD	1.083
/ParkingBPH5/Run2018B-05May2019-v2/MINIAOD	1.083
/ParkingBPH6/Run2018B-05May2019-v2/MINIAOD	1.083
Total	6.49
/ParkingBPH1/Run2018C-05May2019-v1/MINIAOD	1.079
/ParkingBPH2/Run2018C-05May2019-v1/MINIAOD	1.079
/ParkingBPH3/Run2018C-05May2019-v1/MINIAOD	1.079
/ParkingBPH4/Run2018C-05May2019-v1/MINIAOD	1.079
/ParkingBPH5/Run2018C-05May2019-v1/MINIAOD	1.079
Total	5.39
/ParkingBPH1/Run2018D-05May2019promptD-v1/MINIAOD	6.542
/ParkingBPH2/Run2018D-05May2019promptD-v1/MINIAOD	6.542
/ParkingBPH3/Run2018D-05May2019promptD-v1/MINIAOD	6.542
/ParkingBPH4/Run2018D-05May2019promptD-v1/MINIAOD	6.542
/ParkingBPH5/Run2018D-05May2019promptD-v1/MINIAOD	6.542
Total	32.7
ParkingBPH Total	50.78

1.2 Monte Carlo Samples

1.2.1 Signal Model and Simulation

The ggH process (see Figure 1) is generated at next-to-next-to-leading order (NNLO) and next-to-next-to-leading-log (NNLL) QCD and next-to-leading order (NLO) EW accuracies [1]. The Higgs boson mass is set to 125 GeV for all signal samples. The cross sections, computed at NNLO+NNLL QCD and NLO EW accuracies and obtained from the CERN Report 3, are 4.414 pb. The CMS detector response is modeled with GEANT4 [2].

Table 2 lists the signal Monte Carlo samples.

Figure 1: Leading Feynman diagrams for ggH production mode

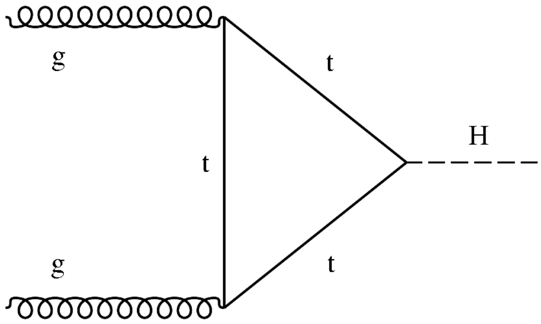

Table 2: gg($h \to ss \to \tau\bar{\tau}\tau\bar{\tau}$) Signal Monte Carlo samples.

Sample
/ggH_HToSSTo4Tau_MH-125_TuneCP5_13TeV-powheg-pythia8/CAMPAIGN/MINIAODSIM
/ggH_HToSSTo4Tau_MH-125_MS-55_ctauS-1_TuneCP5_13TeV-powheg-pythia8/CAMPAIGN/MINIAODSIM
/ggH_HToSSTo4Tau_MH-125_MS-55_ctauS-10_TuneCP5_13TeV-powheg-pythia8/CAMPAIGN/MINIAODSIM
/ggH_HToSSTo4Tau_MH-125_MS-55_ctauS-100_TuneCP5_13TeV-powheg-pythia8/CAMPAIGN/MINIAODSIM
/ggH_HToSSTo4Tau_MH-125_MS-55_ctauS-1000_TuneCP5_13TeV-powheg-pythia8/CAMPAIGN/MINIAODSIM
/ggH_HToSSTo4Tau_MH-125_MS-40_ctauS-1_TuneCP5_13TeV-powheg-pythia8/CAMPAIGN/MINIAODSIM
/ggH_HToSSTo4Tau_MH-125_MS-40_ctauS-10_TuneCP5_13TeV-powheg-pythia8/CAMPAIGN/MINIAODSIM
/ggH_HToSSTo4Tau_MH-125_MS-40_ctauS-100_TuneCP5_13TeV-powheg-pythia8/CAMPAIGN/MINIAODSIM
/ggH_HToSSTo4Tau_MH-125_MS-40_ctauS-1000_TuneCP5_13TeV-powheg-pythia8/CAMPAIGN/MINIAODSIM
/ggH_HToSSTo4Tau_MH-125_MS-15_ctauS-1_TuneCP5_13TeV-powheg-pythia8/CAMPAIGN/MINIAODSIM
/ggH_HToSSTo4Tau_MH-125_MS-15_ctauS-10_TuneCP5_13TeV-powheg-pythia8/CAMPAIGN/MINIAODSIM
/ggH_HToSSTo4Tau_MH-125_MS-15_ctauS-100_TuneCP5_13TeV-powheg-pythia8/CAMPAIGN/MINIAODSIM
/ggH_HToSSTo4Tau_MH-125_MS-15_ctauS-1000_TuneCP5_13TeV-powheg-pythia8/CAMPAIGN/MINIAODSIM
/ggH_HToSSTo4Tau_MH-125_MS-7_ctauS-1_TuneCP5_13TeV-powheg-pythia8/CAMPAIGN/MINIAODSIM
/ggH_HToSSTo4Tau_MH-125_MS-7_ctauS-10_TuneCP5_13TeV-powheg-pythia8/CAMPAIGN/MINIAODSIM
/ggH_HToSSTo4Tau_MH-125_MS-7_ctauS-100_TuneCP5_13TeV-powheg-pythia8/CAMPAIGN/MINIAODSIM
/ggH_HToSSTo4Tau_MH-125_MS-7_ctauS-1000_TuneCP5_13TeV-powheg-pythia8/CAMPAIGN/MINIAODSIM

