The Standard Model Higgs and beyond

✓ The Higgs boson and beyond
✓ (Charged Higgs in top quark decays)
✓ BSM Higgs: light pseudo-scalar, non-SM Higgs decay
✓ Higgs boson and Dark Matter
H → ZZ → 4e, 4μ, 2e2μ

- Signal: 4 isolated leptons from same vertex
  - Small background
  - Fully reconstructed, mass resolution ~1%

The golden channel
2012: A new boson discovery
July 4th, 2012: A Higgs boson

First observations of a new particle in the search for the Standard Model Higgs boson at the LHC.

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Higgs boson

• Progress since Higgs discovery (July 2012)
  – Observation in boson channels
  – Evidence for fermion couplings
  – Precision mass measurement (~125 GeV)
  – Spin determined

• It looks more like SM Higgs boson

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Mass in the individual channels

- Most accurate measurement in the $\gamma\gamma$ and 4l channels
- Some “tension” between the four measurements (p-value ~10%)
Couplings: individual channels

Results based on the full Run 1 data samples

\[ \mu = 1.09^{+0.11}_{-0.10} \]
Search for rare decays

$H \rightarrow \ell \ell \gamma$

$S/B \sim 1:40$

$H \rightarrow ee, \mu\mu$

$S/B \sim 1:150$

$H \rightarrow \text{invisible}$ (difficult at LHC)

$B(H \rightarrow \text{inv}) \sim 0.0011$

$H \rightarrow J/\psi \gamma$, and $H \rightarrow Y^+ \gamma$

$B(H \rightarrow J/\psi \gamma, Y^+ \gamma) \sim 2.8 \times 10^{-6}$
Standard Model theory of everything?

• Discovery of the Higgs boson marks the triumph of the SM
• However, even with the inclusion of the Higgs boson, SM is an incomplete theory
Beyond the Standard Model

The SM answers many of the questions about the structure of matter. But SM is not complete; still many unanswered questions:

a) Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?

b) What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

c) Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

d) Why are there three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

e) How does gravity fit into all of this?
Higgs and BSM

• Is there BSM physics hidden in the “Higgs sector”?

Strategy: parametrize deviations wrt SM in production and decay ⇒ loops are sensitive to BSM physics

Experimental approach

• Measure H(125) properties
• Search for additional Higgs bosons
• Search for BSM in signatures with Higgs bosons
• Search for BSM Higgs decays
Looking for new particles

- Constrain $\text{BR}_{\text{BSM}}$ in a scenario with free parameters
- $\Gamma_{\text{tot}} = \Gamma_{WW} + \Gamma_{ZZ} + \Gamma_{bb} + \ldots + \Gamma_{\text{BSM}}$
- Likelihood scan vs $\text{BR}_{\text{BSM}}$
- Assuming couplings bound by SM expectations ($k_\nu < 1$)
- $0 \leq \text{BR}_{\text{BSM}} \leq 0.34$ at 95%CL
BR_{BSM} can be measured

BR_{BSM} < 0.34 at 95% C.L. (assuming \( \kappa_V \leq 1 \))

BR_{BSM} includes non standard decays, visible or invisible

\( \Rightarrow \) Results in agreement with SM \((k_V=k_F=1)\) within \(1\sigma\)
High mass: $H \rightarrow WW/ZZ$

- Search for a heavy Higgs boson
  - $H \rightarrow ZZ \rightarrow 4\ell, 2\ell 2\nu, 2\ell qq$
  - $H \rightarrow WW \rightarrow 2\ell 2\nu, 2\ell qq$
- Optimized separately for VBF and gluon fusion production processes
- SM-like Higgs boson excluded in $4\ell$ and $2\ell 2\nu/2\ell qq$ channels at 95%CL in mass ranges up to 1000 GeV
- Search interpreted in BSM scenario (heavy Higgs, heavy EWK singlet state)
  - Evolution of signal strength of the singlet state with modified couplings/width wrt SM.
  - Assume new scalar does not decay to any new particle

