Study of Higgs boson production in bosonic decay channels at CMS

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Higgs bosonic decays: directions

CMS

- Low mass:
 - Study of the properties of H(125). $H \rightarrow WW(2l2v),$ $H \rightarrow ZZ(4l),$ $H \rightarrow \gamma\gamma$
 - Rare processes eg. H \rightarrow Z γ , ttH \rightarrow tt $\gamma\gamma$
- High mass:
 - Search for additional states from ¹⁰ extended Higgs sector (and eventually the study of VV-scattering):

 $\begin{array}{l} H \rightarrow ZZ(4I,2I2\nu,2I2q), \\ H \rightarrow WW(2I2\nu,I\nu jj) \end{array}$



Higgs bosonic decays: references



Channel		approx. L(√s=7+8TeV) [fb⁻¹]	Ref	*Covered in		
$H \rightarrow WW(IvIv)^*$		5+19.5	HIG-13-003	this talk		
$WH \rightarrow WW$	/W(3l3v)	5+19.5	HIG-13-009			
$H \rightarrow WV$	V(lvj)*	0+19.5	HIG-13-008	New		
$H \rightarrow ZZ$	Z(4I)*	5+19.5	HIG-13-002			
H → ZZ(2l2v)*	5+19.5	HIG-13-014	New		
$H \rightarrow r$	γγ*	5+19.5	HIG-13-001			
ttH →	ttγγ*	0+19.5	HIG-13-015	New		
$H \rightarrow Z$	Z(II)γ	5+19.5	HIG-13-006			

(Only showing analyses that use the full 8TeV dataset. Full list at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG)

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$H \rightarrow WW(|v|v)$

- Large $\sigma \times BR$.
- Clean signature:
 - $_{-}$ Two isolated high p_T leptons.
 - Missing transverse energy
- No mass resolution.
- Main backgrounds:
 - Non-resonant WW, tt.
- Discriminating variables:
 - $p_{T\parallel}, m_{\parallel}, m_{T}, \Delta \phi_{\parallel}$

Vectors from the decay of a scalar and V-A structure of W decay lead to a small opening angle between leptons (especially true for on-shell Ws)



CMS Experiment at LHC, CERN Data recorded: Thu Apr 19 09:14: Run/Event: 191721 / 76089774 Lumi section: 111 Orbit/Crossing: 28960009 / 815

CM



Analysis overview



- Analysis performed in exclusive jet multiplicity bins.
 - _ 0-1jet: 5+19fb⁻¹ (√s=7+8TeV)
 - _ (VBF signature: last update with 5+12fb⁻¹)
- Also split events in same and opposite flavor channels.





Signal extraction

- Same flavor: cut-and-count analysis.
- Opposit flavor: 2D fit of m_{μ} vs m_{τ} .

100

90

80

70

60

50

40

30

20

60

70

M_{II} (GeV)

 Signal and background templates from MC corrected using control regions.

80

- Non resonant WW normalization freely floating.



Data



Results





Significance @ 125 GeV: 4.0 σ (5.1 expected)



CMS How because

- Golden channel: 4 isolated leptons.
 - Very high S/B ratio, excellent mass resolution (1-2%), fully reconstructed final state.
 - Low even yield. Demanding requirements in terms of efficiency down to p_T of 5-10GeV.







Matrix element analysis



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- Events categorized according to jet multiplicities.
- Signal extracted 3D from simultaneous fit.
 - $_{-}$ 0-1jet: m₄₁ vs MELA vs p_{T41}
 - 2jets (20% ggH): m₄₁ vs MELA vs Fisher discriminant(m_{jj}, $\Delta \eta_{jj}$)











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Overview



- Search for a narrow peak on a smoothly falling background.
 - Excellent mass resolution (1-2%).
 (Energy resolution and vertex identification).
 - Rejection of reducible background also crucial.
 - _ Background estimated using m_{yy} side-bands.
 - Signal model using inputs from $Z \rightarrow ee$, $Z \rightarrow II\gamma$ and $Z \rightarrow \mu\mu$ control samples.





