Higgs decaying into bosons

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on behalf of the CMS collaboration
Bosonic Higgs Decays

Higgs analyses are huge experimental challenges!
Bosonic decays (WW, ZZ, γγ, Zγ) include the cleanest channels to search for and study the SM Higgs boson.
Talk Outline

H→ZZ→4l channel drives mass measurement

H→WW→2l2ν most sensitive for signal strength

No new results and time is short: my choice is to focus on H→ZZ→4l and H→WW→2l2ν analyses.

Only highlights from other analyses.
**H→ZZ→4l: Analysis Summary**

- **Golden channel, clean experimental signature**
  - Narrow peak in the 4l mass spectrum on top of a flat and small bkg
  - But small signal yield

- **Analysis performed in two categories**
  - untagged: ≤1 jets
  - tagged: ≥2 jets (p_T>30)
    - ~20% of signal events are VBF ones
    - no evidence for VBF signal events yet

- **Signal model:**
  - Empirical parametric shape from simulation
  - Corrected for data/simulation scale

- **Backgrounds:**
  - irreducible from simulation
    - empirical parametric shape
  - instrumental from data
    - two methods: from OS and SS events, ~40% uncert.

- **Key features:**
  - Lepton reconstruction
  - Zγ*→4l
  - Kinematic discriminants
**H → ZZ → 4l: Lepton Reconstruction**

- Off-shell Z in Higgs decay (40 < m\(Z_1\) < 120, 12 < m\(Z_2\) < 120 GeV)
- Need high efficiency down to \(p_T = 5\) (7) GeV for \(\mu\) (el)
  - measured with tag–and–probe on Z, MC corrected accordingly
- Final state radiation recovery using close–by photons
  - 1–3% efficiency gain
- Optimized lepton scale and resolution
  - narrow peak and better mass measurement
  - validation on resonances show data–MC differences of the order of 0.1% for scale and 20% for resolution
- Closure test on Z events, comparing computed resolution from lepton uncertainties and from mass peak fit
  - 10 categories with different expected mass resolution
  - assign 20% systematic error

**Predicted relative mass resolution**

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<tr>
<th>Predicted relative mass resolution</th>
<th>Measured relative mass resolution</th>
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**CMS Simulation, \(\sqrt{s} = 8\) TeV**

- H → ZZ\(^*\) → 2e2\(\mu\)
- \(m_H = 125\) GeV
- \(p_T\) before and after analysis selection

**CMS Preliminary**
- \(\sqrt{s} = 8\) TeV, \(L = 19.6\) fb\(^{-1}\)
- J/\(\Psi\), \(p_T\) = 5-7 GeV
- Z, p\(T\) = 20-45 GeV
- Z, p\(T\) = 45-90 GeV
- J/\(\Psi\), p\(T\) = 10-15 GeV
- \(Y\), p\(T\) = 10-20 GeV

**HIG–13–002**
**H→ZZ→4l: Zγ*→4l Candle**

- How well can we measure the properties of a resonance decaying into 4l?
- $Z\gamma^*\rightarrow 4l$ represents a natural candle for validating $H\rightarrow ZZ$ analysis features
- Verify that the relative uncertainty on $m_{4l}$ matches expectations
- Perform the mass measurement on $Z\gamma^*$ with identical procedure as for the new boson mass measurement
  - Relaxed phase space due to the limited statistics ($m_{Z2} > 4$ GeV)
- Measured $m_{4l} = 91.17\pm0.22$ GeV
  - PDG value of Z boson mass of 91.188 GeV

80<m_{4l}<100$ GeV

- Data
- $Z\gamma^*$

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**H→ZZ→4l: Kinematic Discriminants**

- Multiple kinematic variables can be used as signal/background or SM/BSM kinematic discriminant
  - fully reconstructed final state
- Discriminator $K_D$ to separate SM Higgs from backgrounds:
  - Use the ratio of LO matrix elements
  - Matrix elements computed using JHUGen and MCFM
    - validated with analytical parametrization, Madgraph, also BDT/BNN.
- Discriminator $D_{JP}$ to separate the SM Higgs hypothesis from an alternative $J^P$ hypothesis:

\[
K_D = \frac{p_{\text{kin}}}{p_{\text{kin}} + p_{\text{bkg}}} = \left[ 1 + \frac{p_{\text{kin}}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4\ell})}{p_{\text{kin}}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4\ell})} \right]^{-1}
\]

\[
D_{JP} = \frac{p_{\text{SM}}}{p_{\text{SM}} + p_{\text{bkg}}} = \left[ 1 + \frac{p_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4\ell})}{p_{\text{SM}}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4\ell})} \right]^{-1}
\]

\[
\vec{\Omega} = (\theta^*, \Phi_1, \theta_1, \theta_2, \Phi)
\]

