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The Study of Higgs properties in the CMS experiment

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Combining all Higgs analysis results, the properties of the new particle at about 125 GeV are examined. The mass, spin and couplings are studied. These results are based on the full data sample of the first run of the LHC collider with data collected by the CMS experiment.

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Channel	Sub-channels	Integrated Luminosity (fb^{-1}) $\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
$\gamma\gamma$	Untagged, VBF, VH	0.0-5.1	19.6
ZZ	Untagged, VBF	5.1	19.6
WW	Untagged, VBF, VH	4.9	12.1-19.5
bb	VH, ttH	5.0	5.1
$\tau\tau$	Untagged, VBF, VH	4.9-5.0	19.5-19.6

Table 1: Decay channels included in the combined measurement of Higgs couplings including corresponding sub-channels targeting specific production modes, and the included integrated luminosity.

1. Introduction

Probing the nature of electroweak symmetry breaking has been a primary physics goal of the Large Hadron Collider (LHC). In the Standard Model (SM) [1, 2, 3] this occurs as a consequence of the Higgs Mechanism, predicting an additional scalar field and associated scalar boson[4, 5, 6, 7, 8, 9]. A Higgs boson broadly consistent with the Standard Model was discovered by the ATLAS and CMS experiments in the summer of 2012[10, 11]. Since then, additional data has been collected and incorporated into the Higgs analyses. Results are given here for measurements of the properties of the Higgs using up to 5.1 fb^{-1} of data at $\sqrt{s} = 7$ TeV and 19.6 fb^{-1} of data at $\sqrt{s} = 8$ TeV collected in pp collisions by the CMS experiment[12]. The Higgs couplings to other SM particles have been studied using decays to pairs of photons, Z bosons, W bosons, b quarks, and τ leptons, with the mass of the new boson being measured in diphoton and ZZ decays[13]. The spin and parity of the Higgs have also been studied in the ZZ[14], and WW[15] channels.

2. Summary of Included Channels

Higgs production at the LHC is dominated by the gluon-fusion process, but additional production mechanisms with smaller cross sections nevertheless provide additional information on the Higgs couplings. Analyses of the five decay channels are therefore further subdivided into sub-channels enriched in the different production mechanisms. A summary of the included channels is given in Table 1, and a brief description of the analyses is given below, with additional details available in the corresponding conference notes.

2.1 $H \to \gamma\gamma$

The Higgs$\to \gamma\gamma$ analysis[16] consists of a search for a narrow signal peak in the diphoton mass distribution on top of a large but smoothly falling background, primarily from continuum $\gamma\gamma$ production and γ+jet production. Untagged events are selected and categorised according to a diphoton multivariate classifier, incorporating information on kinematics (excluding the diphoton mass itself), diphoton mass resolution, and photon-jet discrimination. Additional exclusive event classes are formed using dijet kinematics to tag events enriched in VBF production, using one cut-based category for the 7TeV analysis, and two categories according to a multivariate classifier incorporating photon and jet kinematics for 8 TeV. For the 8 TeV data, additional exclusive-tagged event classes are selected with either an additional lepton, or missing transverse momentum, enriched in W/Z associated production. The signal is extracted by a simultaneous likelihood fit to the diphoton mass spectrum across event classes.

2.2 H $\to$ ZZ $\to 4\ell$

The Higgs$\to$ ZZ $\to 4\ell$ analysis[14] consists of a search for a narrow mass peak in the four-lepton mass distribution (including ee, $\mu\mu$ and eμ final states) on top of a small background, mainly from continuum ZZ production. The analysis is characterised by a large signal to background ratio, but relatively low event yield. Events are divided into untagged and dijet tagged classes. The signal is extracted in the untagged event class from a three-dimensional maximum likelihood fit of the four-lepton mass, a matrix element discriminator based on event kinematics, and the transverse momentum of the four-lepton system. In the dijet event class, the transverse momentum is replaced in the fit with a linear discriminant based on dijet kinematics in order to bring additional sensitivity to the VBF production mode.

2.3 H $\to$ WW $\to 2\ell2\nu$

The Higgs$\to$ WW $\to 2\ell2\nu$ analysis[15] consists of a search for an excess of events in the 2e2ν, e$\mu\nu\nu$, and 2μ2ν final states with kinematics consistent with the spin-0 nature of the Higgs. Due to the neutrinos in the final state, it is not possible to fully reconstruct a mass peak, and the extraction of the signal requires a careful estimate of the background from control regions in the data. The analysis is divided into zero-, one-, and two-jet bins, as well as according to lepton flavour. In opposite-flavour zero- and one-jet final states, the signal is extracted using a binned two-dimensional likelihood fit to the dilepton mass and transverse mass of the dilepton plus missing transverse momentum system. The remaining final states are analyzed with a simple cut and count approach, including an additional final state with three leptons, enriched in W/Z associated production.