No significant excess
\[ \Rightarrow \text{set limits: } \sigma \cdot B(X \rightarrow ZZ \rightarrow 4\ell) \]
\[ \sim \text{a few fb at } m_X=400\text{GeV} \]
\[ \sim 1\text{fb at } m_X=1\text{TeV} \]

High-mass searches improve at 13TeV
Extending searches

• Minimal Supersymmetric SM (MSSM)
  – Neutral Higgs: $\phi \rightarrow \tau \tau / bb / \mu \mu$
  – Charged Higgs

• Next-to-MSSM
  – Light pseudoscalar: $h \rightarrow aa$
  – Non-SM decays: $h \rightarrow 2a \rightarrow 4\tau / 4\mu$
  – Heavy Higgs: $H \rightarrow h_{125} h_{125}$ or $A \rightarrow Zh_{125}$

• FCNC: $t \rightarrow cH$
Higgs sector in the MSSM

Higgs sector in SUSY contains two scalar doublets:

- **5 physical Higgs bosons**
  - 3 neutral: CP-even $\phi=h,H$ CP-odd $A$
  - 2 charged $H^\pm$

- **SM-like Higgs boson: $h$**

Neutral Higgs $\phi$ decay modes:

- $\text{BR}(\phi \rightarrow b\bar{b}) \sim 90\%$
- $\text{BR}(\phi \rightarrow \tau\tau) \sim 10\%$
- $\text{BR}(\phi \rightarrow \mu\mu) \sim 0.1\%$

Two main production modes:

- $gg \rightarrow H$
- $bbH$
Neutral MSSM Higgs

- Enhanced couplings of MSSM Higgs to down-type fermions (large $\tan\beta$)
  \[ \Rightarrow \text{increased BR to } \tau \text{ leptons and } b\text{-quarks} \]

- Search for neutral MSSM Higgs boson
- 5 final states used: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, $e\mu$, $\mu\mu$
  - Reconstruct tau-pair invariant mass
  - Split in b-tag/no b-tag categories to enhance sensitivity
- Main backgrounds: $Z\rightarrow\tau\tau$, QCD/W+jets, DY, ttbar, dibosons

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Neutral MSSM Higgs: $\phi \rightarrow \tau\tau$

- Direct search: inclusive and b-tagged
- $\tau$ in both leptonic and hadronic decays

Model-independent limits by separating production modes

No significant excess over bkg expectations

$\tan\beta$ vs $m_A$ window becoming smaller

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Neutral MSSM Higgs: $\phi \rightarrow \mu \mu$

- Search for a $\mu \mu$ mass resonance
- Good mass resolution
  - full and clean reconstructed final state
- Split in b-tagged and non b-tagged categories to be sensitive to $gg\rightarrow \phi$ and $bb\phi$ production modes
- Main backgrounds: $Z(\text{bbar})$, $tt\bar{t}$, $WW$

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Charged Higgs

- If found, a clear indication of BSM
- Study non-SM Higgs in two mass regimes:
  - $m_H < m_{\text{top}}$
    - Mostly produced in top quark decays
    - Large $\tan\beta$: $H^\pm \rightarrow \tau^+\nu$
    - Small $\tan\beta$ (<1): $H^+ \rightarrow c\bar{s}$
  - $m_H > m_{\text{top}}$
    - Produced in gluon-gluon fusion
    - Main decays: $H^+ \rightarrow t\bar{b}$, $H^+ \rightarrow \tau^+\nu$
- Main backgrounds: ttbar, W+jets
Charged Higgs (cont.)