An example PYTHIA v8.230 fragment for the Higgs decay to scalars (scalars) and their subsequent decay to tau leptons is given below. In this example the mass of the scalar is 15 GeV and its lifetime ($c\tau$) is 10,000 mm.

```
'9000006:all = sk skbar 0 0 0 15 1.9732e-17 1.0 75.0 10000',
'9000006:oneChannel = 1  1.0 101  15 -15',
'9000006:mayDecay = on',
'9000006:isResonance = on',
'25:m0 = 125.0',
'25:onMode = off',
'25:addChannel = 1 0.000000001 101 9000006 -9000006',
'25:onIfMatch = 9000006 -9000006',
'9000006:onMode = off',
'9000006:onIfAny = 5',
```

1.2.2 Background Monte Carlo

All samples were processed as recommended in the PPD Run2 Analysis Guideline [3]. Tables **??**-6 summarizes the background Monte Carlo used in this analysis.

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Table 3: QCD MuEnriched Pt5 background Monte Carlo samples, RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15

Sample
/QCD_Pt-15to20_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*-v3/MINIAODSIM
/QCD_Pt-20to30_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*-v4/MINIAODSIM
/QCD_Pt-30to50_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*-v3/MINIAODSIM
/QCD_Pt-50to80_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*-v3/MINIAODSIM
/QCD_Pt-80to120_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*_ext1-v2/MINIAODSIM
/QCD_Pt-120to170_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*_ext1-v2/MINIAODSIM
/QCD_Pt-170to300_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*-v3/MINIAODSIM
/QCD_Pt-300to470_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*_ext3-v1/MINIAODSIM
/QCD_Pt-470to600_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*_ext1-v2/MINIAODSIM
/QCD_Pt-600to800_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*-v1/MINIAODSIM
/QCD_Pt-800to1000_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*_ext3-v2/MINIAODSIM
/QCD_Pt-1000toInf_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*-v1/MINIAODSIM

Table 4: W,Z,H background Monte Carlo samples, RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15

Sample
/DYJetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/MINIAODSIM
/WJetsToLNu_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/*-v2/MINIAODSIM
/WW_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/*-v2/MINIAODSIM
/WZ_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/*-v3/MINIAODSIM
/ZZ_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/*-v2/MINIAODSIM
/GluGluHToBB_M125_13TeV_amcatnloFXFX_pythia8/*-v1/MINIAODSIM

Table 5: Top background Monte Carlo samples, RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15

Sample
/TTJets_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/MINIAODSIM
/ST_s-channel_4f_hadronicDecays_TuneCP5_13TeV-madgraph-pythia8/*_ext1-v1/MINIAODSIM
/ST_t-channel_top_5f_TuneCP5_13TeV-powheg-pythia8/*-v1/MINIAODSIM
/ST_t-channel_antitop_5f_TuneCP5_13TeV-powheg-pythia8/*-v1/MINIAODSIM
/ST_tW_antitop_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8/*_ext1-v1/MINIAODSIM
/ST_tW_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8/*_ext1-v1/MINIAODSIM

Table 6: Monte Carlo sample summary, RunIIAutumn18DRPremix-102X_upgrade2018_realistic_v15

Sample
/QCD_Pt-15to20_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*-v3/MINIAODSIM
/QCD_Pt-20to30_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*-v4/MINIAODSIM
/QCD_Pt-30to50_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*-v3/MINIAODSIM
/QCD_Pt-50to80_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*-v3/MINIAODSIM
/QCD_Pt-80to120_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*_ext1-v2/MINIAODSIM
/QCD_Pt-120to170_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*_ext1-v2/MINIAODSIM
/QCD_Pt-170to300_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*-v3/MINIAODSIM
/QCD_Pt-300to470_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*_ext3-v1/MINIAODSIM
/QCD_Pt-470to600_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*_ext1-v2/MINIAODSIM
/QCD_Pt-600to800_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*-v1/MINIAODSIM
/QCD_Pt-800to1000_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*_ext3-v2/MINIAODSIM
/QCD_Pt-1000toInf_MuEnrichedPt5_TuneCP5_13TeV_pythia8/*-v1/MINIAODSIM
/DYJetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/MINIAODSIM
/WJetsToLNu_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/*-v2/MINIAODSIM
/WW_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/*-v2/MINIAODSIM
/WZ_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/*-v3/MINIAODSIM
/ZZ_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/*-v2/MINIAODSIM
/GluGluHToBB_M125_13TeV_amcatnloFXFX_pythia8/*-v1/MINIAODSIM
/TTJets_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/MINIAODSIM
/ST_s-channel_4f_hadronicDecays_TuneCP5_13TeV-madgraph-pythia8/*_ext1-v1/MINIAODSIM
/ST_t-channel_top_5f_TuneCP5_13TeV-powheg-pythia8/*-v1/MINIAODSIM
/ST_t-channel_antitop_5f_TuneCP5_13TeV-powheg-pythia8/*-v1/MINIAODSIM
/ST_tW_antitop_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8/*_ext1-v1/MINIAODSIM
/ST_tW_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8/*_ext1-v1/MINIAODSIM
/ggH_HToSSTo4Tau_MH-125_TuneCP5_13TeV-powheg-pythia8/*-v1/MINIAODSIM