**CMS preliminary** $\sqrt{s} = 7 \text{ TeV, } L = 5.1 \text{ fb}^{-1}$ $\sqrt{s} = 8 \text{ TeV, } L = 19.6 \text{ fb}^{-1}$

**HIG-13-002**
H→ZZ→4l: Results

- Limits, significance, signal strength: 3D fit on m_{4l}, K_D, p_T
  - significance = 6.7σ (7.2σ exp)
  - signal strength μ=0.91^{+0.30}_{-0.24}

- Mass measurement: 3D fit on m_{4l}, K_D, σ(m_{4l})
  - m_H = 125.8 ± 0.5 (stat.) ± 0.2 (syst.) GeV

- Spin/parity hypothesis: 2D fit on D_{bkg} and D_{JP}
  - where D_{bkg} combines m_{4l} and K_D information
  - tested various models with spin (0,1,2), parity (+,−) and production modes (gg or qq)
  - alternative models disfavored by data with respect to 0^+ (from 1.7σ to >4σ)
H→WW→2l2v: Analysis Summary

- Large signal yield but also large backgrounds
- No mass peak due to neutrinos
- Default analysis:
  - 2D fit in the \( m_T - m_{ll} \) plane for DF final state (0,1 jet)
    - uncorrelated variables
    - range for \( m_h < 300 \text{ GeV} \): 60 < \( M_T \) < 280 GeV, 12 < \( m_{ll} \) < 200 GeV
  - 2D fit used for spin–parity hypothesis testing
  - cut based for SF final state (0,1 jet)
    - \( m_h \)-dependent cut values
  - VBF channel for 2–jet bin
- Key features:
  - Background estimation
  - Systematics
  - 2D fit validation

\[
M_T = \sqrt{2 p_T^l \cdot \text{MET} \cdot (1 - \cos(\Delta \phi_{ll-\text{MET}}))}
\]

\( \mu p_T = 23.6 \text{ GeV} \)

\( \mu p_T = 38.7 \text{ GeV} \)

\( \text{MET} = 56.0 \text{ GeV} \)

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• Background control is crucial for this analysis
  - event count in signal region, no mass peak
  - WW (light blue): dominant background, irreducible, extends to higher m_{ll} and m_{T} regions
  - Top (yellow): largest background in 1–jet bin, small in 0–j
  - Wjets (grey): similar size and kinematic region as signal
  - W\gamma^* (grey): small but similar kinematic as signal

• WW background normalization is a free parameter in the 2D fit
  - fit constrains the dominant background from signal free regions

• Fully data–driven background estimation for most important backgrounds
  - Wjets – Method based on tight–to–loose lepton ID – 36%
    ‣ ratio derived on QCD, applied to dilepton events w/ one lepton failing ID
  - Top – Based on Njets and b–tagging – 20/5% (0/1–jet)
    ‣ measured on top enriched sample, applied on top tagged events
  - W\gamma^* – Measure k–factor in 3l sample – 30%
  - Backgrounds from MC: WZ/ZZ, W\gamma
  - Background estimation for cut based only:
    ‣ Drell–Yan (on–off Z peak, tight–loose MET), WW (low–high m_{ll})
H→WW→2l2v: Systematics and Fit Validation

- Systematics in the 2D fit are both normalization and shape variations
  - Correlated systematics: experimental measurements, theoretical uncertainties
  - Uncorrelated systematics: background normalizations
  - Shape variations done through a morphing parameter between alternative shapes
- Huge effort to validate and understand the fit results
- Full fit performed on data control regions
  - b-tagged events for top, same sign events for Wjets (fakes), WY and WY*
  - shapes compatible, nuisance parameters are stable, no artificial signal introduced
- Test fit model for WW background
  - two WW control regions, with large mT or large mll
  - predict WW shape in CR2 from fit results in other CR1
- Experiments with pseudo-data
  - no bias on signal, both under nominal conditions and with input bias on backgrounds
  - good compatibility between nuisance parameters pulls from toys and data fit
H→WW→2l2ν: Results

