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

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Abstract: Limits on the cross-section times branching fraction for neutral Higgs bosons, produced in pp collisions at $\sqrt{s} = 7$ TeV, and decaying to two tau leptons with pseudorapidities between 2.0 and 4.5, are presented. The result is based on a dataset, corresponding to an integrated luminosity of 1.0 fb^{-1}, collected with the LHCb detector. Candidates are identified by reconstructing final states with two muons, a muon and an electron, a muon and a hadron, or an electron and a hadron. A model independent upper limit at the 95% confidence level is set on a neutral Higgs boson cross-section times branching fraction. It varies from 8.6 pb for a Higgs boson mass of 90 GeV to 0.7 pb for a Higgs boson mass of 250 GeV, and is compared to the Standard Model expectation. An upper limit on $\tan\beta$ in the Minimal Supersymmetric Model is set in the $m_{h^0}^{\mathrm{max}}$ scenario. It ranges from 34 for a *CP*-odd Higgs boson mass of 90 GeV to 70 for a pseudo-scalar Higgs boson mass of 140 GeV.

Keywords: Hadron-Hadron Scattering, Higgs physics

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Contents

1 Introduction

The discovery of a boson with a mass of about 125 GeV by the ATLAS [1] and CMS [2] collaborations requires further investigations to confirm whether its properties are compatible with a Standard Model (SM) Higgs boson or if it is better described by theories beyond the SM, such as supersymmetry. The ATLAS and CMS measurements have been made at central values of pseudorapidity, η; investigations in the forward region can be provided by the LHCb experiment, which is fully instrumented between $2 < \eta < 5$. Both measurements of cross-sections and branching fractions allow different models to be tested. In this paper, model-independent limits on the Higgs boson[1] cross-section times branching fraction into two tau leptons are presented for the forward region and compared to SM Higgs boson predictions. Model-dependent limits for the Minimal Supersymmetric Model (MSSM) Higgs bosons, in the scenario where the lightest supersymmetric Higgs boson mass is maximal ($m_{h^0}^{\max}$) [3], are also given for the ratio between up- and down-type Higgs vacuum expectation values ($\tan\beta$) as a function of the *CP*-odd Higgs boson (A^0) mass.

2 Detector and datasets

The LHCb detector [4] is a single-arm forward spectrometer. The components of particular relevance for this analysis are a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the *pp* interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet. Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and pre-shower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and

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[1] The symbol Φ^0 is used throughout to indicate any neutral Higgs boson. Additionally, charge conjugation is implied and the speed of light is taken as 1.

multiwire proportional chambers. The trigger [5] consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction.

Simulated data samples are used to calculate signal and background contributions, determine efficiencies, and estimate systematic uncertainties. Each sample was generated as described in ref. [6], with PYTHIA 6.4 [7] using the CTEQ6L1 leading-order PDF set [8] and passed through a GEANT4 [9, 10] based simulation of the detector [11]. The LHCb reconstruction software [12] was used to perform trigger emulation and full event reconstruction.

The dataset used for this analysis is identical to that described in our previous measurement of the Z cross-section using tau final states [13], which corresponded to an integrated luminosity of $1028 \pm 36\ \text{pb}^{-1}$, taken at a centre-of-mass energy of 7 TeV. The $Z \to \tau\tau$ decays are identified in five categories: $\tau_\mu\tau_\mu$, $\tau_\mu\tau_e$, $\tau_e\tau_\mu$, $\tau_\mu\tau_h$ and $\tau_e\tau_h$, defined so as to be exclusive, where the subscripts indicate tau decays containing a muon (μ), electron (e), or hadron (h) and the ordering specifies the first and second tau decay product on which different requirements are applied. The first tau decay product is required to have transverse momentum, p_T, above 20 GeV and the second to have $p_\mathrm{T} > 5$ GeV. Both tracks are required to have pseudorapidities between 2.0 and 4.5, to be isolated with little surrounding activity, to be approximately back-to-back in the azimuthal coordinate, and their combined invariant mass must be greater than 20 GeV. The tracks in the $\tau_\mu\tau_\mu$, $\tau_\mu\tau_h$, and $\tau_e\tau_h$ categories are required to be displaced from the primary vertex. Additionally, the $\tau_\mu\tau_\mu$ category requires a difference between the p_T of the two tracks and excludes di-muon invariant masses between 80 and 100 GeV, to suppress the direct decays of Z bosons into two muons. Full details on the selection criteria can be found in ref. [13].

