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for the CMS collaboration --

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Beyond the Discovery: Higgs Results from CMS
Higgs Road of Discovery

- After the discovery of a Higgs state at 125 GeV:
  - final word on Higgs sector according to LHC Run-I

- **Huge number of new results**
  - properties of the H(125) state
  - search for additional Higgs bosons beyond the Standard Model

- Only **selected highlights** can be shown in this presentation
Properties of the H(125)
H(125) Properties

- **H(125) firmly established** in di-boson decay channels
- Mass measured to ~0.19 % precision (ATLAS+CMS, see presentation by P. Vanlaer)
  \[ m_H = 125.09 \pm 0.24 \text{ GeV} \]
- Spin-parity analysis: state consistent with JP=0+
- Fermionic decay modes more elusive
- Evidence for \( H\rightarrow\gamma\gamma \) at the level of 3.2\( \pm \) observed (3.7\( \pm \) expected)
Higgs channel: largest BR, but also difficult background conditions

First studies focused on production with associated vector boson (VH, V=W,Z)
  - improved signature (S/B)
  - excess of 2.1 ± significance (3.8 ± combined with H±±)
  - signal strength ± / ±SM =1.0 ± 0.5

New: search in vector boson fusion (VBF)
  - first SM Higgs search in fully hadronic state!
  - electroweak process, no QCD color exchanged

arXiv:1506.01010; Accepted by Phys. Rev. D
- BDT categorization. Validate with $Z(\tau\tau)+\text{jets}
- Signal significance of $2.2\sigma$ observed (0.8\sigma expected)
- Combination VBF+VH+ttH: $|t_\text{SM}| = 1.03 \pm 0.44$
  - significance of $2.6\sigma$ observed (2.7\sigma expected)
  - Convincing hint for H(125) coupling to \(b\) quarks
  - follow up in Run-II with 13 TeV data

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Top-Higgs Coupling

JHEP 09 (2014) 087

CMS \( \sqrt{s} = 7 \text{ TeV}, 5.0 \pm 0.1 \text{ fb}^{-1} \); \( \sqrt{s} = 8 \text{ TeV}, 19.3 - 19.7 \text{ fb}^{-1} \)

\( tH, H \rightarrow b\bar{b}, \tau\tau, \gamma\gamma, WW, ZZ \)

\( m_H = 125.6 \text{ GeV} \)

\( \mu_{tH} = 2.8 \pm 1.0 \)

-2 \Delta \ln L

\( \text{SM} \) \( \text{Data} \)
Matrix elements of signal and most prominent background process (ttbb) known

To each event, assign probability density value under signal or background hypotheses

- use ratio in a likelihood fit to extract the signal

- optimized separation of signal and background
Differential Cross Sections ($H\rightarrow...$)

- Direct test of perturbative QCD calculations in the Higgs sector
- $p_T^{\ell\ell}$ and $p_T^{j1}$ distributions: sensitive to HO corrections in perturbative QCD

All distributions agree with QCD predictions within errors.

Higgs Results from CMS
At the level of current precision, the H(125) couples as expected in the SM

Is the H(125) state the standard model Higgs boson, or only standard-model-like?

Observed boson could well be only the first member of an extended Higgs sector

Would indicate New Physics

Needs to be clarified via direct search for additional Higgs bosons
Higgs Beyond the Standard Model

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Additional Higgs Bosons According to SUSY

Model | Structure | CP-even | CP-odd | Charged
--- | --- | --- | --- | ---
MSSM | 2 doublets | h, H | A | H
NMSSM | 2 doublets+1 singlet | h1, h2, h3 | a1, a2 | h

Low mass Higgs

NMSSM, if existing constraints (LEP…) are avoided

H(125) found!

h (MSSM) ?
h1 or h2 (NMSSM) ?

High mass Higgs

(N)MSSM at large tan

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Search for degenerate H and A in higher mass region
- large BR(ʻbb)
- Main challenge: huge background rate from QCD multijet production

- b-associated production: cross section enhanced by \( \sim 2 \tan^2 \beta \), better background control
  - require at least three b-tagged jets
  - dedicated trigger

Background-only hypothesis describes data very well
- no signal observed

CMS analysis is unique at the LHC
- Best sensitivity in this channel to date
Low expected BR, but excellent mass resolution (±m~1.2 GeV at m=125 GeV) → good control of background
largest background Drell-Yan production
Parametric signal + background model

Signal model:

Data:
Interpretation in **mhmod scenario** [1], upper limits for MSSM parameter $\tan \beta$

- Published $H\rightarrow\tau\tau$ results [JHEP 10 (2014) 160] updated, with improved $\tau$ had identification

- Different mass resolutions clearly visible (best for $\tau\tau$, worst for $\tau\mu$)

- Most **stringent direct limits** from $\tau\mu$ mode. $bb$ and $\tau\tau$ comparable to each other.

Light NMSSM Higgs Search

- Light Higgs (<100 GeV) with "standard" couplings excluded by LEP
- In NMSSM: “P4” benchmark scenario [2]
  - associate h2 \( \equiv \) H(125), SM-like
  - light h1 with large singlet component
  - suppressed in "standard" Higgs production channels, but copious production in SUSY cascades

\[ \square \text{Discover BSM Higgs and SUSY simultaneously?} \]

- For the first time explored at the LHC
- other resonances (Z, h2, a1) should appear as well

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Results

CMS Preliminary

_σ × BR (pb)_

- Observed
- QCD multijet prediction
- W → ν + jets
- Z^0 → νν + jets
- syst. + stat. uncertainty
- h_0 (m = 65 GeV, NMSSM P4)
- SUSY (non-h_0, NMSSM P4)

19.7 fb^{-1} (8 TeV)

(Data - Pred) / Pred

m_{bb} (GeV)

m_{h_1} (GeV)

NE W!