- Different strategies for low- and high-mass searches
- tau+lepton, lep+jets, and e\(\mu\) final states
- b-tagged jet categorization
- limited by statistics at high-mass

\[ m_H < m_{top} \] 

\[ m_H > m_{top} \]
Look for charged Higgs in four final states:

- Tau+lepton (electron or muon)
- Dilepton (tau decays leptonically)
- lepton+jets
- Fully hadronic: tau+jets
Looking at tau decays

Low $H^+$ mass:

- Use R variable in the limit extraction: binned maximum-likelihood fit
- Tau fake component is data-driven, includes uncertainties

![Diagrams showing SM vs BSM processes](image.png)
Number of b-tagged jets

High-mass H⁺ search: look at b-tag multiplicity
Is there a charged Higgs?

- If anomalous tau/lepton production in ttbar decays there may be contribution from $H^+$

  Yields in agreement with expectations $\Rightarrow$ set limits

$m_{H^+}$: 80-160 GeV  \quad B(t \to bH^+) < 1.2-0.3\%$

200-600 GeV  \quad \sigma(pp \to \bar{t}(b)H^+) < 2.0-0.2 \text{ pb}$

At 13TeV, expect improvement with 5-10/fb for $m_{H^+} > 300\text{GeV}$

$\Rightarrow$ ttbar xsection increases x3.3

$\Rightarrow$ signal increases x6(x7) for $m_{H^+} =$500(600)GeV

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Still hope for MSSM?

- A new modified MSSM scenario: $m_{h}^{\text{mod}}$ (arXiv:1302.7033)
- Reduce amount of mixing in the stop sector ($X_{t}/M_{\text{SUSY}}$)
- A/H decays to chargino/neutralinos allowed (arXiv:0709.1029)
- Allows for reduction of decays into $\tau\tau$ and $bb$
Cross section ratios

Many systematic uncertainties cancel in the ratio.

Study of cross section ratios is sensitive to BSM.

1. $\text{BR}(\ell+\text{jets})/\text{BR}(\ell\ell)$
2. $\text{BR}(\ell+\tau)/\text{BR}(\ell\ell)$

![Graph showing cross section ratios and Higgs boson mass peaks]
Combination of more channels

- Search for charged Higgs boson
- Use $\tau_{\text{had}}^{\pm} + \text{lep}$ and $\tau_{\text{had}} + \text{jets}$ final states
  - compare to $e\mu$ yields
- Search for anomalous decays

ATLAS Simulation

Set limits on:

\[ \mathcal{B}(t \rightarrow bH^+) \]
Light charged Higgs: csbar

- \( H \rightarrow \text{csbar} \) decay
  - dominant in low \( \tan \beta \) region
- Lepton+jet final states
- Dominant bkg from ttbar
- Kinematic fit to reconstruct W/H mass
- Set model-independent limits on \( \text{BR}(t \rightarrow H^+ b) \sim 2-7\% \)

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Doubly charged Higgs

• Model
  – SM extended with scalar triplet ($\Phi^{++}$, $\Phi^+$, $\Phi^0$)
  – Triplet responsible for neutrino masses
  – Search for doubly- and singly-charged
  – DY pair production is most common
  – SS lepton pair of any flavor combination

• Search with $\geq 3$ leptons of any flavor
  – Search for excess of events in one or more flavor combinations of SS lepton pairs

• Dilepton invariant mass as discriminant
non-SM Higgs decay: $h \rightarrow aa \rightarrow 4X$

- Standard search for light (pseudo)-scalar Higgs with $m_a < m_h/2$
  - generic prediction of BSM theories (extended Higgs sector, NMSSM, etc)
  - Final states go to fermions ($b, \tau, \mu, \ldots$)
  - BR depends on boson mass, model parameters
**non-SM Higgs decay: h \rightarrow aa \rightarrow 4\mu**

- Explore non-SM decays of a Higgs boson (h)
  - Higgs boson (h) can be SM or not
  - include production of two new light boson (a^0)
- Search for generic Higgs decays: h \rightarrow 2a+X \rightarrow 4\mu+X
  - Require two dimuon pairs with consistent masses
  - Observe 9 events in off-diagonal region
  - Signal region: 1 event (2.2\pm0.7 bkg)
  - Limits on production rates, benchmark models
Results interpreted in NMSSM and dark SUSY