2.4 H $\to$ bb

The Higgs$\to$ bb analysis[17] consists of a search for b-quark pairs in association with a boosted W or Z boson, targeting W/Z associated production of the Higgs. Events are selected with a pair of b-tagged jets and a W/Z boson decaying to a dilepton pair, lepton plus neutrino, or neutrino pair with large transverse momentum. The signal is extracted using the shape of a BDT classifier using event kinematics and b-tagging information. An additional channel is included targeting ttH associated production with the top pair decaying leptonically or semi-leptonically[18] . The signal in this channel is extracted as well from the shape of a BDT classifier based on event kinematics and b-tagging information

2.5 H $\to\tau\tau$

The Higgs$\to$ $\tau\tau$ analysis[19] is split into a number of sub-channels according to e, μ, and hadronic decays of the τ's, as well as the number of jets or additional leptons in the final state, with sub-channels dominated by gluon fusion, VBF, and W/Z associated production. The signal is extracted from the reconstructed ditau mass distribution, where a likelihood-based approach is

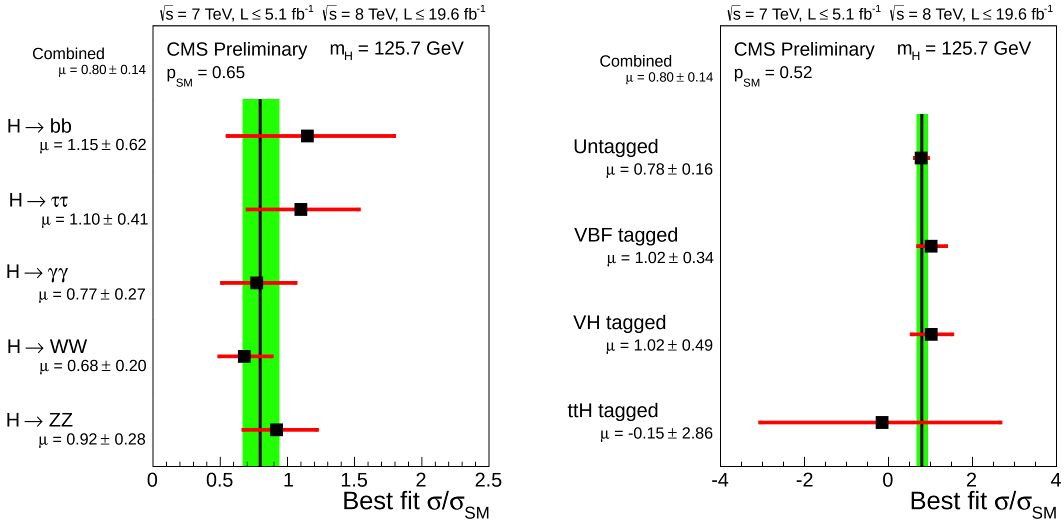

Figure 1: Fitted signal strength μ, expressed as a ratio to the standard model expectation and grouped by Higgs decay mode (left) and by dominant production mode per sub-channel (right). The signal strength and uncertainty for the full combination of all channels is shown by the black line and green band.

Channel	Expected (pre-fit)	Expected (post-fit)	Observed
ZZ	7.1σ	7.1σ	6.7σ
$\gamma\gamma$	4.2σ	3.9σ	3.2σ
WW	5.6σ	5.3σ	3.9σ
bb	2.1σ	2.2σ	2.0σ
$\tau\tau$	2.7σ	2.6σ	2.8σ
(bb+$\tau\tau$)	3.5σ	3.4σ	3.4σ

Table 2: Expected and observed statistical significance for the Higgs signal with respect to the background-only hypothesis for each decay channel, as well as the combination of bb and $\tau\tau$ channels. Expected significance is quoted for both pre-fit and post-fit values of the nuisance parameters corresponding to systematic uncertainties in the analyses.

used to estimate the ditau mass using the kinematics of the visible decay products together with the missing transverse momentum in the event.

3. Results

3.1 Signal Strength and Coupling

The overall fitted signal strength for each decay mode, given as a ratio to the standard model expectation μ, is summarised in Figure 1. The measured signal strengths are compatible with the SM prediction. The expected and observed statistical significance for the signal with respect to the background-only (SM with no Higgs) hypothesis are given for each decay channel in Table 2.