HIG-14-030

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Beyond the Higgs boson discovery, a large number of new CMS results have been obtained, constituting the "final word" from LHC Run-I.

Properties of the H(125) state determined to remarkable precision:
- methodology enhanced in many places; will fully bear fruit with future data.

At the current measurement accuracy, the state is compatible with the SM Higgs boson:
- any mild deviations are covered by the uncertainties.

Search for New Physics looking for additional Higgs states:
- stringent limits for MSSM parameters obtained (three direct search channels), large values of mass and tan β still allowed.
- still wide open Higgs parameter space in NMSSM.
- also other scenarios being tested.
Outlook

Run-II just started, exciting program ahead...

... stay tuned!
Backup Slides
Links to Information


- CMS Collaboration, "Measurement of differential cross sections for Higgs boson production in the diphoton decay channel in pp collisions at sqrt(s) = 8 TeV", HIG-14-016, to be submitted to arXiv and EPJ C.


• CMS Collaboration, "Search for additional neutral Higgs bosons decaying to a pair of tau leptons in pp collisions at √s= 7 and 8 TeV", CMS-HIG-14-029, http://cds.cern.ch/record/2041463?ln=en

ttH ME Method (cont'd)


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Fiducial Cross Sections (H→4l)

HIG-14-028, to be submitted to arXiv and JHEP

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Definition of fiducial phase space volume

<table>
<thead>
<tr>
<th>Requirements for the $H \to 4\ell$ fiducial phase space</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lepton kinematics and isolation</strong></td>
</tr>
<tr>
<td>leading lepton $p_T$</td>
</tr>
<tr>
<td>next-to-leading lepton $p_T$</td>
</tr>
<tr>
<td>additional electrons (muons) $p_T$</td>
</tr>
<tr>
<td>pseudorapidity of electrons (muons) $</td>
</tr>
<tr>
<td>$p_T$ sum of all stable particles within $\Delta R &lt; 0.4$ from lepton</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Event topology</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>existence of at least two SFOS lepton pairs, where leptons satisfy criteria above</td>
</tr>
<tr>
<td>inv. mass of the $Z_1$ candidate $40$ GeV &lt; $m(Z_1)$ &lt; 120 GeV</td>
</tr>
<tr>
<td>inv. mass of the $Z_2$ candidate $12$ GeV &lt; $m(Z_2)$ &lt; 120 GeV</td>
</tr>
<tr>
<td>distance between selected four leptons $\Delta R(\ell_i\ell_j) &gt; 0.02$ for any $i \neq j$</td>
</tr>
<tr>
<td>inv. mass of any opposite sign lepton pair $m(\ell^+\ell'^-)$ &gt; 4 GeV</td>
</tr>
<tr>
<td>inv. mass of the selected four leptons $105$ GeV &lt; $m_{4\ell}$ &lt; 140 GeV</td>
</tr>
<tr>
<td>the selected four leptons must originate from the $H \to 4\ell$ decay</td>
</tr>
</tbody>
</table>
- Good compromise between relatively large BR and manageable backgrounds
- Mass of \( \tau \) pair is reconstructed from visible \( \tau \) decay products and missing ET
  - maximum likelihood technique
- Con

\[ \tau \tau \]
- Very low $\tan \beta$ upper limits ($\tan \beta < 5$ for $m_A<250$ GeV !)
- Interpretation in mhmod scenario [1]: better suited for known mass of $H(125)$, than mhmax scenario
- Low values of $\tan \beta$ indirectly excluded, since $m_h$ incompatible with $H(125)$
Background-only hypothesis describes data very well, $\chi^2 / \text{Ndof} = 205.2 / 208$

- no signal observed
Hbb MSSM: $\mu$ Dependence

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Interpretation in mhmod scenario [1], upper limits for MSSM parameter tan β

Published Higgs results [JHEP 10 (2014) 160] updated, improved had identification

Different mass resolutions clearly visible (best for bb, worst for WW)

Most stringent direct limits from WW mode. bb and WW ~comparable to each other.

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Besides the h1, other resonances (Z, h2, a1) would be produced in the SUSY cascade, as well as combinatorial background complex signal model.

Two search strategies:
- single peak over SM background
- full SUSY spectrum (with Z, h2, a1+nonresonant contribution)

Dominant backgrounds:
- tt + jets normalization NLO, shape MC
- QCD multijet normalization & shape data-driven

Validated in control regions

\[ m_{\text{bb}} (\text{GeV}) \]

Events/(10 GeV)

Signal + SUSY (non-h)
- $h_1 (m = 65 \text{ GeV})$
- Z
- h2
- a1
- Non-resonant bkg.

CMS Simulation

Events/(10 GeV)

observed
- $h_1 (m = 65 \text{ GeV})$
- SUSY (non-h)
- $t\bar{t} + \text{jets}$
- QCD multijet (MC)
- $W \rightarrow l + \text{jets}$
- $Z \rightarrow \ell^+ \ell^-$
- single top
- $W^\pm Z$
- $Z^0$
- stat. uncertainty

QCD Prediction CR

Veto on isol. leptons
- $100 < \text{ETmiss} < 200 \text{ GeV}$

Data-Pred
- 50 < ETmiss < 200 GeV

Comparison of observed and predicted yields in CMS control regions.