- **Dark SUSY:** $h$ decay to pair of neutralinos ($n_1$): LSP
  
  \[ n_1 \rightarrow n_D \gamma_D \] decays
  
  \[ \mu\mu \]invisible

- **NMSSM:** Extend MSSM by adding a complex singlet field (1 CP-even+1 CP-odd boson)

- **NMSSM:** $h_{1,2} \rightarrow 2a_1; a_1 \rightarrow 2\mu$

- Compare to SM Higgs cross section
non-SM Higgs decay: $H_{125} \rightarrow 2h(a) \rightarrow 4\tau$

- Search for very light Higgs in NMSSM
  - $h_{1,2}$ (CP-even), $a_{1,2}$ (CP-odd) to a pair of $\tau$ leptons
  - $H(125) \rightarrow h_1 h_2 (a_1 a_2) \rightarrow 4\tau$

- Reconstruct $\mu$-track invar. mass ($m_1, m_2$)
  - SS dimuon sample (removes DY)
  - bin in 2-dim distribution, fit signal and bkg
  - QCD bkg from control region

- No excess over SM backgrounds
Summary for Higgs exotic decays
Low mass Higgs: $a(\rightarrow\tau\tau)bb$

- Low mass Higgs in the NMSSM
- Low mass pseudo-scalar ($a_1 \rightarrow \tau\tau$) in association with $b\bar{b}$: $a_1 b\bar{b} \rightarrow \tau\tau b\bar{b}$
- Similar strategy to $H \rightarrow \tau\tau$
- Search for $a_1$ masses below Z mass
- No evidence for signal
- Set limits: $\sigma x B \sim 9-39 \text{ pb}$
di-Higgs searches

- Destructive interference in SM
- Could be altered in BSM
- If constructive, it could be large enhancement
- In SM, only $\sigma=33\text{fb}$ at 13 TeV
- Study different final states

<table>
<thead>
<tr>
<th>Final State</th>
<th>BR (%)</th>
<th>Mass Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}b\bar{b}$</td>
<td>34%</td>
<td>High</td>
</tr>
<tr>
<td>$b\bar{b}\tau\tau$</td>
<td>7.3%</td>
<td>High</td>
</tr>
<tr>
<td>$b\bar{b}WW$</td>
<td>27%</td>
<td>Low</td>
</tr>
<tr>
<td>$b\bar{b}\gamma\gamma$</td>
<td>0.26%</td>
<td>Low</td>
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</table>
Heavy Higgs to $h_{125}h_{125} \rightarrow \tau\tau bb$

- Resonant and non-resonant production
  - Double Higgs production to determine $\lambda_{hhh}$
  - Check couplings: $\kappa_\lambda = \lambda_{hh}/\lambda_{hhh}^{SM}$; $\kappa_t = y_t/y_t^{SM}$
  - BSM could enhance non-resonant $hh$ production
  - $H \rightarrow h_{125}h_{125} \rightarrow bb\tau\tau$

- $h_{125}$ decay products nearly collinear
  - boosted “single” merged jet ($\rightarrow bb$)

- use $\tau_e\tau_h$, $\tau_\mu\tau_h$, and $\tau_h\tau_h$ final states
  - sidebands/inverted isolation to estimate bkg

- set limits as function of mass

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Heavy Higgs: \( H \rightarrow h_{125}h_{125}, \ A \rightarrow Z\ h_{125} \)

- MSSM: Heavy Higgs searches
  - Search for \( A \rightarrow Z_{125} \) and \( H \rightarrow hh \)
- Exclusive search in multilepton and +lepton channels
- Search for FCNC decays

- Search for \( tt \rightarrow (bW)(ch) \)
  - Not forbidden but highly suppressed
  - enhanced w/some parameter models
- SM Higgs now a background
  - ATLAS: \( H \rightarrow \gamma\gamma \)
  - CMS: \( H \rightarrow \gamma\gamma \) and multileptons
- b-tag provides bkg suppression

