Invisible Higgs decays, SUSY searches and BSM Higgs at the LHC

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DM and LHC

- There is strong evidence for the existence of DM
- DM outnumbers visible matter: 27% vs 5%
  - detect through gravitational effects
- DM: one of the important unsolved problems of the Universe

- one of the important physics programs after the discovery of the Higgs boson at the LHC
- At the LHC, we try to create it ourselves!
- Complementary to other DM experiments
- The searches of DM at the LHC can be more sensitive in some cases
  - if DM is light or if interactions are spin-dependent
**LHC and DM signatures**

- **DM signatures:**
  - mono-X
  - mono-Z, mono-H, mono-γ, ........
  - dijet
  - long-lived particles
  - invisible Higgs decays
  - SUSY
  - BSM Higgs

- higher $\sqrt{s}$ gives better sensitivity to BSM physics in the high mass region

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See the talk by Millie McDonald
Higgs couplings: currently allowed BSM BR

ATLAS + CMS: JHEP 06 (2016) 045
5/fb @ 7 TeV + 20/fb @ 8 TeV

| Parameter value | \( \kappa_Z \) | \( \kappa_W \) | \( \kappa_t \) | \( |l_{\kappa_l}| \) | \( |l_{\kappa_\ell}| \) | \( |l_{\kappa_{\nu}}| \) | \( |l_{\kappa_{\mu}}| \) | \( B_{BSM} \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Run 1 LHC       | ATLAS           | CMS             | ATLAS+CMS       | ATLAS           | CMS             | ATLAS           | CMS             | ATLAS+CMS       |
| ±1σ             | ±2σ             | ±1σ             | ±2σ             | ±1σ             | ±2σ             | ±1σ             | ±2σ             | ±1σ             |

potential invisible or undetectable \( B_{BSM} < 34\% \) (39\% exp.) @ 95\% C.L.
→ still allow ample space to look for BSM Higgs decays
Invisible Higgs decay

- a number of BSM models allow for this
  - decays to neutralinos in SUSY
  - graviscalars in models with extra spatial dimensions
  - interactions between the Higgs and DM
    - complementary to direct detection
  - DM mass < $m_H/2$

http://rejuvenatte.blogspot.tw
qqH

- most sensitive mode
- VBF topology
- reject extra leptons
\( Z(\rightarrow ll)H \)

- smaller cross section than VBF
- clean final state with low background
- select good Z bosons back-to-back with MET

\[ m_T = \sqrt{2 p_T^{ll} E_T^{miss} [1 - \cos \Delta \phi(ll, \vec{p}_T^{miss})]} \]
$V(\rightarrow qq)H$

- large background but relatively larger signal contribution
- ATLAS : 2 & 3 jets & b-tags (leading $p_T > 45$ GeV)
- CMS : large radius jet ($R = 0.8$), $p_T > 200/250$ GeV for 8/13 TeV
  - rely on jet substructure techniques
Monojet + H

- events failing V(jj)-tagging but satisfying jet $p_T > 150/100$ GeV ($R = 0.5/0.4$) for 8/13 TeV are included
- large background
- improve V(jj)H sensitivity by $\sim$15% after adding this mode

Combination of V(qq)H and gH
Combined $H \rightarrow \text{invisible limits}$

- No significant deviations from SM expectation are observed in any search mode
- ATLAS: Run-1 dataset
- CMS: Run-1 + 2015 dataset

Direct search increases the sensitivity beyond indirect constraints

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>VBF H</th>
<th>Z(\text{ll})H</th>
<th>V(qq)H</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp.</td>
<td>0.31</td>
<td>0.62</td>
<td>0.86</td>
<td>0.27</td>
</tr>
<tr>
<td>Obs.</td>
<td>0.28</td>
<td>0.75</td>
<td>0.78</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Comparison to direct DM detection

- Direct detection: sensitive to elastic interactions between DM and nuclei via H
  - nuclear recoil signatures → interpreted in terms of DM-nucleon interaction cross section
- the invisible Higgs decay width is translated into the spin-independent DM-nucleon elastic cross section if DM mass < \( m_H/2 \)
- LHC results: complementary phase space

ATLAS JHEP 11 (2015) 206
CMS HIG-16-016
Outlook of $H \rightarrow \text{invisible}$

- SM BR($H \rightarrow \text{inv.}$) = 0.001

S1: all systematic uncertainties are fixed to 2015 values

S2: experimental systematic uncertainties decrease with $L$ and theoretical ones are scaled by 1/2

→ improved by a factor of 2 by the end of 2018 and 5 at HL-LHC
SUSY searches

• Solution to the hierarchy problem

• Unification of gauge couplings

• Dark Matter in the Universe
  • LSP : stable, electrically neutral, interact weakly with the SM particles
    • may be an excellent DM candidate

• the known fundamental particles have superparticle partners : quark → squark, gluon → gluino
Selected Run 1 SUSY results

