PROCEEDINGS OF SCIENCE

Limits on neutral Higgs production in the forward region in pp collisions at $\sqrt{s} = 7$ TeV

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Limits on the cross-section for neutral Higgs bosons decaying into tau lepton pairs, produced in pp collisions at $\sqrt{s} = 7$ TeV between pseudorapidities of 2 and 5, are presented using data corresponding to an integrated luminosity of 1 fb^{-1} collected with the LHCb detector. An upper limit on forward neutral Higgs boson production into tau lepton pairs is set at 8.6 pb for a Higgs boson mass of 90 GeV down to 0.7 pb for a mass of 250 GeV. An upper limit on $\tan\beta$ for the $m_{h^0}^{\max}$ scenario of the Minimal Supersymmetric Model is set from 34 at a pseudoscalar Higgs boson mass of 90 GeV up to 70 for a mass of 140 GeV.

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1. Introduction

The Higgs-like boson discovered by the ATLAS and CMS collaborations requires further investigation to fully determine its nature. While the current ATLAS and CMS measurements are for central pseudorapidities, the LHCb detector is fully instrumented in the forward region, $2 < \eta < 5$, and can be used to provide complementary results. These proceedings summarise the forward upper limits of [1] set by LHCb at a centre-of-mass energy of 7 TeV for model independent neutral Higgs boson and neutral Minimal Supersymmetric Model (MSSM) Higgs boson production. This analysis considers Higgs bosons decaying into tau lepton pair final states, and uses an event selection based on [2].

The dataset used was collected with the LHCb detector [3] during 2011 at a centre-of-mass energy of 7 TeV, and corresponds to an integrated luminosity of 1028 ± 36 pb^{-1}. The detector is instrumented with a silicon-strip vertex locator surrounding the interaction region, a silicon-strip detector upstream of a dipole magnet, silicon-strip and straw drift tube detectors downstream of the magnet, a pre-shower and electromagnetic calorimeter, a hadronic calorimeter, and a muon system. The trigger system consists of a calorimeter and muon system based hardware stage and a software stage using full event reconstruction. A single muon trigger requiring a transverse momentum (p_{T}) greater than 10 GeV and a single electron trigger requiring $p_{\mathrm{T}} > 15$ GeV were used to collect the data for this analysis. Background and signal samples were simulated with PYTHIA 6.4 [4], GEANT4 [5], and the LHCb reconstruction software.

2. Selection

Muons (μ), electrons (e), and single charged hadrons (h) are considered as tau lepton decay products within a pseudorapidity range $2 < \eta < 4.5$. Muon candidates are required to have associated hits in all muon stations downstream of the calorimeters, while electrons must have an associated pre-shower energy greater than 5 MeV, an electromagnetic calorimeter energy to momentum ratio greater than 10%, and a hadronic calorimeter energy to momentum ratio less than 5%. Hadrons must have a hadronic calorimeter energy to momentum ratio greater than 5% and a pseudorapidity within the range $2.25 < \eta < 3.75$. Both electron and hadron candidates are required not to have hits in more than 60% of the muon stations downstream of the calorimeters.

Events are split into five categories of two oppositely-charged tau lepton decay product candidates. In each category the first candidate must have $p_{\mathrm{T}} > 20$ GeV, the second must have $p_{\mathrm{T}} > 5$ GeV, the invariant mass of the candidates must be greater than 20 GeV, and the candidates must be back-to-back in the transverse plane with $|\Delta\phi| > 2.7$. Additional requirements on the candidate lifetime with IPS, the impact parameter significance, and the candidate isolation $I_{p_{\mathrm{T}}}$, the summed p_{T} of the charged tracks within a cone of $\Delta R < 0.5$, are applied to suppress backgrounds. The categories are defined as:

$\tau_\mu \tau_\mu$: two muons, one of which triggers the event. Both muons must have IPS > 9, $I_{p_{\mathrm{T}}} < 2$ GeV and a combined invariant mass not within $80 < m_{\mu\mu} < 100$ GeV.

$\tau_\mu \tau_e$: a muon and electron, where the muon triggers the event and both leptons must have $I_{p_{\mathrm{T}}} < 2$ GeV.

$\tau_e\tau_\mu$: an electron and muon, one of which triggers the event. The muon must have $p_{\mathrm{T}} < 20$ GeV and both leptons must have $I_{p_{\mathrm{T}}} < 2$ GeV.

$\tau_\mu\tau_h$: a muon and hadron, where the muon triggers the event and both candidates must have IPS > 9 and $I_{p_{\mathrm{T}}} < 1$ GeV.

$\tau_e\tau_h$: an electron and hadron, where the electron triggers the event and both candidates must have IPS > 9 and $I_{p_{\mathrm{T}}} < 1$ GeV.