- Exclusion limits: 128–600 GeV (115–575 GeV exp.)
- Significance: 4.0σ (5.1σ expected)
  - broad excess, compatible with SM m_H=125 GeV
- Signal strength: μ = 0.76 ± 0.13 (stat.) ± 0.16 (syst.)
  - good compatibility across channels and datasets
- Spin–parity hypothesis test performed in 0/1–jet eμ categories
  - Model of spin–2 resonance, with minimal dibosons couplings
  - Compatibility: 0.5σ with 0^+, 1.3σ with 2^+ model
- Using SM Higgs as background no significant excess for m_X=100–600 GeV
VBF H→WW→2ℓ2ν

- Similar selection and background estimation techniques as in 0/1-jet analysis
- Requires ≥2 jets plus a VBF-topology selection:
  - $m_{jj}>500\text{ GeV}$, $\Delta\eta_{jj}>3.5$, central jet veto
- Analysis strategy:
  - Shape based (1D on $m_{ll}$) for different-flavor
  - Cut based for same-flavor
- Results (7+8 TeV, SF+DF):
  - Limit at $m_H=125\text{ GeV}$: 1.7 (1.1 exp.)
  - Significance: 1.3 (2.1 exp.)
  - Signal strength: $\mu=0.62^{+0.58}_{-0.47}$

![Diagram of VBF H→WW→2ℓ2ν](image)

![Histograms of VBF H→WW→2ℓ2ν](image)

![Graph of 95% CL limit on $\sigma/\sigma_{SM}$](image)
H→γγ: Overview

- High resolution fully reconstructed invariant mass
  - Large QCD backgrounds (γ–γ, γ–jet, jet–jet)
  - Small BR(H→γγ) ~ 0.1%
- 2 analyses: MVA–based and Cuts–in–Categories
- Separate events into classes to improve the analysis sensitivity and coupling measurements
  - 4 tagged categories, 4 untagged categories
- MVA diphoton categories:
  - Mass independent classification (BDT)
    - variables = diphoton kinematics (excluding m_{γγ}), evt diphoton mass resolution, photon ID
  - 4 categories in high–score region of BDT output
  - MVA ~15% better expected sensitivity wrt CiC
- Cut–in–Categories:
  - 4 categories: high/low R_9 (shower shape); EB / EE

![Diagram with categories and classifications](image)
**H → γγ: Results**

- Excess with observed significance of 3.2σ
  - 4.2σ expected
- Best fit strength $\sigma/\sigma_{\text{SM}} = 0.78^{+0.28}_{-0.26}$
  - $\mu(\text{ggH}+\text{ttH})=0.52$, $\mu(\text{qqH}+\text{VH})=1.48$
- Measured $m_H = 125.4 \pm 0.5(\text{stat.}) \pm 0.6(\text{syst.})$ GeV
- Cut-based analysis sees a slightly larger excess
  - $\sigma/\sigma_{\text{SM}} = 1.1^{+0.32}_{-0.30}$
  - the two results are compatible at 1.5σ level once correlations are properly taken into account
Other Results (Low Mass)

- Other production and decay modes needed to complete the picture for SM Higgs boson
  - VH production decaying into VWW
    - $3\ell 3\nu$ and $2j2\ell 2\nu$ final states
  - ttH production decaying into $\gamma\gamma$
    - All–hadronic and semileptonic $tt$ decays with loose selection and at least one $b$–tagged jet
- $Z\gamma$ decay (where $Z\rightarrow 2\ell$)
  - Similar approach as in $H\rightarrow \gamma\gamma$
- Need more data to probe SM in this channels!
High Mass Results

- Search for high-mass SM-like Higgs boson and explore modified couplings of an additional Higgs boson
- Combined high-mass ZZ search to full statistics
  - Including fully leptonic and semi-leptonic (where the other Z decays hadronically or invisible) final states
  - Probes SM-like heavy Higgs up to ~1 TeV
- Search in the $W(l\nu)W(\ell')$ channel in a boosted regime
  - Highly boosted $W$: its decay products are contained in one jet.
  - Jet substructure techniques are used in identifying the hadronically decaying $W$
  - Sensitive to Higgs masses above ~600 GeV