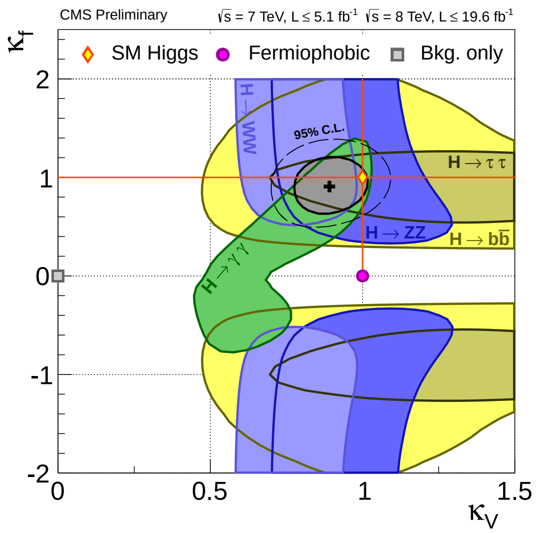

Figure 2: Two dimensional likelihood contours for a two-parameter coupling fit in terms of fermion couplings κ_f and vector boson couplings κ_v. Coloured contours are shown for each decay channel, with the combined result shown by the grey contours.

It is also possible to parametrise the signal strength in each channel in terms of a scale factor to the leading order Higgs coupling to each SM particle, taking into account the effect on both production cross sections and decay widths. Fitting for these scale factors then serves as a compatibility test of the SM. The full set of coupling modification factors for which the current channels provide sensitivity are $\kappa_W, \kappa_Z, \kappa_b, \kappa_t, \kappa_\tau$. The loop-mediated couplings to gluons and photons can either be decomposed into the SM t and W couplings, or alternatively parametrised by independent κ_g and κ_γ factors to allow for beyond Standard Model contributions to the loop amplitudes. In order to reduce the number of free parameters in the fits, couplings can also be grouped together, considering for example an overall scale factor for fermionic couplings κ_f and vector-boson couplings κ_V. The results for a two-parameter coupling fit in terms of κ_f and κ_V are shown in Figure 2. The combined fit, as well as the individual channels, are compatible with the SM expectation.

3.2 Mass

The Higgs mass is measured using the $\gamma\gamma$ and ZZ channels, which are the two channels with fully reconstructed final states resulting in high-resolution mass peaks. One- and two-dimensional likelihood scans for signal strength and mass are shown in Figure 3. The measured mass for the $\gamma\gamma$ channel is 125.4 ± 0.5(stat)±0.6(syst) GeV, and for the ZZ channel it is 125.8 ± 0.5(stat)±0.2(syst) GeV. The measurements in the two channels are compatible with each other, and the combined mass measurement is 125.7 ± 0.3(stat)±0.3(syst) GeV.

3.3 Spin and Parity

The Higgs spin is tested in the ZZ, WW, and $\gamma\gamma$ channels, and the parity is tested in the ZZ channel. Spin and parity are tested in the ZZ channel using a two-dimensional likelihood fit to

