WIMP Dark Matter interpretation of Higgs results

The Galileo Galilei Institute
For Theoretical Physics
Arcetri, Firenze

Collider Physics and the Cosmos
9-13 Oct. 2017

Ren-Jie Wang
LPNHE, Institut Lagrange de Paris
on behalf of ATLAS and CMS Collaborations
Outline

- Motivation and strategy of Dark Matter (DM) searches with Higgs boson
  - *directly coupling to the Higgs boson (invisible-H)*
  - *adding extra scalar/vector mediator coupling to the Higgs boson (mono-H)*
- Results from ATLAS&CMS on
  - invisible branching fraction from invisible-H
  - production cross section times branching fraction of mono-H
- DM interpretations
- Conclusions
Motivation of invisible decay of the Higgs Boson

- In the SM, the Higgs boson has $\text{BR}(H \rightarrow ZZ^* \rightarrow \nu\nu\nu\nu) \sim 0.1\%$
- Observation with a sizable $\text{BR}(H \rightarrow \text{invisible})$ would be a strong sign of BSM Physics:
  - LSP of SUSY: neutralinos, gravitinos
  - Graviscalars (large extra dimensions)
  - more general interaction between the Higgs boson and dark matter
- Higgs-portal DM: the Higgs bosons acts as mediator between SM and DM particles
  - 125 GeV Higgs has been discovered – see how often it decays invisibly
- **How to detect a decay mode which is invisible?**

Find a recoiling system $\Rightarrow$

See talks from Yann Mambrini and Abdelhak Djouadi
Vector Boson Fusion

- **Signal**
  - two final-state quark jets, separated by a large rapidity gap, high invariant mass
  - large missing transverse momentum (MET)

- **Backgrounds**
  - $Z(\nu\nu)+$jets, $W(\ell\nu)+$jets; QCD multijet; single top, ttbar, diboson, DY($\ell\ell$)+jets

- jet energy scale and resolution (8% of total bkg), $Z(\ell\ell)+$jets/$W(\ell\nu)+$jets ratio (10-30%)

CMS: $\text{BR}_{\text{inv}} < 0.44$ @ 95%CL, 2.3 fb$^{-1}$, 13 TeV
ATLAS: $\text{BR}_{\text{inv}} < 0.28$ @ 95%CL, 20.3 fb$^{-1}$, 8 TeV
**Z(→ℓ⁺ℓ⁻)H**

- **ZZ**: MC estimated; **WZ**: data-driven
- **Z/γ*+jets**: fake MET from instrumental effects
  - **ATLAS**: extrapolate from 2D sideband regions using MET and MET/H_T (50-90% systematic)
  - **CMS**: use γ+jets data to model, photon p_T spectrum reweighted to match Z p_T (100% systematic, limited events at large p_T)
- **Top/WW/Z→τ+τ⁻**: no resonant Z→ee, μμ are estimated from eμ events in data (systematic CMS/ATLAS: 10-15%/14%)

---

**CMS: σ_{ZH} × BR_{inv} < 1.1 pb @ 95%CL, 2.3 fb⁻¹, 13 TeV**

**ATLAS: BR_{inv} < 0.67% @ 95%CL, 36.1 fb⁻¹, 13 TeV**

---

**ATLAS EXPERIMENT**

arXiv:1708.09624

JHEP 02 (2017) 135
V($\rightarrow jj$)H and gH

- Main backgrounds: Z(\nu\nu)+jets and W(\ell\nu)+jets, simultaneous fits to control regions (CRs)
  - ATLAS: W(\mu\nu)+jets, W(enu)+jets, and Z/\gamma*(\mu\mu)+jets
  - CMS: W(e/\mu\nu)+jets, Z/\gamma*(ee/\mu\mu)+jets, and \gamma + jets
- Dominant systematics: 20% uncertainties in the differential XS ratios of $\gamma/Z + jets$ and W/Z + jets
- Combination: the fraction of various production mode are assumed to be as in the SM prediction

with large statistics
- similar jet multiplicity, underlying event, and pileup conditions with the DY process at high p_T region

Observed (expected) upper limits:
B(H->inv.) < 0.24 (0.23) @95%CL
Indirect limits using constraints from visible decays

- With visible Higgs decay results in hand
  - explore a general scenario that agrees with observed modes
  - but allows for non-vanishing BR for Higgs boson decays beyond SM
- Non-SM Higgs decay modes will modify the total Higgs decay width
  - an upper limit on invisible branching ratio $\text{BR}_{\text{inv}}$ can be achieved by global fits of visible Higgs decay modes (& invisible Higgs decays)

\[ \Gamma_{\text{tot}} = \Gamma_{\text{SM}} \cdot \frac{\sum_{X} \kappa_{X}^{2} \cdot \text{BR}_{X}^{\text{SM}}}{1 - \text{BR}_{\text{BSM}}} \]