3. Results

Six backgrounds to the model independent and MSSM Higgs boson signals are considered: irreducible $Z \to \tau\tau$ events, QCD events where the candidates are produced from jets, EWK events where one of the candidates is produced from an electroweak boson and the other from the underlying event, WW events, $t\bar{t}$ events, and $Z \to \ell\ell$ events where ℓ is an electron or muon. The combined mass distributions of the two candidates from all five event categories for the six backgrounds and an example MSSM signal, each normalised to its expected number of events from table 1, are compared to the observed data in figure 1.

Table 1: Estimated number of events with systematic uncertainties for each background, the total background, the observed number of events, and the expected number of Standard Model Higgs boson events for $M_H = 125$ GeV, separated by event category.

	$\tau_\mu\tau_\mu$	$\tau_\mu\tau_e$	$\tau_e\tau_\mu$	$\tau_\mu\tau_h$	$\tau_e\tau_h$
$Z \to \tau\tau$	79.8 ± 5.6	288.2 ± 26.2	115.8 ± 12.7	146.1 ± 9.7	62.1 ± 8.0
QCD	11.7 ± 3.4	72.4 ± 2.2	54.0 ± 3.0	41.9 ± 0.5	24.5 ± 0.6
EWK	0.0 ± 3.5	40.3 ± 4.3	0.0 ± 1.3	10.8 ± 0.5	9.3 ± 0.5
$t\bar{t}$	$< 0.1 \pm 0.1$	3.6 ± 0.4	1.0 ± 0.1	$< 0.1 \pm 0.1$	0.7 ± 0.4
WW	$< 0.1 \pm 0.1$	13.3 ± 1.2	1.6 ± 0.2	0.2 ± 0.1	$< 0.1 \pm 0.1$
$Z \to \ell\ell$	29.8 ± 7.0	–	–	0.4 ± 0.1	2.0 ± 0.2
Total	121.4 ± 10.2	417.9 ± 26.7	172.4 ± 13.1	199.3 ± 9.7	98.7 ± 8.0
Observed	124	421	155	189	101
SM Higgs $\times 100$	3.9 ± 0.5	11.9 ± 1.6	3.8 ± 0.5	9.7 ± 1.3	4.2 ± 0.6

The Higgs boson signals and $Z \to \tau\tau$, WW, and $t\bar{t}$ backgrounds are taken from simulation and normalised to the product of the theoretical cross-section, integrated luminosity, and efficiencies taken from data [2]. The mass distributions for these signals and backgrounds are calibrated using $Z \to \mu\mu$ events from data and are also re-weighted for any differences observed between the efficiencies from data and simulation. The Higgs boson cross-sections are determined using the recommendations of the LHC Higgs Cross Section Working Group [6], while the $Z \to \tau\tau$ cross-section is calculated using DYNNLO [7]. The systematic uncertainties for these backgrounds are dominated by the uncertainties on the integrated luminosity and the efficiencies.

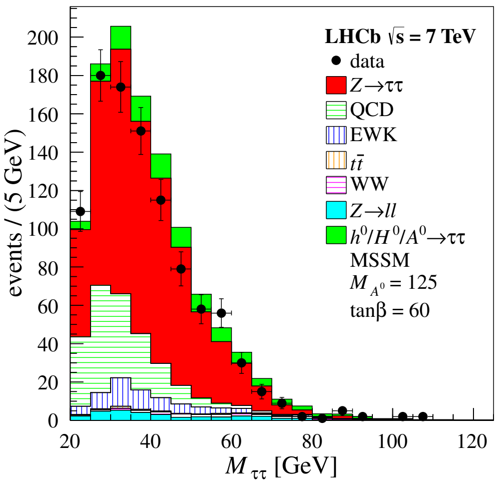

Figure 1: The invariant mass distribution of the two tau lepton decay product candidates from data (points) is compared with the invariant mass distributions for the expected $Z \to \tau\tau$ (red), QCD (green), EWK (blue), $t\bar{t}$ (orange), WW (magenta), and $Z \to \ell\ell$ (cyan) backgrounds. An example expected signal (green) from the three neutral MSSM Higgs bosons is given for $M_{A^0} = 125$ GeV and $\tan\beta = 60$.

The QCD and EWK backgrounds are extrapolated from a template fit of same-sign events to opposite-sign events. The QCD template is from non-isolated data, while the EWK template is taken from simulation. The systematic uncertainties for these two backgrounds are estimated from the uncertainty of the template fit and the extrapolation from same-sign to opposite-sign events.

The $Z \to \ell\ell$ background for the $\tau_\mu\tau_\mu$ event category is estimated by normalising an invariant mass template from prompt data with IPS < 1 to the number of observed events within the excluded mass window $80 < m_{\mu\mu} < 100$ GeV. The systematic uncertainty on this background is estimated from this normalisation. The $Z \to \ell\ell$ backgrounds for the $\tau_\mu\tau_h$ and $\tau_e\tau_h$ categories are calculated by scaling $Z \to \mu\mu$ and $Z \to ee$ distributions from data by the rates at which muons and electrons are mis-identified as hadrons. The systematic uncertainties for these backgrounds are estimated from the mis-identification uncertainties.