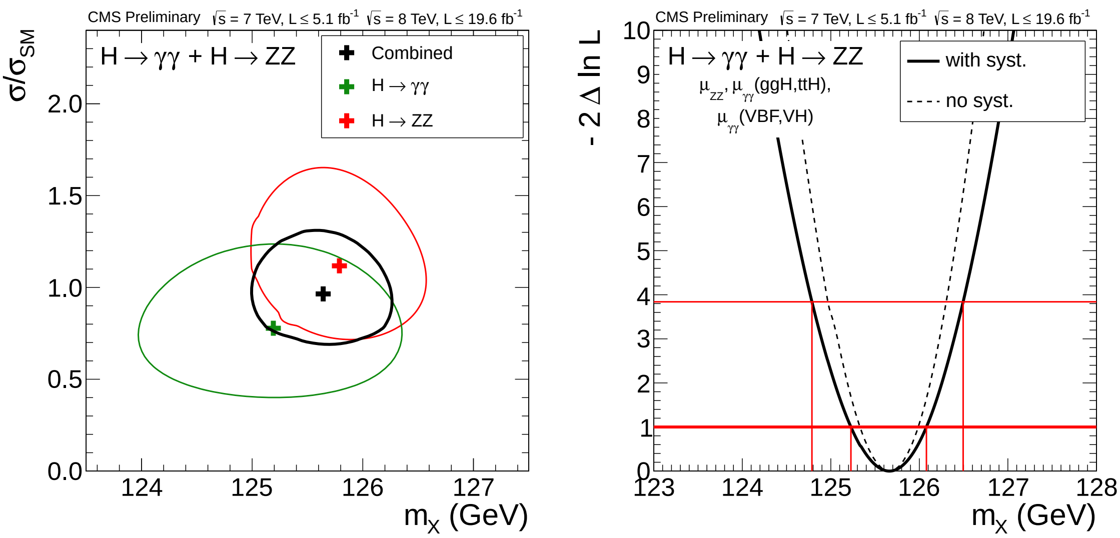

Figure 3: Two-dimensional likelihood contours for signal strength vs mass (left) for the two contributing channels and their combination. One dimensional profile likelihood scan vs mass for combination of both channels, with signal strengths profiled (right).

pair of matrix-element discriminants, constructed to separate signal from background, and a scalar boson from a variety of alternate spin-parity hypotheses, using the various decay angles and masses in the event. Performing a hypothesis test in the ZZ channel between a scalar and pseudo-scalar boson, the pseudo-scalar hypothesis is disfavoured with a CLs value of 0.16%, corresponding to an exclusion at greater than 3σ. A spin 2^+ model with minimal couplings is similarly excluded at the 2.81σ level with respect to the scalar hypothesis.

The Higgs spin is tested in the WW channel using a two dimensional fit to the dilepton mass and dilepton plus missing transverse momentum transverse mass. A spin 2^+ model with minimal couplings is disfavoured at the 1.33σ level. Combining this test with the ZZ channel leads to an exclusion for this model at the 2.84σ level with respect to the scalar hypothesis. The test statistic distributions for the parity hypothesis test in ZZ and the combined spin 2^+_M hypothesis test are shown in Figure 4.

4. Conclusion

The properties of the recently discovered Higgs boson have been measured in a combination of channels covering five decay modes and four production mechanisms, including the full 7 TeV and 8 TeV data samples for most of the channels. Signal strengths have been measured with a precision ranging from 20% to 62% of the SM rate for individual decay channels and 14% for the combination, and signal strengths and couplings are fully compatible with the SM prediction. The mass of the boson has been measured with a combined precision of 0.3%. Tests of spin and parity favour the SM scalar nature of the new state compared to alternate spin-parity hypotheses which have been tested.

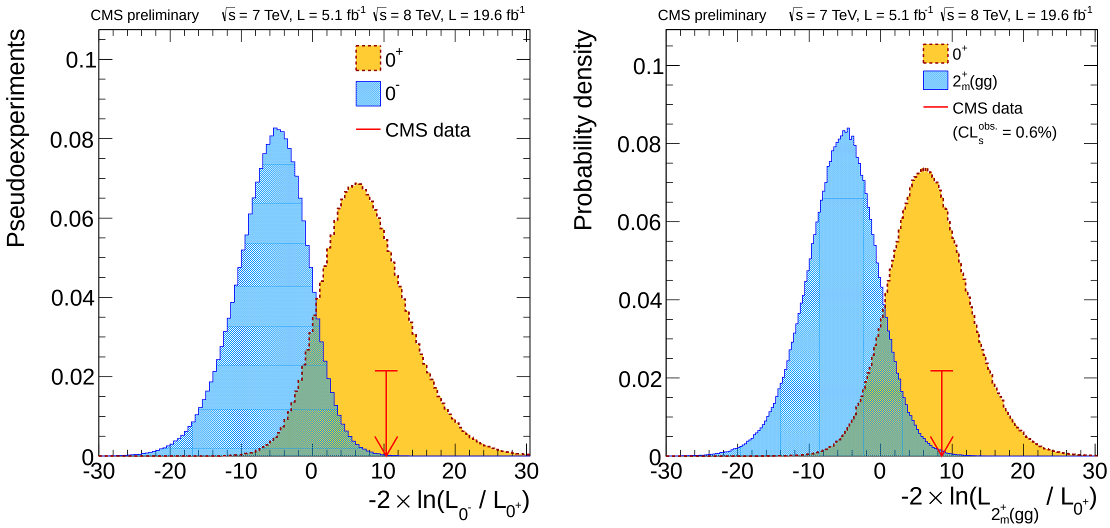

Figure 4: Expected and observed test statistic distributions corresponding to hypothesis tests comparing the SM to a pseudoscalar boson in the ZZ channel (left) and a spin 2_M^+ model in the combination of ZZ and WW channels (right). Both tests favour the standard model with respect to the alternate hypotheses with a high degree of confidence.

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