The invariant mass distribution of the two final state particles for the selected $\Phi^0 \to \tau\tau$ candidates is plotted in figure 1 for each of the five categories separately and combined together. No candidates are observed with a mass above 120 GeV. The distributions of figure 1 differ from those of ref. [13] as the simulated mass shapes are calibrated to correct for differences between data and simulation, and the $Z \to \tau\tau$ distributions are normalised to theory.

Six background components are considered: $Z \to \tau\tau$; hadronic processes (QCD); electroweak (EWK), where one τ decay product candidate originates from a W or Z boson and the other comes from the underlying event; $t\bar{t}$; WW; and $Z \to \ell\ell$ where $\ell\ell$ indicates electrons or muons originating from a leptonic Z decay.

All backgrounds, except $Z \to \tau\tau$, have been estimated in ref. [13]. The distribution and normalisation of QCD background events is found from data using same-sign events. The electroweak invariant mass distribution is taken from simulation and normalised using data. The small contributions from $t\bar{t}$ and WW production are taken from simulation, while the $Z \to \ell\ell$ invariant mass shape and normalisation are determined from data.

The invariant mass distributions for $\Phi^0 \to \tau\tau$ and $Z \to \tau\tau$ decays are evaluated from simulation where the mass resolution has been calibrated using the $Z \to \mu\mu$ invariant mass peak. Each event is re-weighted by a factor $(\sigma \times \varepsilon)/(\sigma_\mathrm{sim} \times \varepsilon_\mathrm{sim})$, which provides a negligible correction in comparison to the mass resolution calibration. The efficiency, ε, for triggering, reconstructing and selecting candidates has been evaluated as a function of