- A large number of searches were done with Run-1 data
- No significant signals consistent with SUSY have yet been observed
  - constrain the allowed SUSY model space

CMS summary plots: https://twiki.cern.ch/twiki/bin/view/CMSPublic/SUSYSMSSummaryPlots8TeV
pMSSM interpretations

- more than 20 EWK SUSY results → the impact on the constraints on DM
- interpreted with 19 independent weak-scale parameters (phenomenological MSSM)
  - considered model: EWKH → described by 5 parameters
  - the results can be assessed in a relatively straightforward way
- probe regions of the parameter space that are difficult to reach with direct-detection dark matter experiments
CMS results from Run-1 started to test the most interesting region with LSP masses below about 400-500 GeV

Neutralino mass is strongly correlated with the gluino and LCSP mass

Neutralino mass is correlated most strongly with the cross section
  • a light neutralino is disfavored
**SUSY production cross section : 8 vs 13 TeV**

- **Cross section ratio (13TeV/8TeV)**
  - gluino for mass = 1.4 TeV : ~25
  - stop/sbottom for mass = 750 GeV : ~10
  - $t\bar{t}$ : ~3.3 $\rightarrow$ S/B boosts

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\( \tilde{g} \rightarrow tt\tilde{\chi}_1^0 \)

- highly motivated decay channel due to natural SUSY scenarios
- the strongest limits is about 1.9 TeV
$\tilde{q} \to q\tilde{\chi}_1^0$

$\tilde{q} \to \tilde{q}\tilde{q}$, $\tilde{q} \to q\tilde{\chi}_1^0$

- large production cross section $\rightarrow$ primary target for early SUSY searches
- squark masses below $\sim 1.4$ TeV are excluded for a massless lightest neutralino

ATLAS CONF-2016-078
CMS SUS-016-014
CMS SUS-016-015
• stop plays an important role in cancelling the dominant top loop diagram contributions to the divergence of the Higgs mass
• LHC starts having sensitivity with 0.9-1 TeV for stop
• new results from ATLAS fill in the regions unfilled in Run-1
$H \rightarrow \text{undetectable} + \gamma$

- several BSM models predict this final state
- In certain low-scale SUSY models, $H \rightarrow$ a gravitino + a neutralino or a pair of neutralinos
Heavy Long-Lived Particles

- an attempt to address the hierarchy problem
- SUSY allows for long-lived sparticles
- new results improve the previous limits from the LHC

**ATLAS PLB 760 (2016) 647**
**CMS EXO-16-036**
BSM Higgs searches

- Two-Higgs Doublet Models (2HDM)
  - simplest possible extensions of the SM
  - MSSM, axion, baryogenesis models
- five “Higgs” bosons: h, H, H⁺, H⁻, A

CMS PRD 90 (2014) 112013

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$H^\pm \rightarrow \tau^\pm \nu_T$

- ATLAS: $pp \rightarrow H^+ t$ ($m_{H^+} > m_{top}$)
- CMS: $pp \rightarrow H^+tb$ ($m_{H^+} > m_{top}$), $pp \rightarrow H^+W^-bb$ ($m_{H^+} < m_{top}$)

$\sigma \times BR$ enhanced at large $\tan \beta$

$\rightarrow$ large $\tan \beta$ is excluded

significantly improve the limit for high mass region

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Di-Higgs production

ATLAS CONF-2016-049
CMS HIG-16-029

ATLAS Preliminary
\(\sqrt{s} = 13\) TeV, 13.3 fb\(^{-1}\)

CMS Preliminary
\(\sqrt{s} = 13\) TeV

SM

BSM

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Di-Higgs production

**CMS Preliminary**

$L = 2.70 \text{ fb}^{-1} (13 \text{ TeV})$

- $pp \rightarrow X \rightarrow HH \rightarrow b\bar{b}\gamma\gamma$
- Spin-2 Resonance
- Bulk Graviton, $k/M_\text{Pl} = 1$

**Observed 95% upper limit**

**Expected 95% upper limit**

- $\sigma (pp \rightarrow X \rightarrow HH \rightarrow b\bar{b}\gamma\gamma)$ (fb)
- $M_X$ (GeV)

**ATLAS Preliminary**

$\sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1}$

**Obs. limit**

- $\sigma (gg \rightarrow X) \times \text{BR}_{X \rightarrow hh}$ (fb)
- $m_X$ (GeV)

**At $\sqrt{s} = 13 \text{ TeV}, 13.3 \text{ fb}^{-1}$**

- $\gamma\gamma$ production

- $b\bar{b}\nu\bar{\nu}$ (CMS-PAS-HIG-16-011, 2.3 fb$^{-1}$)
- $b\bar{b}t\bar{t}$ (CMS-PAS-HIG-16-029, 12.9 fb$^{-1}$)
- $b\bar{b}b\bar{b}$ (CMS-PAS-HIG-16-002, 2.3 fb$^{-1}$)
- $b\bar{b}\gamma\gamma$ (CMS-PAS-HIG-16-032, 2.7 fb$^{-1}$)

