Search for Higgs Bosons
Beyond the Standard Model

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Photo: Eleni Ntomari
H(125) = Standard Model Higgs?

- Most relevant question after discovery of a Higgs boson at ~125 GeV:
  - structure of the Higgs sector
  - are there additional Higgs bosons?
- At the level of current measurements, the observed state is compatible with the Standard Model Higgs
  - but SM features quadratically divergent self-energy corrections at high energies (Hierarchy problem)
  - many other open questions: dark matter, CP violation in early universe, …
  - SM very likely incomplete
- Concluding from the Higgs couplings analysis, there is still plenty of room for non-SM decays of the H(125)
  - $\text{BR}_{\text{BSM}} < 32\%$ at 95\% CL
  - assuming no modification at tree-level
Fingerprints of Extended Higgs Sectors

- Heavy Neutral Higgs: $\phi \rightarrow \tau\tau$
- Invisible Higgs Decays: ZH and VBF
- Charged Higgs: $H^+ \rightarrow cs$
- Lepton-Flavor Violating Higgs Decays: $H \rightarrow \mu\tau$
- Resonant Higgs Pair Production: $X \rightarrow HH \rightarrow (\gamma\gamma)bb$

(N)MSSM, 2HDM, WED*, SUSY, WED*

*Warped Extra Dimensions
(N)MSSM Higgs Sectors

- Supersymmetry presents an elegant solution to the quadratic divergences in the Higgs mass corrections → cancellation by super partners
  - requires additional Higgs bosons
- Minimal supersymmetric extension (MSSM) features two complex Higgs doublets
  - Five physical Higgs bosons
    - three neutral: h, H, A
      - CP-even
      - CP-odd
      - denoted $\Phi$
    - two charged: $H^\pm$
    - two tree-level parameters: $m_A$ and $\tan \beta$
- Next-to-Minimal Supersymmetric Model (NMSSM):
  - two complex Higgs doublets + additional scalar field
    - seven physical Higgs states, which are mixtures:
      - $h_1, h_2, h_3, a_1, a_2, h^\pm$
      - CP-even
      - CP-odd

Usually identify $h \equiv H(125)$

$h_1$ or $h_2 \equiv H(125)$?
Other Models

- **Two-Higgs Doublet Models (2HDM)**
  - Effective theory; extension of SM by adding a second complex Higgs doublet
  - Five Higgs bosons: $h$, $H$, $A$, $H^\pm$
  - Flavor conservation can be enforced via symmetries
    - Four types of 2HDM, depending on the way the Higgs doublets couple
  - MSSM Higgs structure corresponds to a Type II 2HDM
  - Flavor-changing Yukawa couplings are in principle possible (Type III models)

- **Models inspired by Warped Extra Dimensions (WED, Randall-Sundrum model)**
  - Predict new heavy particles ($m_X > 2m_H$) that can decay to a pair of Higgs bosons
  - Examples:
    - Radion (spin 0)
    - First Kaluza-Klein excitation of the graviton (spin 2)

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2HDM with natural flavor conservation:

<table>
<thead>
<tr>
<th>Model</th>
<th>$u^i_R$</th>
<th>$d^i_R$</th>
<th>$e^i_R$</th>
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<td>Type I</td>
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<td>$\phi_2$</td>
<td>$\phi_2$</td>
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<td>Flipped</td>
<td>$\phi_2$</td>
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</tbody>
</table>

Heavy Neutral $\Phi \rightarrow \tau\tau$

- Good compromise between relatively large BR and manageable backgrounds
- Analysis covers five of six possible $\tau\tau$ decay patterns: e+$\mu$, e+had, $\mu$+had, had+had, $\mu$+$\mu$
- Production: gg fusion + b-associated
- Mass of $\tau$ pair is reconstructed from visible $\tau$ decay products and missing $E_T$
  - maximum likelihood technique
- Main backgrounds (in broad strokes – may differ from channel to channel):
  - $Z\rightarrow\tau\tau$:
    - embedding technique: take $Z\rightarrow\mu\mu$ from data, replace $\mu$’s by simulated $\tau$ decays
  - $Z\rightarrow\mu\mu$: suppress using the distance of closest approach (DCA)
  - $t\bar{t}$ and di-boson
  - QCD multijet, W+jets

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### Production mechanisms & event categories

<table>
<thead>
<tr>
<th>B-Tag</th>
<th>No B-Tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>at least 1 b-tagged jet</td>
<td>no b-tagged jet</td>
</tr>
<tr>
<td>associated production</td>
<td>gluon-gluon fusion</td>
</tr>
<tr>
<td>$g g \rightarrow \tau\tau$</td>
<td>$g g \rightarrow \tau\tau$</td>
</tr>
<tr>
<td>$b$</td>
<td>$b$</td>
</tr>
<tr>
<td>$H(A)$</td>
<td>$H(A)$</td>
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Background compositions differ significantly across the various decay channels.