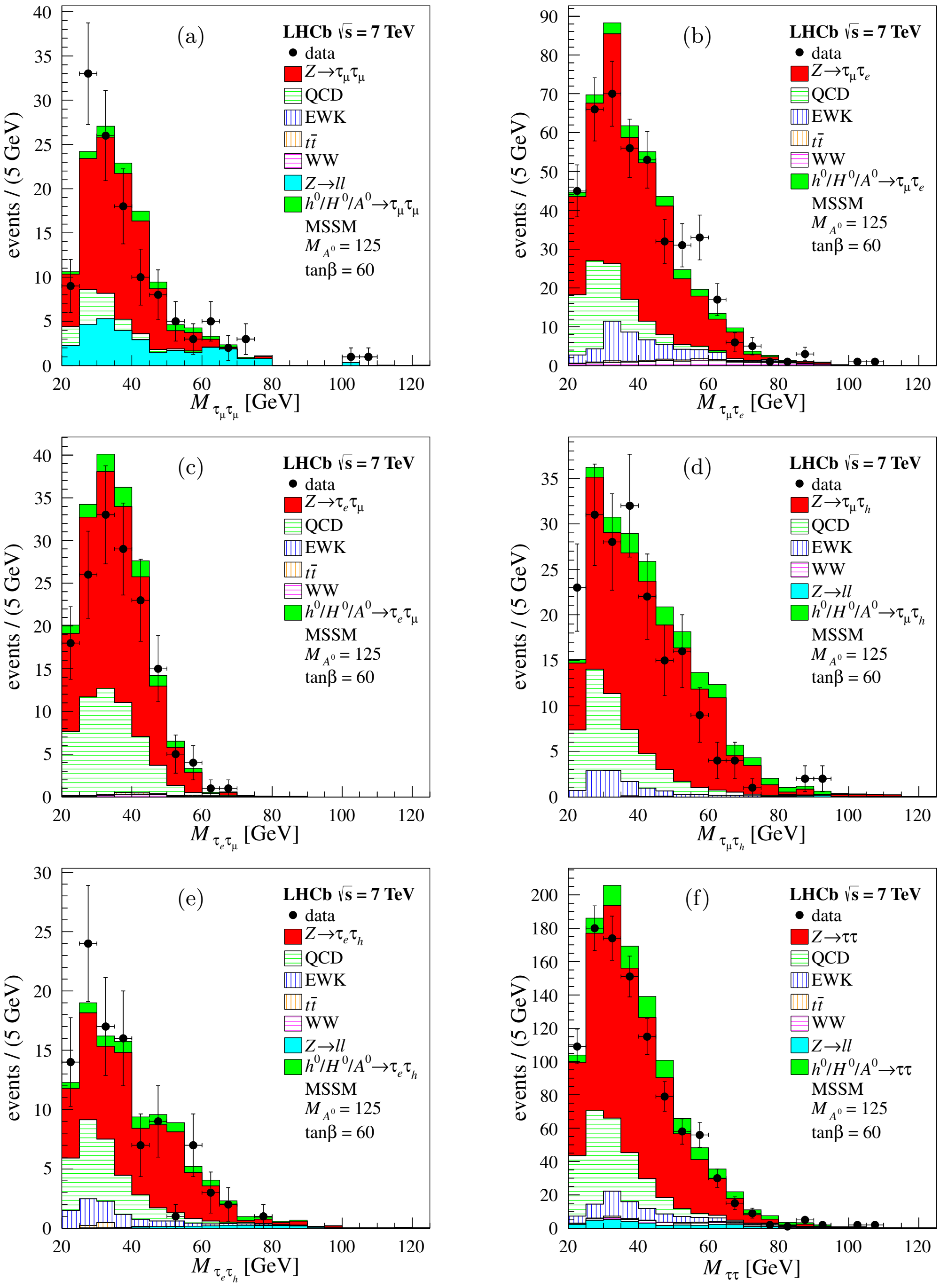

Figure 1. Invariant mass distributions for (a) $\tau_\mu\tau_\mu$, (b) $\tau_\mu\tau_e$, (c) $\tau_e\tau_\mu$, (d) $\tau_\mu\tau_h$, (e) $\tau_e\tau_h$, and (f) all candidates. The $Z \to \tau\tau$ background (solid red) is normalised to the theoretical expectation. The QCD (horizontal green), electroweak (vertical blue), and Z (solid cyan) backgrounds are estimated from data. The $t\bar{t}$ (vertical orange) and WW (horizontal magenta) backgrounds are estimated from simulation and generally not visible. The contribution that would be expected from an MSSM signal for $M_{A^0} = 125$ GeV and $\tan\beta = 60$ is shown in solid green.

	$\tau_\mu\tau_\mu$	$\tau_\mu\tau_e$	$\tau_e\tau_\mu$	$\tau_\mu\tau_h$	$\tau_e\tau_h$
$Z \to \tau\tau$	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 × 100	3.9 ± 0.5	11.9 ± 1.6	3.8 ± 0.5	9.7 ± 1.3	4.2 ± 0.6

Table 1. Estimated number of events for each background component and their sum, together with the observed number of candidates and the expected number of SM signal events for $M_H = 125$ GeV, separated by analysis category.

momentum and pseudorapidity using data-driven techniques and is described in ref. [13], while ε_{sim} is the corresponding efficiency in simulation. The cross-section for the process in simulation is represented by σ_{sim}, while σ is the theoretical cross-section. The $Z \to \tau\tau$ sample is normalised using the cross-section calculated with Dynnlo [14] using the MSTW08 PDF set [15]. The $\Phi^0 \to \tau\tau$ signal distribution is found from simulated gluon-fusion events. The signal samples were generated in mass steps of 10 GeV from 90 GeV to 250 GeV. For both the SM and MSSM Higgs bosons, the normalisation of the signal uses the theoretical calculations described below.

The SM cross-sections, using the recommendations of Refs. [16] and [17], are calculated at $\sqrt{s} = 7$ TeV with the program dfg [18] in the complex-pole scheme at next-to-next-to-leading log in QCD contributions and next-to-leading order (NLO) in electroweak contributions. The large parameter space in the MSSM necessitates the use of benchmark scenarios [3]. Only the $m_{h^0}^{\text{max}}$ scenario is considered for comparison with previous results. Both gluon-fusion and associated $b\bar{b}$ production mechanisms are considered; the former is calculated at NLO in QCD using Higlu [19] with the top-loop corrected to NNLO using ggh@nnlo [20], while the latter is calculated at NNLO in QCD using bbh@nnlo [21] with the five flavour scheme. For both SM and MSSM Higgs bosons, the branching fractions are calculated using FeynHiggs [22] at the two-loop level.

The expected distributions of background events are displayed in figure 1 and the estimated numbers of events with their associated systematic uncertainties, as well as the observed numbers of candidates from data, are given in table 1. The systematic uncertainty on the $Z \to \tau\tau$ background is dominated by the statistical uncertainty on the data-driven determination of the efficiency; the other background uncertainties are described in ref. [13].