<table>
<thead>
<tr>
<th>Process</th>
<th>SM</th>
<th>QS</th>
<th>2HDM-III</th>
<th>FC-2HDM</th>
<th>MSSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t \rightarrow u\gamma )</td>
<td>3.7 \times 10^{-16}</td>
<td>7.5 \times 10^{-9}</td>
<td>—</td>
<td>2 \times 10^{-6}</td>
<td>—</td>
</tr>
<tr>
<td>( t \rightarrow uZ )</td>
<td>8 \times 10^{-17}</td>
<td>1.1 \times 10^{-14}</td>
<td>—</td>
<td>2 \times 10^{-6}</td>
<td>—</td>
</tr>
<tr>
<td>( t \rightarrow uH )</td>
<td>2 \times 10^{-17}</td>
<td>4.1 \times 10^{-5}</td>
<td>5.5 \times 10^{-6}</td>
<td>10^{-5}</td>
<td>—</td>
</tr>
<tr>
<td>( t \rightarrow c\gamma )</td>
<td>4.6 \times 10^{-14}</td>
<td>7.5 \times 10^{-9}</td>
<td>\sim 10^{-6}</td>
<td>\sim 10^{-9}</td>
<td>2 \times 10^{-6}</td>
</tr>
<tr>
<td>( t \rightarrow cZ )</td>
<td>1 \times 10^{-14}</td>
<td>1.1 \times 10^{-14}</td>
<td>\sim 10^{-7}</td>
<td>\sim 10^{-10}</td>
<td>2 \times 10^{-6}</td>
</tr>
<tr>
<td>( t \rightarrow cH )</td>
<td>3 \times 10^{-15}</td>
<td>4.1 \times 10^{-6}</td>
<td>1.5 \times 10^{-3}</td>
<td>\sim 10^{-5}</td>
<td>10^{-5}</td>
</tr>
</tbody>
</table>

\( \text{BR}(t \rightarrow cH) \) (95\%CL)

<table>
<thead>
<tr>
<th>ATLAS obs(exp)</th>
<th>CMS</th>
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<tbody>
<tr>
<td>&lt;0.79% (0.51%)</td>
<td>&lt;0.56% (0.65%)</td>
</tr>
</tbody>
</table>
Some BSM models allow for LFV Higgs decays

Search for $H \rightarrow e\tau$, $e\mu$, $\mu\tau$ final states

Categories: $N_{\text{jet}}$, lepton kinematics
- $N_{\text{jet}}$ to target ggH and VBF production

Main background from DY, ttbar, WW

<table>
<thead>
<tr>
<th></th>
<th>95%CL (obs/exp)</th>
<th>Best fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h \rightarrow \mu\tau$ (run1)</td>
<td>&lt;1.51/0.75%</td>
<td>0.84$^{+0.39}_{-0.37}$%</td>
</tr>
<tr>
<td>$h \rightarrow \mu\tau$ (run2)</td>
<td>&lt;1.20/1.62%</td>
<td>-0.76$^{+0.81}_{-0.84}$%</td>
</tr>
</tbody>
</table>
Dark Matter+Higgs

- Generic search: \( pp \rightarrow X + \text{MET} \)
- Search for DM + h(\( \rightarrow \text{bb} \))
- Model-independent search
  - Signature: h(\( \rightarrow \text{ZZ/bb/\( \gamma\gamma \)} \)+MET)
  - Simplified model with Z' or pseudo-scalar Higgs A(\( \rightarrow \chi\chi \))
- Signal events at large MET

DM particle (\( \chi \)): can be scalar or fermion

Pseudo-scalar Higgs A

Summary

• Excellent consistency of SM but **SM is incomplete**
• Extensions foresee existence of additional bosons
• Searches for BSM bosons natural companion to precision SM Higgs boson measurements
  – Charged Higgs searches with top quark decays
  – Other BSM searches show no indication of deviations
• Searches provide **no hints for BSM yet**