Searches for new Higgs bosons at CMS

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University of Illinois at Chicago and Fermilab

Workshop on Baryon and Lepton Number Violation
May 16, 2017
Introduction

- Discovery and first characterization of a Higgs boson was defining achievement of CMS and ATLAS in Run 1 of the LHC

- Additional Higgs bosons well-motivated and generically present in extensions of the Standard Model
  
  → Doublets and/or singlets, including in supersymmetry
  
  → Triplets as in left-right symmetric models (neutrino mass)
  
  → Connection between additional scalars and electroweak baryogenesis

- Extensive LHC searches, plus ever-improving measurements of the observed Higgs boson strongly constrain additional Higgs bosons

- Broad search program at CMS adapts accordingly
  
  → Cascades of multiple new Higgs bosons
  
  → Production by and decay to fermions
  
  → Invisible decays
  
  → Triplet models, including doubly-charged Higgs boson
Two-Higgs-doublet models
Two-Higgs-Doublet Model

- 2HDM is a workhorse of BSM Higgs physics
  - Second SU(2) doublet compared to the SM
    - Five physical particles: $h$, $H$, $H^\pm$, $A$
  - Compatible with electroweak baryogenesis
    - Can modify phase transition, include additional sources of CP violation
  - “Type 2” similar to Higgs sector of Supersymmetry

- Parameterized by $\tan \beta = v_2/v_1$ ratio of VEVs, and $\alpha$ = angle of rotation that diagonalizes the mass matrix of CP-even states

- $h$ and $H$ “share” couplings to SM fermions and vector bosons

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<thead>
<tr>
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<th>type 1</th>
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<tr>
<td>$W, Z$</td>
<td>up-type q</td>
<td>$\sin (\beta-\alpha)$</td>
<td>$\cos \alpha / \sin \beta$</td>
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<td>$- \sin \alpha / \cos \beta$</td>
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Pragmatist’s interpretation

2HDM strongly constrained by direct searches and indirectly by measurements of observed Higgs boson

→ Very good agreement in vector boson couplings
→ Suggests “alignment”: $H \rightarrow VV$ and $H^{\pm} \rightarrow WZ$ suppressed
→ and/or “decoupling”: additional particles very massive

<table>
<thead>
<tr>
<th></th>
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<th>$H^{\pm}$</th>
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<tr>
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<td>even</td>
<td>even</td>
<td>odd</td>
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<tr>
<td>couplings</td>
<td>SM-like</td>
<td>tt, (hh)</td>
<td>$\tau\nu$, $tb$, $bc$</td>
<td>$tt$, $bb$, $\tau\tau$, (Zh)</td>
</tr>
</tbody>
</table>

("pseudoscalar")
A $\rightarrow$ Zh

- Classic search for 2HDM
- Use $h \rightarrow bb$, largest branching ratio for light SM-like $h$
- Search for $llbb$ resonance

$A \rightarrow Zh \rightarrow \ell\ell b\bar{b}$ ($\ell = e, \mu$)  $L = 19.7$ fb$^{-1}$ (8 TeV)

CMS Low mass

95% CL limits
- Observed
- Excluded region
- Expected
- Expected ± 1σ
- Expected ± 2σ

Type-II 2HDM  $m_A = 300$ GeV

alignment limit

$\tan\beta$
h, H, A → ττ

- Any of h, H, A (= ϕ) can decay to τ pair
- Hadronic and leptonic decays in analysis

→ All-hadronic (τ_hτ_h) most sensitive for
  m_ϕ > 200, μτ_h for m_ϕ < 200 GeV

\[ m_T^{\text{tot}} = \sqrt{m_T(E_{T}^{\text{miss}}, \tau_1^{\text{vis}})^2 + m_T(E_{T}^{\text{miss}}, \tau_2^{\text{vis}})^2 + m_T(\tau_1^{\text{vis}}, \tau_2^{\text{vis}})^2} \]