Overview (2)



Events categorized in terms of S/B and mass ×10³ MC 53 DiphotonJets + PhotonJets + DiJets / Data vs = 8 TeV L = 19.62 fb⁻¹ resolution. # of events/0.04 60 Prompt-Eake Two analyses: 50 rompt-Prompt ID Shape Systematics • MVA mass-factorized: BDT-based categorization 40 (using energy resolution, vertex ID probability, 30 photon kinematics other than m_m). 20 . Cut-based analysis: simple categorization according to photon rapidity and EM shower shape based conversion 10 tag. -0.5 0 0.5 1.0 Signal extracted from simultaneous fit to m. di-Photon BDT







Exclusive categories



- In addition to the untagged categories, high S/B categories are defined using additional objects in the event.
 - Di-jet: 2 categories (loose/tight) with increasing VBF purity (loose ~50%, tight ~80%). MVA analysis uses a dijet BDT-based selection.
 - Additional leptons (electrons and muons pT>20 GeV) or MET (>70 GeV) with increased VH content.
- Improve significantly the ability to measure Higgs couplings.
- Events assigned to categories in the following order:



Results





(Taking into account correlations, the results of the two analyses are statistically compatible at less than 2σ level).

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Search for ttH with H $\rightarrow \gamma\gamma$

- Use cut-based photon identification.
- Require additional jets and leptons on top of di-photon selection.
 - $_{-}$ Expected and observed limits ~5 x SM.
 - See poster from Francesco Micheli.









Summary



m.,=125.0 GeV

(H→ZZ^(*)→4I m_u=125.8 GeV)

Best Fit $\sigma/\sigma_{SM}(\mu)$

- Bosonic final states are an excellent tool for Higgs Physics at the LHC.
- The properties of the newly discovered ~125GeV state compatible with CMS preliminary those of the SM Higgs boson $H \rightarrow \gamma \gamma$ cms hig-13-001 within (still sizeable) Vs = 7 TeV. L = 5.1 fb⁻¹ Vs = 8 TeV. L = 19.6 fb⁻¹ uncertainties. $H \rightarrow ZZ^{(*)} \rightarrow 4I$ CMS HIG-13-002
 - See talk from Andrea Benaglia for further details.
- Higher energy and luminosity -2 -3 will provide more precise information on the properties of the new state.
- Searches for additional Higgs like bosons at high mass will eventually start to probe VV-scattering.

Vs = 7 TeV. L = 5.1 fb⁻¹ vs = 8 TeV. L = 19.6 fb⁻¹

vs = 7 TeV. L = 4.9 fb⁻¹ vs = 8 TeV. L = 19.5 fb⁻¹

 $H \rightarrow WW^{(*)} \rightarrow 2I2v \text{ cms Hig-13-003}$

-1

0



Additional material







Mass measurement





$H \rightarrow ZZ \rightarrow 4\ell$:

Mass estimation with m4l, KD and s(m4l) Very small systematics due the very good Control of the leptons scale and resolution: $mH = 125.8 \pm 0.5$ (stat.) ± 0.2 (syst.) GeV.

 $H \rightarrow \gamma \gamma$: Systematics on the extrapolation from Z→ee to H→γγ (0.25% e → γ, 0.4% m_z → m_H) $mH = 125.4 \pm 0.5$ (stat.) ±0.6 (syst.) GeV

mX = 125.7 \pm 0.3(stat) \pm 0.3(syst) GeV = 125.7 \pm 0.4 GeV



- Simple hypothesis test:
 - SM Higgs;
 - Minimal graviton-like spin 2 model "2⁺_m" produced in gluon fusion.
- Fit m₁ vs m₇ under the two hypotheses

2⁺ hypothesis disfavored at CLs = 14%



CMS Preliminary vs = 7 TeV, L = 4.9 fb⁻¹; vs = 8 TeV, L = 19.5 fb⁻¹





Dedicated Matrix Element discriminants (D^(h)) for each hypothesis test.

- Hypotesys test: 3D fit of m4I vs MELA vs D^(h).





Distribution of JP discriminants



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Electron energy scale and resolution





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Muon energy scale and resolution







- Very good ECAL performance in 2012
 - Z→ee mass resolution better than 1.2% for electrons with low bremsstrahlung in the barrel.
- Stable performance already using promptly reconstructed data.