![Graph of H→ZZ combined 4l, 2l2ν, 2l2q](image1)

![Graph of H→WW→lνJ](image2)
Thank you!
backup
\( \sqrt{s} = 8 \text{TeV} \)

- VBF H \rightarrow \tau^+\tau^-
- \text{WH} \rightarrow l^+l^+b\bar{c}
- WW \rightarrow l^+q\bar{q}
- WW \rightarrow l^+l^+l^-
- ZZ \rightarrow l^+l^-q\bar{q}
- ZZ \rightarrow l^+l^-l^+l^-
- ZZ \rightarrow l^+l^-\nu\bar{\nu}
- ZH \rightarrow l^+l^-b\bar{b}
- \gamma\gamma
- t\bar{t}H \rightarrow t\bar{t}b\bar{b}
- t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^-

\( \sigma \times \text{BR} \text{[pb]} \) vs. \( M_H \text{[GeV]} \)
H→ZZ→4l: backgrounds

- **Irreducible background**
  - Empirical param. shapes from simulation
  - Corrected for data/simulation scale

- **Instrumental backgrounds estimated from data**
  - Extrapolation from samples enriched with misidentified leptons (iso+ID)

- **2 independent methods**
  - 2P+2F (2 pass + 2 fail) sample, dedicated correction for γ conversions in Z+γ+jets
  - 2P+2F & 3P+1F (3 pass + 1 fail) sample, measures contributions from Z+γ+jets & WZ+jets

- **Total uncertainty ~40%**
  - statistics, systematics of method/shape
H→ZZ→4l: spin parity results

<table>
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<tr>
<th>J'</th>
<th>production</th>
<th>comment</th>
<th>expect (μ=1)</th>
<th>obs. 0⁺</th>
<th>obs. J'⁺</th>
<th>CLₜₜ</th>
</tr>
</thead>
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<td>0⁻</td>
<td>g g → X</td>
<td>pseudoscalar</td>
<td>2.6σ (2.8σ)</td>
<td>0.5σ</td>
<td>3.3σ</td>
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<tr>
<td>0⁺</td>
<td>g g → X</td>
<td>higher dim operators</td>
<td>1.7σ (1.8σ)</td>
<td>0.0σ</td>
<td>1.7σ</td>
<td>8.1%</td>
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<tr>
<td>2⁻ₖ</td>
<td>g g → X</td>
<td>minimal couplings</td>
<td>1.8σ (1.9σ)</td>
<td>0.8σ</td>
<td>2.7σ</td>
<td>15%</td>
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<td>4.0σ</td>
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<td>&lt;0.1%</td>
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H\rightarrow ZZ\rightarrow 4l: more results

CMS Preliminary

$H\rightarrow ZZ\rightarrow 4l$

$\sqrt{s} = 7\,\text{TeV}$, $L = 5.1\,\text{fb}^{-1}$

$\sqrt{s} = 8\,\text{TeV}$, $L = 19.6\,\text{fb}^{-1}$

95% CL limit on $\sigma/\sigma_{SM}$

-2$\Delta$ ln $L$

Local $p$-value

CMS Preliminary

$H\rightarrow ZZ\rightarrow 4l$

$\sqrt{s} = 7\,\text{TeV}$, $L = 5.1\,\text{fb}^{-1}$

$\sqrt{s} = 8\,\text{TeV}$, $L = 19.6\,\text{fb}^{-1}$

$\mu_F$

Combined

$H\rightarrow ZZ\rightarrow 4e$

$H\rightarrow ZZ\rightarrow 4\mu$

$H\rightarrow ZZ\rightarrow 2\theta_2\mu$

68% CL

95% CL

- best fit

- SM

CMS preliminary $\sqrt{s} = 7\,\text{TeV}$, $L = 5.1\,\text{fb}^{-1}$; $\sqrt{s} = 8\,\text{TeV}$, $L = 19.6\,\text{fb}^{-1}$

$\sigma_{m_1}(1D - m_2) / \delta m_H = 0.60\,\text{GeV}$

$\sigma_{m_1}(2D - m_2 / \delta m_H) / K_D = 0.53\,\text{GeV}$

$\sigma_{m_1}(3D - m_2 / \delta m_H) / K_D = 0.48\,\text{GeV}$
**H→WW→2l2ν: Systematics**