HIG-16-037-pas
General 2-scalar search

- EW baryogenesis: look for $A \rightarrow ZH$, $H \rightarrow ZA$, not just $A \rightarrow Zh$
  - All of $H$, $A$, and $h$ decay to $b\bar{b}$ or $\tau\tau$
  - Release mass constraint on $m(b\bar{b})$ or $m(\tau\tau)$

CMS, 8 TeV
1603.02991
~1.5$\sigma$ excess
General 2-scalar search

for $\tan(\beta) = 1.5$, $\cos(\beta - \alpha) = 0.01$, 
scan mass:

for a given mass, 
scan parameter space:
H/A $\rightarrow$ invisible

- “Invisible” means missing transverse momentum
  $\rightarrow$ Identify as Higgs production via production mode

- Designed for $h[125]$, but sensitive to a pseudoscalar and/or heavy Higgs boson: discriminating variables sensitive to production mechanism but not mass of particle produced
Run 2: Raised trigger thresholds (pileup) limit 13 TeV analysis
  → example: VBF-channel MET threshold raised 90 → 200 GeV

Leading systematics theoretical: BG extrapolation from control regions

It will take some time for Run 2 to catch up

VBF ("qqH") channel most sensitive

BR (H → invis.) < 0.24 at 95% CL (0.23 expected)
Charged Higgs to $\tau\nu$

- Decay to fermions preferred in alignment limit
- Produce via $tHb$ coupling if $m_{H^+} > M_t$
- In top-quark decay if $m_{H^+} < M_t$
- All-hadronic: $\tau_h + E_T^{miss} + 3$ jets
  - $\tau_h + E_T^{miss}$ trigger
  - Discriminant: $\tau_h + E_T^{miss}$ transverse mass ($m_\tau$)
  - Key background $\tau$ from mis-ID at high transverse mass
Charged Higgs to $\tau\nu$

- Heavy $H^+$: limits out to $m_{H^+} = 3$ TeV ($\sigma \times \text{BR} < 3$ fb @ 95% CL)
- Challenging interpretation for light $H^+$: constraints from $b \rightarrow s\gamma$ and Higgs mass in SUSY interp.
Leptonic decay of other top quark
→ $e/\mu + E_T^{\text{miss}} + 4$ jets (2 or more $b$-tagged)
→ Background almost all $t\bar{t}$
  - Signal has one more $b$-jet (3 total)

Kinematic fitter assigns jets to quarks
→ No $W$-mass constraint on hadronic side
→ top-specific jet energy corrections
beyond the 2HDM-scape
h decay to light singlet

- Light (pseudo)scalar appears in many models: nMSSM, 2HDM+S, technically possible in 2HDM alone
- Decays to fermions (μμ, ττ, bb) have challenging backgrounds
- For \( m_a < 2m_h \), workaround: look for \( h[125] \rightarrow aa \)

Stats-limited, much to be learned in Run 2 and beyond

1701.02032 [hep-ex]

\[ m_a \ (GeV) \]
Light scalar decay to muons

- $h \rightarrow 2a \rightarrow 4\mu$ motivated by nMSSM; 13 TeV update of result in prev. slide
  
  $\rightarrow$ Require consistent invariant mass for the muon pairs but no constraint on $m_{4\mu}$
  
  $\rightarrow$ Scan dimuon mass $0.25 < m_{2\mu} < 8.5$ GeV and four-$\mu$ mass $86 < m_{4\mu} < 150$ GeV

- One candidate event at $(m_1, m_2) = (0.40, 0.56)$ GeV
- $0.74 -0.35 +0.46$ background events expected (dominant background is b-bbar)
Light scalar decay to muons

- b-associated production, new 8 TeV analysis
  - 2 muons, one may be soft ($p_T > 5$ GeV), one b-jet (second may be soft)
  - Competitive with $a \rightarrow \tau \tau$ even if lower BR
Higgs triplet models

• SU(2) triplet rather than doublet or singlet
  → Need UV completion, issues w/custodial symmetry