$H \rightarrow WW$: background control

- **WW**:
 - mH<200 GeV: events with mll>100 GeV (from data). MC to extrapolate into signal region
 - mH>200 GeV: from MC.
- Ζ/γ* :
 - events with mll±7.5 GeV around Zmass. (residual bkg subtracted)
 - $_{-}$ extrapolation to signal region from MC. Cross-checked with data.
- Wy* :
 - _ MC (Madgraph) for shape
 - Normalization from high purity control sample (data).
- WZ/ZZ/ Wy:
 - _ from MC.
 - $_{-}$ Wy estimate cross-checked

 $H \rightarrow WW$: background control (2)

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> W+jets/QCD:

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- Control sample with "tight+fail" sample.
- Extrapolation to signal region with mis-identified probability
- Validation on same-sign/DF control sample

> Top (tt/tW):

- Control sample with inverted top veto
- Background surviving the veto estimated by weighting events with per-event tagging efficiency per-jet tagging efficiency measured in separated control sample.
- Validation in 1-jet DF top-enriched sample (inverting b-tag requirement)





- Exclusion at 95% CL in the mass range 128 600 GeV.
- Large excess in the low mass makes the limits weaker than expected.
- When including mH=125 GeV as a part of background, no significant excess is seen over the entire range.

$H \rightarrow WW$: signal strength



Low mass resolution gives a shallow likelihood prole as a function of mH



Consistent results among the exclusive categories & data taking periods

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6% of event affected, 50% efficiency, 80% purity

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90 100 110 120 130 140 150 160 m_{4l+γ} [GeV]

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\rightarrow ZZ: spectrum and tables



110 < m4l < 1000 GeV

Channel	4e	4μ	2e2µ
ZZ background	78.9 ± 10.9	118.9 ± 15.5	192.8 ± 24.8
Z+X	$6.5^{+2.6}_{-2.6}$	$3.8^{+1.5}_{-1.5}$	$9.9^{+4.0}_{-4.0}$
All background expected	85.5+11.2	$122.6^{+15.5}_{-15.5}$	202.7+25.2
$m_H = 125 \text{ GeV}$	3.5 ± 0.5	6.8 ± 0.8	8.9 ± 1.0
$m_H = 126 \text{ GeV}$	3.9 ± 0.6	7.4 ± 0.9	9.8 ± 1.1
Observed	86	125	240



110 < m4l < 160 GeV

Channel	4e	4μ	2e2µ	4ℓ
ZZ background	6.6 ± 0.8	13.8 ± 1.0	18.1 ± 1.3	38.5 ± 1.8
Z+X	2.5 ± 1.0	1.6 ± 0.6	4.0 ± 1.6	8.1 ±2.0
All background expected	9.1±1.3	15.4 ± 1.2	22.0 ± 2.0	46.5 ±2.7
$m_H = 125 \text{ GeV}$	3.5 ± 0.5	6.8 ±0.8	8.9 ±1.0	19.2 ±1.4
$m_H = 126 \text{ GeV}$	3.9 ± 0.6	7.4 ± 0.9	9.8 ±1.1	21.1 ± 1.5
Observed	16	23	32	71

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$H \rightarrow ZZ m_{Z1} vs m_{Z2}$



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- Energy scale and resolution validated and corrected using Z → ee.
 - Excellent stability of energy resolution across the whole 8TeV dataset.
 - Good modelling of mass shape in analysis categories.



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- Higgs production vertex is selected using a Boosted Decision Tree (BDT)
 _ Inputs: Σp₁² of vertex tracks, vertex recoil wrt diphoton system, pointing from converted photons.
- An additional BDT is used to estimate the vertex probability in the MVA analysis.
- Control samples: $Z \rightarrow \mu\mu$ for unconverted photons, γ +jets for converted photons





- CMS
- MVA classifier validated in data using $Z \rightarrow ee$ events.
 - Good agreement observed within uncertainties.