95\% CL $\Gamma_{\text{tot}} < \Gamma_{\text{SM}}$ for observing Higgs boson decays beyond SM

$\text{BR}_{\text{inv}} < 0.34$

$\text{BR}_{\text{inv}} < 0.23$

No assumption on $k_{V}$, ATLAS Combination of visible & inv. Higgs channels
Higgs-portal DM interpretation (1)

- Higgs-portal DM models with two assumptions:
  - the Higgs boson is the only mediator between DM and SM sectors
  - the mass of the DM is less than half of the Higgs mass

\[
\begin{align*}
\Delta \mathcal{L}_S &= \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S S^2 - \frac{1}{4} \lambda_S S^4 - \frac{1}{4} \lambda_{hSS} H^\dagger H S^2 \\
\Delta \mathcal{L}_f &= -m_f \bar{\chi} \chi - \frac{1}{4} \frac{\lambda_{hff}}{\Lambda} H^\dagger H \bar{\chi} \chi \\
\Delta \mathcal{L}_V &= \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4} \lambda_V (V_\mu V^\mu)^2 + \frac{1}{4} \lambda_{hVV} H^\dagger H V_\mu V^\mu
\end{align*}
\]

Djouadi, Lebedev, Mambrini, Quevillon, PLB 790, 65;
Djouadi, Falkoski, Mambrini, Quevillon, Eur. Phys. J. C73, 2455

- The limit on $\text{BR}_{\text{inv}}$ can be interpreted as bounds of coupling strength $\lambda_{hXX}$
  - finally give constraints on DM-nucleon cross sections
Spin-1 and 1/2 Higgs-portal DM model are not renormalizable, should be more careful when doing reinterpretation (PRD 90, 055014, 2014)
Search for DM via adding extra mediator coupling to the Higgs (1)

Simplified models:

Spin-1 mediator: \(- \sum q \mathcal{A}_\mu \bar{q}  \gamma^\mu (\gamma^5) q - g_X \mathcal{A}_\mu \bar{\chi}  \gamma^\mu (\gamma^5) \chi\)

Spin-0 mediator: \(- \sum q \mathcal{A} q \phi \bar{\phi} (\gamma^5) q - g_X \mathcal{A} \phi \bar{\phi} (\gamma^5) \chi\)

- focus on new mediator particle
- consistent at LHC energies, an extension to the EFT approach
- But less model-independent

Effective field theory (EFT) models: several nonrenormalizable operators without the UV physics specified
- largely model-independent
- but not reliable when parton energies in the events are comparable to the effective mass scale
- don’t account the constraints on the UV physics generating these operators (e.g. constraints from recent dijet/dilepton searches)
Search for DM via adding extra mediator coupling to the Higgs (2)

- Mono-X: a final state of MET+Jet(s), photon, W, Z, Higgs, top/b quark
- X can be emitted either directly from ISR through SM gauge interactions or from a BSM vertex coupling

See talks from Jeroen Schouwenberg and Adish Vartak for other channels
Introduction — mono-Higgs

- Difference between mono-Higgs and other mono-X searches
  - ISR Higgs boson is Yukawa suppressed, a mono-Higgs signal can only be through BSM vertex
- Higgs decaying to $\gamma\gamma$, $bb$, and $ZZ$ are considered
- Three benchmark models:
  - $Z'_B$: a vector boson $Z'$ with baryon number coupling with Higgs;
  - $Z'$-2HDM: vector mediator ($Z'$), two-Higgs-doublet: $h$; $H$ (CP-even); $A^0$ (CP-odd); $H^\pm$; DM only coupling to pseudo-scalar $A^0$, $Z'\rightarrow A^0 + h$
  - Heavy scalar model: an EFT-based $H$-$h$-$\chi$-$\bar{\chi}$ interaction

![Feynman diagrams for three benchmark models](image)

**CMS**

- $Z'\rightarrow DM + h$
- $m_{Z'} = 1200$ GeV
- Varying $m_h$ from 300 to 700 GeV

**13 TeV**

<table>
<thead>
<tr>
<th>$p_T^{miss}$ (GeV)</th>
<th>0</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_h = 300$ GeV</td>
<td>0.05</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
<td>0.25</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_h = 500$ GeV</td>
<td>0.05</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
<td>0.25</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_h = 700$ GeV</td>
<td>0.05</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
<td>0.25</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Mono-Higgs(→ZZ*→4ℓ)