All distributions well described by background hypothesis.
\( \Phi \rightarrow \tau\tau: \) Cross Section Limits

- Separate for the two production mechanisms
- Expected limits take a SM H(125) into account
→ Very low $\tan \beta$ upper limits ($\tan \beta < 5$ for $m_A < 250$ GeV !)
  ● touching the LEP constraint at low $m_A$. Presence of $H(125)$ weakens the MSSM limits
→ Latest interpretation (right) takes implications of $H(125)$ explicitly into account
→ $m_h^{\text{mod}}$ scenario [1]: better suited for known mass of $H(125)$, than $m_h^{\text{max}}$ scenario

Charged Higgs (H$^+ \rightarrow c\bar{s}$)

- H$^+ \rightarrow c\bar{s}$ dominant decay mode for $\tan \beta < 1$ and $m(H^+) < m_t$
- Same topology as $t\bar{t}$ decays in lepton + jets channel
  - Search for second peak in the di-jet mass distribution

**Event selection:**
- isolated muon, $\geq 4$ jets ($\geq 2$ b-tagged)
- $E_T^{miss} > 20$ GeV $\rightarrow$ suppress QCD, Z+jets
- $M_{jj}$ : invariant mass of non-b-tagged jets
- Kinematic fit $\rightarrow$ both top candidates $m=172.5$ GeV
  - improves mass resolution of $c\bar{s}$ candidate
- Backgrounds: $t\bar{t}$, W/Z+jets, di-bosons, QCD

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**CMS Simulation, $\sqrt{s} = 8$ TeV**

**Standard $t\bar{t}$ semi-leptonic**

**H$^+$ production in top decays**
H$^+ \rightarrow c\bar{s}$ (cont'd)

- $M_{jj}$ distribution after kinematic fit $\rightarrow$ no signal

- Determine $\text{BR}(t \rightarrow bH^+)$ assuming $\text{BR}(H^+ \rightarrow c\bar{s})=100\%$
  - observed upper limit of 2-3% in the range 100-150 GeV
  - applies to any BSM resonance with the corresponding production & decay topology
Lepton-Flavor Violating Higgs Decays

- Forbidden in the SM, but in principle possible in general 2HDM, composite Higgs and Randall-Sundrum models
  - this search focuses on $H \rightarrow \mu \tau$
  - direct search in $\mu \tau_e$ and $\mu \tau_{\text{had}}$ decay modes
  - signatures similar to $H \rightarrow \tau\tau$ searches, but kinematics differ

- Selection:
  - isolated muon + isolated electron ($\mu \tau_e$) or hadronic tau candidate ($\mu \tau_{\text{had}}$)
  - categorize according to #jets

- Signal variable: "collinear mass", reconstructed from visible decay products
LFV $H \rightarrow \mu \tau$ Mass Distributions

0-jet

1-jet

2-jet (VBF)

$\mu \tau_e$

$\mu \tau_{\text{had}}$
BR(H → μτ) < 1.57% observed (0.75% exp'td)

- best fit: BR(H → μτ) = (0.89^{+0.40}_{-0.37})% 

- We observe a mild excess of ~2.5 σ

- still compatible with Standard Model

- Significant improvement (4.4x) wrt. existing indirect measurements

- Best limits on τ anomalous Yukawa couplings to date
In the SM, rate of Higgs pair production is very small.

But resonant pair production, motivated by BSM physics, can already be probed with existing dataset:

- Heavy (N)MSSM Higgs decaying to pair of H(125)
- Radion or Kaluza-Klein excitation of graviton (Warped Extra Dimensions)

Combine H(125) decay channels $b\bar{b}$ (large BR) and $\gamma\gamma$ (good mass resolution).

→ selections similar to SM analyses

Mass-constraint fit on $b\bar{b}$ candidate, using known H(125) mass:

→ significant improvement of $m_X$ resolution

→ essential to suppress the SM $H \rightarrow \gamma\gamma$ background
Signal searched in $m_{\gamma\gamma}$ distribution for low $m_X$ (260—400 GeV), and in $m_{\gamma\gamma\text{kin}}$ for high $m_X$ (400—1100 GeV)
- beyond 1100 GeV, increased merging of $b\bar{b}$ pair into single fat jet

Medium and High Purity selections
- $b$-tagging on one or both legs of the di-jet candidate
- $85 < m_{jj} < 155$ GeV
- QCD background low due to required $\gamma$’s

Exclude radions with $m<970$ GeV for the radion scale $\Lambda_R=1$ TeV
Exclude RS1 KK-graviton in mass range 340—400 GeV.
Invisible Higgs Decays

- Invisible Higgs decay modes may be possible through:
  - decays to neutralinos (in supersymmetric models)
  - via graviscalars (in models with extra dimensions)
- Analysis of couplings only constrain invisible modes at best to $\leq 32\%$ (assumptions-dependent)
- Can we directly search for invisible Higgs decays?
  - Yes, if the Higgs is accompanied by something visible!

Reminder:

- Vector boson fusion (VBF):
- Vector boson-associated production (VH):

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Invisible Higgs (VBF)

- Cross section in VBF higher than in ZH production
  - signature: two jets + large missing energy
  - central jet veto
- Main background: V+jets, where the vector boson is not seen
  - e.g. $Z \rightarrow \nu\nu$
  - estimated by selecting Z+jets events in visible decay modes, and removing the Z decay products from the event
- Signal analyzed in variables missing $E_T$ and di-jet mass

$\rightarrow$ Data in good agreement with SM backgrounds
Invisible Higgs Combination

- **Invisible BR_{inv} < 58%** observed (44% expected) for a SM Higgs @ 125 GeV (95% C.L.)