2 Physics object definitions

In this section, we provide the definitions of physics objects used in the analysis. We make use of Regions of Interest, muons, taus, and jets.

2.1 Muons

The analysis sources SlimmedMuons from MINIAOD to produce `selectedPatMuons`. Muons require Muon objects require

- $p_{\mathrm{T}} > 12$ GeV to reach BPH trigger plateau
- $|\eta| < 1.5$ due to L1 seed $|\eta|$ cut in BPH HLT path
- Pass the Loose ID criterion (isLooseMuon). As described in the Muon POG [4].

The Isolation requirements on muons are discussed in Section **??**.

2.2 Jets

The analysis sources SlimmedJets from MINIAOD to produce `selectedJets`. CMS reconstruct jets from calorimeter energy deposits using the anti-k_T clustering algorithm with a distance parameter of $R = 0.4$ [5]. Then, the calojets are inputed into the Particle-Flow (PF) algorithms to produce PFJets. Variables in PFJets class are then slimmed to be saved into MINIAOD files. The analysis uses these SlimmedJets for the jets' b-tagging scores and others. Jet objects require

- $p_{\mathrm{T}} > 20$ GeV
- $|\eta| < 2.4$
- $0 \leq$ emEnergyFraction ≤ 0.9
- $0 \leq$ energyFractionHadronic ≤ 0.9
- No selected electron or muon within $\Delta R = 0.4$

The energy fraction cuts above are inspired by the recommended Run2 Tight jet-ID cuts for particle flow jets [6–8].

2.3 Taus

The analysis sources PAT::slimmedTaus from MINIAOD for MC and RECO::slimmedTaus for Data to produce `selectedTaus`. τ objects decay hadronically for 64% of its decay. Hadron-Plus-Strip (HPS) algorithm enables the reconstruction of τ's hadronic decay. HPS uses PFJets as its starting point. τ's hadronic decay can be reconstructed with PFJets' charged Hadrons in HCAL and 2 γs from π^0 in ECAL. Tau objects require

- $p_{\mathrm{T}} > 20$ GeV
- $|\eta| < 2.4$

2.4 Region of Interest

The complete construction procedures of Regions of Interest are detailed in the following subsections.

- Good quality track selection
- Vertex Fitted from pair-wise tracks by V0Fitter in CMSSW
- Cluster the fitted vertices to form a Region of Intrest (ROI)

- Look for tracks around $\Delta R = 0.3$ to save ROI isolation information

2.4.1 Tracks

The analysis sources packedPFCandidates and lostTracks from MINIAOD. Track parameters and convariance values will be propagated along the ROI production process and no value should either be infinite or N/A

- !isinf(tracks.parameter) !isnan(tracks.parameter)
- !isinf(tracks.covariance) !isnan(tracks.covariance)
- Number of valid hits > 3
- $p_{\mathrm{T}} > 0.35$
- Track $IPSig_{XY}$ >2.
- Track $IPSig_{Z}$ >-1.
- Track normalized χ^2 <10.

2.4.2 Vertex Fitter

The analysis sources offlineBeamspot from MINIAOD for beamspot reference. Vertex fitter is KalmanVertexFitter with cuts on the vertex

- Vertex χ^2 <6.63
- Transverse Decay distance significance>15.
- V0mass <13000GeV
- cos(θ_{XY}) betwwen x and p of V0 candidate > 0
- cos(θ_{XYZ}) betwwen x and p of V0 candidate $>$ -2

2.4.3 ROI formation

Fitted V0s are clustered to form a Region of Interest (ROI). These ROIs have cuts on their parameters as below.

- Radius of ROI < 1 cm
- Annulus $\Delta R < 0.3$

References

[1] G. P. R. T. S. Heinemeyer, C. Mariotti et al., "Handbook of LHC Higgs Cross Sections: 3. Higgs Properties", doi:10.5170/CERN-2013-004, arXiv:1307.1347.

[2] GEANT4 Collaboration, "GEANT4: A Simulation toolkit", *Nucl. Instrum. Meth. A* **506** (2003) 250–303, doi:10.1016/S0168-9002(03)01368-8.

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[6] CMS Collaboration, Khachatryan et al., "Jet Identification Run2 – 2016", 2020, https://twiki.cern.ch/twiki/bin/view/CMS/JetID13TeVRun2016.

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