- Cut-based analysis uses:
 - cut-based photon identification
 - a different definition of event categories
- Photon identification data/MC efficiency scale factors computed from $Z \to ee$ and $Z \to \mu \mu \gamma.$

Cat 0	Dath photons in hormal	\mathbf{P} oth shotons $\mathbf{P} > 0.04$		R	9=	E3:	×3/	Esc		
	Both photons in barrel	Both photons $K_9 > 0.94$	R9		H	+	F	Ħ	\blacksquare	-
Cat 1	Both photons in barrel	At least one photon with $R_9 < 0.94$	1.0		H	Ŧ	Ħ	Ħ	\mp	
Cat 2	At least one photon in endcaps	Both photons $R_9 > 0.94$						Ħ		
Cat 3	At least one photon in endcaps	At least one photon with $R_9 < 0.94$								

$H \rightarrow \gamma \gamma$: weighted mass spectra

MVA mass-factorized

Cut-based

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Despite the same names, the untagged categories in MVA and Cut-basd are not equivalent 24

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- Low signal to background ratio a fundamental feature of this channel.
 - _ Uncertainty on signal strength driven by statistical fluctuations of the background.
- Analysis changes can lead to statistical changes due to fluctuations in selected events the reconstructed $m_{_{\rm YV}}$.
- The correlation coefficient between the MVA and cut-based signal strength measurements is found to be r=0.76.

	Signal strength compatibility (including correlation)
MVA vs CiC 7+8 TeV	1.5 σ
MVA vs CiC 8 TeV only	1.8 σ
Updated MVA vs published (5.3/fb 8TeV)	1.6 σ
Updated CiC vs published (5.3/fb 8TeV)	0.5 σ

 $\hfill \ \hfill \ \$



Jackknife resampling

- CMS
- Jackknife resampling can be used to estimate the variance of stat. estimators in a non parametric way.
 - Achieved evaluating the estimator on subsets of the stat. sample.



 Given analyses A and B, used to estimate the variance of of m_A-m_B applying the jackknife resampling to the events selected by

either analysis.



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$\rightarrow \gamma \gamma$: MVA categories

Expected signal and estimated background											
Event classes		SM Higgs boson expected signal ($m_{\rm H}$ =125 GeV)							Background		
		Total	ggH	VBF	VH	ttH	$\sigma_{ m eff}$ (GeV)	FWHM/2.35 (GeV)	$m_{\gamma\gamma} = 1$ (ev./0	l25 GeV GeV)	
-1	Untagged 0	3.2	61.4%	16.8%	18.7%	3.1%	1.21	1.14	3.3	± 0.4	
1 fb	Untagged 1	16.3	87.6%	6.2%	5.6%	0.5%	1.26	1.08	37.5	± 1.3	
5.	Untagged 2	21.5	91.3%	4.4%	3.9%	0.3%	1.59	1.32	74.8	±1.9	
7 TeV	Untagged 3	32.8	91.3%	4.4%	4.1%	0.2%	2.47	2.07	193.6	± 3.0	
	Dijet tag	2.9	26.8%	72.5%	0.6%	1 -	1.73	1.37	1.7	± 0.2	
8 TeV 19.6 fb ⁻¹	Untagged 0	17.6	72.9%	11.6%	13.0%	2.6%	1.38	1.31	21.9	± 0.5	
	Untagged 1	39.4	83.5%	8.4%	7.1%	1.0%	1.51	1.38	93.0	± 1.0	
	Untagged 2	155.3	91.7%	4.4%	3.5%	0.4%	1.78	1.52	559.6	± 2.5	
	Untagged 3	162.1	92.5%	3.9%	3.3%	0.2%	2.63	2.18	1021.3	± 3.4	
	Dijet tight	9.3	20.7%	78.9%	0.3%	0.1%	1.81	1.43	3.3	± 0.2	
	Dijet loose	11.6	46.8%	51.1%	1.7%	0.5%	1.87	1.60	12.0	± 0.4	
	Muon tag	1.4	0.0%	0.2%	79.1%	20.8%	1.87	1.55	0.7	± 0.1	
	Electron tag	1.0	1.1%	0.4%	78.9%	19.7%	1.91	1.55	0.6	± 0.1	
	$E_{\mathrm{T}}^{\mathrm{miss}}$ tag	1.6	21.1%	2.5%	64.5%	11.8%	1.81	1.66	1.7	± 0.1	