4. Limits

Upper limits at a 95% confidence level, using the $\mathrm{CL_s}$ method [8], on the cross-section for model independent Higgs bosons decaying into tau lepton pairs, with the tau leptons within the pseudorapidity range $2.0 < \eta < 4.5$, are shown in the left plot of figure 2 as a function of the Higgs boson mass. The observed limit is given by the solid black line, while the expected limit, assuming the background only hypothesis, is given by the dashed red line with $\pm 1\sigma$ and $\pm 2\sigma$ bands. The limit is compared to the expected Standard Model (SM) production cross-section, given by the dotted black line, with the vertical black line indicating a Higgs boson mass of 125 GeV. Upper limits on $\tan\beta$ for the $m_{h^0}^{\max}$ scenario of the MSSM are given in the right plot of figure 2 as a function of the pseudoscalar Higgs mass. The observed limit is compared to results from ATLAS [9, 10], CMS [11, 12], and LEP [13].

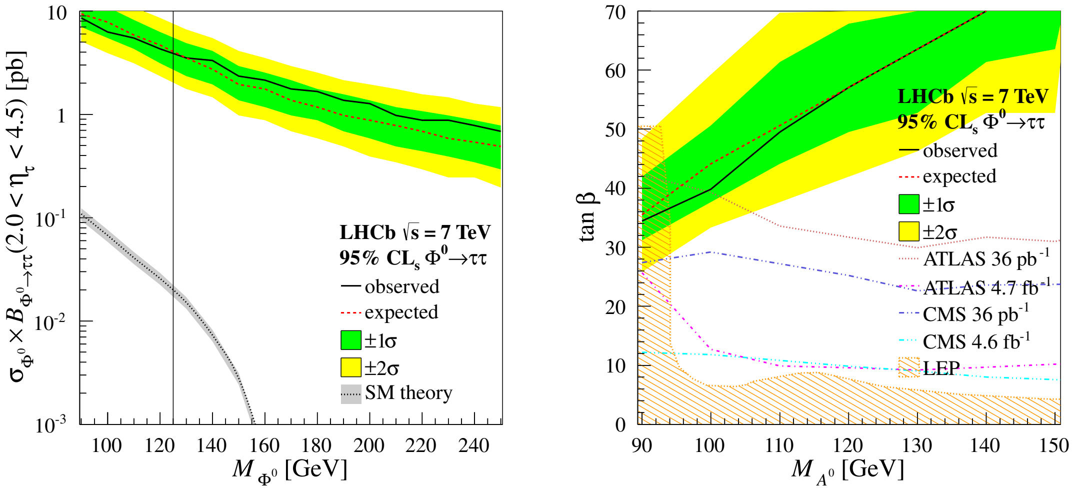

Figure 2: Model independent upper limits on the forward production of a neutral Higgs boson decaying into a tau lepton pair at 95% CL$_s$ as a function of M_{Φ^0} is given on the left. The background only expected limit (dashed red) with $\pm 1\sigma$ (green) and $\pm 2\sigma$ (yellow) bands is compared to the observed limit (solid black) and the expected SM theory (dotted black). On the right, the combined MSSM 95% CL$_s$ upper limit on $\tan\beta$ as a function of M_{A^0} is compared to ATLAS (dotted maroon and dot-dashed magenta), CMS (dot-dot-dashed blue and dot-dot-dot-dashed cyan), and LEP (hatched orange) results.

The limits are calculated using an upper profile likelihood ratio test statistic [14],

$$q_\mu = \begin{cases} -2\left(LL(\vec{x}|\mu,\hat{\hat{\theta}}) - LL(\vec{x}|\hat{\mu},\hat{\theta})\right) & \text{if } \hat{\mu} \leq \mu \\ 0 & \text{else} \end{cases} \tag{4.1}$$

where $\hat{\hat{\vec{\theta}}}$ is the maximum likelihood estimator given $\vec{x}$ and μ, and $\hat{\mu}$ and $\hat{\vec{\theta}}$ are the maximum likelihood estimators given $\vec{x}$. The signal strength parameter is μ, while LL is the extended log-likelihood function, $\vec{x}$ are the observed invariant mass from data, and $\vec{\theta}$ are nuisance parameters. The systematic uncertainties of table 1 are introduced via normally distributed nuisance parameters. The uncertainty on the simulated invariant mass shapes is also introduced via a nuisance parameter. The limits for a median experiment are determined using Asimov datasets [14].

5. Conclusion

A search for neutral Higgs bosons has been performed by LHCb in the pseudorapidity range $2 < \eta < 4.5$, providing important constraints on Higgs models with enhanced forward production. Upper limits for model independent neutral Higgs bosons and MSSM Higgs bosons decaying into tau lepton pairs are set using data from LHCb. The model independent limit is nearly two orders of magnitude larger than the expected SM Higgs production, while the MSSM limit is similar to ATLAS and CMS results from 2010 data. In the future, measurements from LHCb should provide important complementary results to ATLAS and CMS.

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