• Appears in Left-Right symmetric models
  → Higgs sector may be kinematically out of reach in proper L-R symmetric model (1612.09146)

• Also in “type II seesaw models” for generating neutrino masses…

• Extra scalar content / VEV can affect the electroweak phase transition (see 1108.4416)

• Distinctive particle content:

  \[
  H \quad H^\pm \quad H^{\pm\pm}
  \]
Doubly-charged H @CMS

- Analysis using in same-charge leptons, 3- and 4-lepton events
- Also sensitive to $H^{++} \rightarrow W^+W^+$, but not explicitly targeted
  - Semi-leptonic searches for heavy $H \rightarrow WW \rightarrow l\nu jj$ also in principle sensitive

same-charge lepton spectra:
H⁺ via vector-boson fusion

- 3 charged leptons $\rightarrow$ dominant WZ background (QCD and EWK)
- Interpretation in triplet model
  $\rightarrow$ alignment limit $\rightarrow$ no 2HDM
  $\rightarrow$ $s_H^2 =$ fraction of W boson mass squared generated by triplet vev

$$m_{T(WZ)} = \sqrt{(E_T(W) + E_T(Z))^2 - (p_T(W) + p_T(Z))^2}$$

1705.02942
Summary

- Strong motivations to search for extended Higgs sector
  - Cover all decay and production modes
  - 2HDM constraints suggest focus on fermions
  - Doesn’t have to look like the 2HDM
    - Singlets and triplets may also have a role

- Will be a rich program for the life of the LHC – many measurements just getting interesting
  - Detailed Run 1 analysis mostly complete
  - Many Run 2 analyses in place
  - 50x the data yet to come
backup
H/A → ttbar

- Cannot be interpreted as a heavy Higgs search

**Background:**
- g \rightarrow t \bar{t}

**Signal:**
- g \rightarrow H, A \rightarrow t \bar{t}

**Pseudoscalar**

<table>
<thead>
<tr>
<th>Events / 10 GeV</th>
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<tbody>
<tr>
<td>14</td>
</tr>
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**Scalar**

<table>
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<tr>
<th>Events / 10 GeV</th>
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<tr>
<td>10</td>
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**ATLAS Simulation Preliminary**

\( \mathcal{L} = 8 \text{ TeV}, \int \mathcal{L} dt = 20.3 \text{ fb}^{-1} \)

- Before det. sim. and event sel.
- \( m_A = 500 \text{ GeV}, \tan \beta = 0.70 \)

\( m_H, m_A \) [GeV]
Just starting to dip into relevant parameter space

- Exclude $\tan\beta < 0.85$ for $m_A = 500$ GeV
- Exclude $\tan\beta < 0.45$ for $m_H = 500$ GeV

$m_A = 750$ GeV
from ATLAS-CONF-2016-073
Indirect Constraints

- Implication of “shared” couplings: observed Higgs boson must be one of h or H

- Compatibility with SM constrains parameters
  \[ \text{The better the measurement, the stronger the constraint for the corresponding channel} \]

- “alignment” = \( \cos(\beta - \alpha) = 0 \) and h is SM-like

- Many such studies covering the parameter space,….
Run 1 is just the beginning

H → WW, the most precise single-channel measurement*, total uncertainty ~20%

Rare but important ZH, ttH production modes still to be established

* Just recently edged out by Run 2 preliminary measurement

H → bb has highest branching ratio, still not observed
The CMS Detector

CMS DETECTOR
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

STEEL RETURN YOKE
- 12,500 tonnes

SILICON TRACKERS
- Pixel (100x150 μm): ~16 m² ~66M channels
- Microstrips (80x180 μm): ~200 m² ~9.6M channels

SUPERCONDUCTING SOLENOID
- Niobium titanium coil carrying ~18,000 A

MUON CHAMBERS
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
- Silicon strips: ~16 m² ~137,000 channels

FORWARD CALORIMETER
- Steel + Quartz fibres: ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
- Brass + Plastic scintillator: ~7,000 channels

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