  ➔ **Significant improvement** relative to earlier direct searches

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Dark Matter Interpretation

- **Higgs-portal model of DM interactions** → hidden sector with stable DM particles
  - if mass below $m_H/2$, might contribute to $\Gamma_{\text{inv}}$ of Higgs boson

- Complementary to direct DM-detection, sensitive to DM-nucleon cross section
  - Convert $\text{BR}_{\text{inv}}$ to DM-nucleon cross section, assuming $\Gamma_{\text{SM}}$ for total Higgs boson decay width
    - three spin assumptions for DM
  - Attractive limits up to $m_H/2$
Summary

- Addressing the fundamental question whether the observed H(125) is just one member of an extended Higgs sector → potential window into New Physics

- Many new results on key signatures:
  - neutral heavy Higgs (H → ττ): closing the lower mA mass range
    - large mA and tan β still possible. New interpretation takes H(125) into account
  - charged Higgs (t → bH⁺): results in H⁺ → c̅s channel complements H⁺ → τνₜ searches
  - lepton flavor violation (H → μτ): considerably improved limits on anomalous Yukawa couplings
  - resonant Higgs pair production (X → HH → (b̅b)(γγ)): excludes significant parameter range for radion models
  - invisible Higgs search: new combination gives improved upper limits
    - also interpreted in Higgs-portal model of Dark Matter

- 13 TeV running will further extend the reach, especially towards higher masses, and scrutinize further the properties of the H(125)

→ A rich research program for the future
Backup
H^+ \rightarrow c\bar{s} \ (cont'd)

- Control distribution: m_T (\mu^+ E_T^{\text{miss}})
  - good description of BG

- M_{jj} distribution after kinematic fit
  - no indication for H^+ signal

CMS Preliminary, \sqrt{s} = 8 \text{ TeV}, 19.7 \text{ fb}^{-1}

![Control distribution and M_{jj} distribution graphs]
Invisible Higgs (VBF+ZH)

\[ \sigma \times BR \text{ (absolute):} \]

\[ \text{Relative to } \sigma_{\text{SM}}: \]

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<td>$- \cot \beta$</td>
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**Φ → ττ: Categories & Channels**

- “No B-Tag” category has slightly higher sensitivity
- Combination of all channels and categories leads to best sensitivity
MSSM Higgs: Production & Decay

- Of three neutral MSSM Higgs bosons, must identify one as the "observed" H(125)
  - usually assign the lightest neutral boson: h
  - ~Standard-Model-like properties
- Look for additional, heavy Higgs bosons H and A
- Cross sections enhanced with increasing $\tan \beta$
  - Main decay modes: $b\bar{b}$ (~ 90%) and $\tau \bar{\tau}$ (~ 10%) for moderately large $\tan \beta$
  - in contrast to SM Higgs, these decay modes dominate even at large masses
The mass of the CP-odd Higgs boson A is usually ~ degenerate with one of the CP-even bosons:
- \( m_A \approx m_H \) for \( m_A \gg m_h^{\text{max}} \)
- \( m_A \approx m_h \) for \( m_A \ll m_h^{\text{max}} \)

With the exception of the \( \mu\mu \) channel, this degeneracy cannot be resolved within the mass resolution:
- visible cross section effectively doubles

Together with the effect of the Higgs coupling to b quarks, visible cross sections in b-associated production are typically enhanced by a factor of \( \approx 2 \tan^2 \beta \)
Reconstruction of Physics Objects

- Particle flow technique for optimized reconstruction of all particles in the event
  - extensive combination of all CMS detector systems

- Muon: matching tracks in inner tracker & muon chambers

- Electron: EM cluster with associated track

- Photon: EM cluster without associated track

- Jet: anti-$k_T$ algorithm applied to particle flow objects

- Tau lepton (had): narrow jet ("hadron + strips" algorithm)

- b-Tagging: combined secondary vertex algorithm (CSV), discriminant based on
  - track impact parameters
  - secondary vertices inside jets
MSSM Benchmark Scenarios

- $m_h^{\text{max}}$: Designed to yield the maximum value of the light MSSM Higgs mass, $m_h$
  - $M_{\text{SUSY}} = 1$ TeV
  - $X_t = 2M_{\text{SUSY}}$
  - $\mu = 200$ GeV
  - $M_{\text{gluino}} = 1500$ GeV
  - $M_2 = 200$ GeV
  - $A_b = A_t = A_\tau$
  - $M_3 = 1000$ GeV

- $m_h^{\text{mod+}}$: reduced stop mixing parameter to $X_T = 1.5 M_{\text{SUSY}}$ in view of measured $H(125)$, compatible with muon g-2

Limits on the BR

- Expected limit for $H \to \mu \tau$: 0.75% (95% C.L.)
  - observed limit: 1.57%
- We observe a mild excess at $\sim 2.5 \sigma$