3 Results

Limits for model independent and MSSM Higgs boson production are calculated using the method of ref. [23] with $\text{CL}_{\text{s}} = 95\%$ and the test statistic of eq. (14) from ref. [24]. The test

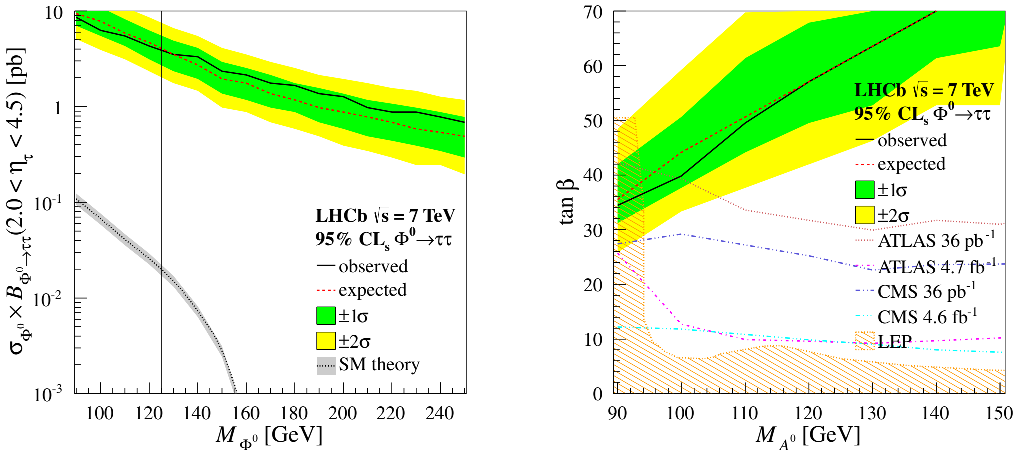

Figure 2. Model independent combined limit on cross-section by branching fraction for a Higgs boson decaying to two tau leptons at 95% CL$_s$ as a function of M_{Φ^0} is given on the left. The background only expected limit (dashed red) and $\pm 1\sigma$ (green) and $\pm 2\sigma$ (yellow) bands are compared with the observed limit (solid black) and the expected SM theory (dotted black) with uncertainty (grey). The combined MSSM 95% CL$_s$ upper limit on $\tan\beta$ as a function of M_{A^0} is given on the right and 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.

statistic is defined using the profile extended-likelihood ratio of the distributions in figure 1, where the systematic uncertainties in table 1 and the uncertainty on the simulated invariant mass shapes have been incorporated using normally distributed nuisance parameters. The uncertainty for the invariant mass shape is determined from the momentum resolution calibration for simulation, while the primary normalisation uncertainties are from luminosity determination and the electron reconstruction efficiency. The distribution of this test statistic is assumed to follow the result of Wilks [25]; this assumption has been validated using a simple likelihood ratio. The expected limits have been determined using Asimov datasets [24].

The upper limit on the cross-section times branching fraction of a model independent Higgs boson decaying to two tau leptons with $2.0 < \eta < 4.5$ is plotted on the left of figure 2 as a function of the Higgs boson mass. The upper-limit on $\tan\beta$ for the production of neutral MSSM Higgs bosons, as a function of the *CP*-odd Higgs boson mass, M_{A^0}, is provided in the right plot of figure 2. Previously published exclusion limits from ATLAS [26, 27], CMS [28, 29], and LEP [30] are provided for comparison.

4 Conclusions

A model independent search for a Higgs boson decaying to two tau leptons with pseudorapidities between 2.0 and 4.5 gives an upper bound, at the 95% confidence level, on the cross-section times branching fraction of 8.6 pb for a Higgs boson mass of 90 GeV with the bound decreasing smoothly to 0.7 pb for a Higgs boson mass of 250 GeV.

Limits on a MSSM Higgs bosons have been set in the $m_{h^0}^{\max}$ scenario. Values above $\tan\beta$ ranging from 34 to 70 are excluded over the *CP*-odd MSSM Higgs boson mass range of 90 to 140 GeV. For $M_{A^0} < 110$ GeV, these are comparable to the limits obtained by ATLAS and CMS using the 2010 data sets but are considerably less stringent than the ATLAS and CMS results using 2011 data. The forthcoming running of the LHC should allow the boson, observed by ATLAS and CMS, to be seen in the LHCb detector through a combination of channels and should provide complementary information on its properties.

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