- **Systematics in the 2D fit are both normalization and shape variations**
  - Correlated systematics: experimental measurements, theoretical uncertainties
  - Uncorrelated systematics: background normalizations or background model parameters from control regions
  - Shape variations done through a morphing parameter between alternative shapes (up and down variation)

- **Theoretical uncertainties on signal following LHC cross section recommendation**
  - PDF + higher order effects + UEPS: 20–30%

- **Instrumental**
  - Luminosity: 4.4% (8TeV), 2.2% (7 TeV)
  - Lepton identification and trigger efficiency: 3(4) % for muon (electron)
  - Lepton Energy/Momentum scale: 1.5% for muon, 2% (5%) for electron in barrel (endcap)
  - MET resolution: 2%, Jet energy scale: 2–10%

- **Shape variations**
  - Instrumental variation: list same as above
  - WW: QCD scale variation and different generators (Madgraph vs MC@NLO)
  - Top: different generators (Madgraph vs Powheg)
  - W+jets: different thresholds used in background estimation method

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**Wjets shape variations**
H→WW→2l2ν: More results
H→γγ: Photon reconstruction

• Single Crystal:
  - Crystal energy calibration: (CMS–PAS–EGM–11–001)
    ‣ transparency loss (laser)
    ‣ inter-calibration (Φ–symmetry, π0/η mass, E/p)

• SuperClustering

• Energy corrections:
  - regression (BDT target = E_{raw}/E_{true});
  - Input variables
    ‣ supercluster η/Φ
    ‣ shower shapes variables
      • R9 = E_{3x3}/E_{SC}; high R9 = γ unconverted, low R9 = γ converted
    ‣ number of vertices
    ‣ median energy density (ρ) per event

• Corrected SuperCluster

• Resolution stability within 0.1%
  - absolute energy scale + long term drifts
  - monitored with Z→e+e–

• Energy uncertainty (evt/evt):
  - regression (BDT target = correction regr − correction true)
  - Used in the MVA analysis
**H→γγ: Photon identification**

- **Preselection:**
  - electron-veto, H/E, loose Isolation, loose shower-shapes
  - $\varepsilon \sim 92\% - 99\%$, SF=1

- **MVA based photon ID:**
  - classification (BDT), variables:
    - $\eta$, shower-shapes
    - Particle flow isolation,
    - median energy density ($\rho$) per event
    - input to diphoton classification

- **Cut-based photon ID:**
  - optimized separately in 4 categories
  - high/low R9, EB/EE
  - variables: H/E, $\sigma\eta\eta$, PF isolation
H→γγ: Vertex assignment

- Running conditions:
  - \( <N_{\text{vtx}}> = 9.5 \) @ 7 TeV (\( \sigma_z = 6 \) cm)
  - \( <N_{\text{vtx}}> = 19.9 \) @ 8 TeV (\( \sigma_z = 5 \) cm)

- No tracking information for photons
  - use kinematics correlations + conversion direction

- MVA–based vertex ID:
  - classification (BDT), variables:
    - sum \( p_T^2 \)
    - tracks/diphoton balance,
    - sum \( p_T \)(tracks)–diphoton asymmetry

- if \( d(\text{vtx}_{\text{true}}–\text{vtx}_{\text{chosen}} < 1 \text{ cm}) \) vtx, contribution to \( \sigma_{\text{mass}} \) negligible
  \[
  m_{\gamma\gamma} = \sqrt{2E_1 E_2 (1 - \cos\theta)}
  \]

- MVA–based vertex probability:
  - classification (BDT)
  - BDT classifier to select events within 1cm
    - score proportional to the right–vertex probability
    - input to diphoton classification

\(<\text{eff}> \approx 80\%\)
H→γγ: Signal and Bkg Model

• Parametric signal model:
  - sum of gaussians
  - up to 3 gaussians depending on the category

• Background model
  - fit the data with different functional forms (sums of exponentials, sums of power law terms, Laurent series and polynomials)
  - choose the lowest order of the functional form fitting the data
    - p-value < 0.05 → “truth functions”
  - use the truth functions to throw toy-MC
  - choose the lowest order functional form such that bias on the signal strength <20% of the uncertainty on the background
    - systematics on the background shape can be neglected
  - Polynomials from 2–5 full fill the requirements
H→γγ: More Results

**MVA**

**CIC**

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