**CMS Unpublished**

Assumes SM Higgs BR

$\sigma (gg \rightarrow X) \times \text{BR}_{X \rightarrow hh}$ (fb)

- $m_X^{\text{spin-0}}$ (GeV)

$2.3 - 12.9 \text{ fb}^{-1} (13 \text{ TeV})$
High mass search for $\gamma\gamma$

- many extensions to the SM predict new resonances decaying into $\gamma\gamma$
- ATLAS and CMS test both of heavy scalar ($J=0$) and Randall-Sundrum (RS) graviton ($J=2$) models and different widths

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ATLAS CONF-2016-059
CMS arXiv:1609.02507
High mass search for $Z\gamma$

- An extended SM incorporating a scalar (or pseudo scalar) decaying to two photons would imply the observation of $Z\gamma$ as well.
- ATLAS and CMS look into $Z \rightarrow ll$ and $Z \rightarrow qq$.

ATLAS PLB 764 (2017) 11
CMS arXiv:1610.02960
CMS EXO-16-035
Summary

- LHC provides alternative, complementary way to search for DM
- Rich DM search programs have been conducted at the LHC since Run-1
  - invisible Higgs decays
  - SUSY
  - BSM Higgs
- Stay tuned with new results updated with full 2016 data
• Backup
“Invisible” particles in detector

- Particles like neutrinos or DM do not leave signatures in the detector → invisible
  - cause large imbalance in the transverse plane
- Missing transverse energy (MET)
  - a powerful variable to discriminate between signal (e.g. DM) and SM background
Additional contributions to the Higgs boson width from BSM processes

\[-2 \ln \Lambda\]

\([k_Z, k_W, k_t, k_\tau, k_b, k_{g'}, B_{BSM}]\]

ATLAS and CMS
LHC Run 1

- Observed
- SM expected
\( \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0 \)
$\tilde{b} \rightarrow b\tilde{\chi}_1^0$

ATLAS EPJC (2016) 76:547
CMS SUS-16-014
CMS SUS-16-015
CMS SUS-16-016

ICHEP 2016

CMS Preliminary

13 TeV

Expected
Observed

$\tilde{b}\tilde{b}, \tilde{b} \rightarrow b\tilde{\chi}_1^0$

Bottom squark pair production, $\tilde{b}_i \rightarrow b\tilde{\chi}_1^0$

$\sqrt{s}=13$ TeV, 3.2 fb$^{-1}$
All limits at 95% CL
Best SR

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$H^+ \rightarrow WZ$ or $tb$

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ATLAS CONF-16-089
CMS HIG-16-027

$\beta$ vs $\tan \beta$

Observed exclusion

Expected exclusion

$\sigma_1 \pm \sigma_2$ ±

$H^+$

$H^+$

$\sqrt{s} = 13$ TeV, 13.2 $fb^{-1}$
$$\Phi \rightarrow \tau \tau$$

(a) \hspace{1cm} (b) \hspace{1cm} (c)

- $g \rightarrow t, \bar{t}$
- $b, \bar{b}$
- $h, H, A$

### CMS Preliminary

**hMSSM scenario**

- $95\%$ CL Excluded:
  - Observed
  - Expected $\pm 1\sigma$
  - Expected $\pm 2\sigma$

**95\% CL Excluded:**

- Observed
- Expected $m_{h^\text{mod+}} = 125 \pm 3$ GeV
- Expected $m_{h^\text{mod+}} = 125 \pm 3$ GeV

- $\tan \beta$
- $m_A$ (GeV)

**m$_{h^\text{mod+}}$ scenario**

- $95\%$ CL Excluded:
  - Observed
  - Expected $m_{h^\text{mod+}} = 125 \pm 3$ GeV
  - Expected $m_{h^\text{mod+}} = 125 \pm 3$ GeV

- $\tan \beta$
- $m_A$ (GeV)
High mass search for $\gamma\gamma$

\[
\begin{array}{c|c}
\tilde{k} & \text{Exclusion} \\
0.01 & 1.95 \text{ TeV, except } 1.75-1.85 \text{ TeV} \\
0.1 & 3.85 \text{ TeV} \\
0.2 & 4.45 \text{ TeV} \\
\end{array}
\]
**A-funnel**: dark matter annihilates through the pseudo scalar Higgs boson pole

**Z-funnel**: annihilation rate is proportional to higgsino fraction of the neutralino

**h-funnel**: neutralino annihilates through a mechanism similar to Z-funnel but involving the lightest Higgs boson instead. Annihilation rate is proportional to the higgsino fraction as well as the combined bino and wino fraction.