- H→ZZ*→4ℓ has low BR, but this channel is very clean
  - at least four well-identified, isolated leptons, same flavor-opposite-charge lepton pair match to Z mass
- Background:
  - ZZ* (irreducible) and ttV/VVV from simulation
  - Z+jets, ttbar: shape and normalization data-driven
- 5.6% systematics on lepton ID and reconstruction efficiencies and energy/momentum scale and resolution (dominant)
- Signal region: m_{4ℓ} [110,140] GeV, MET>100 GeV

No significant BSM excess is observed! Upper limit is set on the production cross section x BR as a function of m_{med}, no exclusion @13TeV, 3.2 fb⁻¹
Mono-Higgs($\rightarrow \gamma\gamma$)

- Signature: two well-identified photons compatible with the 125 GeV Higgs boson plus MET
- MET is calculated w.r.t. the diphoton vertex in ATLAS & CMS
- Non-resonant background: $\gamma\gamma$, $\gamma$+jets (dominant), $V\gamma$, $VV\gamma$: visible contribution after MET Significance/MET cut; Resonant background: SM Higgs

### Table 1:

The selected events are thus divided into five categories based on:

1. The magnitude of the vectorial sum of the transverse momenta photons and jets in the event, provides further classification of the selected events into categories depending on the high-
2. The diphoton transverse momentum,
3. The distance between the diphoton vertex and the highest PV;
4. The high-

The background events that survive the high-

Optimized criteria used in the categorization. The categories are defined sequentially in the rows and each effects and reject a large fraction of the fake

$E_{miss} = \frac{E_T}{\sqrt{\sum E_T}}$,

$\gamma\gamma$, $\gamma$+jets (dominant), $V\gamma$, $VV\gamma$: visible contribution after MET Significance/MET cut; Resonant background: SM Higgs

### Diagram:

- CMS Preliminary
- ATLAS

$S_{E_{miss}}$ = $E_{miss}^T / \sqrt{\sum E_T}$,

$35.9 \, fb^{-1}$ (13 TeV)

Events / GeV

Events / $E_{miss}$

$E_T = 13$ TeV, 36.1 $fb^{-1}$

$Z\rightarrow 2\text{HDM}$, $\text{Drac DM}$ $m_\gamma = 100$ GeV,

$m_\gamma = 1$ TeV, $m_{\chi} = 200$ GeV, $m_{\chi} = 300$ GeV

$\gamma+\text{jets}$

$\text{Dirac DM}$ $m_\gamma = 1$ GeV, $m_{\chi} = 200$ GeV

Heavy scalar, Scalar DM $m_\gamma = 60$ GeV,

$m_\gamma = 275$ GeV

Data

SM Higgs boson

$V\gamma$, $VV\gamma$

Mono-Higgs($\rightarrow \gamma\gamma$)

- Data-driven non-resonant background ($\gamma\gamma$, $\gamma$+jets, $V\gamma$, $V\gamma\gamma$):
  - The signal and backgrounds are extracted by fitting the $m_{\gamma\gamma}$ distribution
- Statistical uncertainties (dominant), non-resonant background modeling 10% in ATLAS (20% in CMS) for mis-modeling

No significant BSM excess is observed!

---

$\gamma = 13$ TeV, 36.1 fb$^{-1}$

**ATLAS**

- Data
- $h$ ($m_h$=125.09 GeV)
- $Z'_B$ ($m_{Z'B}=200$ GeV)
- $m_{Z'}=1$ GeV, $m_{Z'}=400–1400$ GeV and mediator mass $1–1000$ GeV and mediator mass $1 – 1000$ GeV

---

<table>
<thead>
<tr>
<th>Category</th>
<th>Rest</th>
<th>11</th>
<th>15</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono-Higgs</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Diphoton</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$T_1$, $T_2$</td>
<td>0.5</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>$B_0$, $V_0$</td>
<td>0.1</td>
<td>0.0</td>
<td>0.05</td>
<td>0.1</td>
<td>0.15</td>
</tr>
</tbody>
</table>

---

Statistical uncertainties (dominant), non-resonant background modeling 10% in ATLAS (20% in CMS) for mis-modeling.

---

**CMS PAS EXO-16-054**

arXiv: 1706.03948
Mono-Higgs(→γγ)

- Upper limit is set on
  - the production cross section times BR as a function of mediator mass (CMS) / 2D mass plane (ATLAS) for \( Z' \) scenarios
  - The spin independent DM-nucleon cross section (ATLAS)
**Mono-Higgs(→γγ)**

- ATLAS: the heavy scalar EFT model
  - Simultaneous fit of five categories (softer MET)
  - *All the heavy scalar mass points considered in the analysis are excluded*

---

![Graph](attachment:image.png)

- **Observed**
- **Expected**
- **Expected ± 1σ**
- **Expected ± 2σ**
- **α_h × B(H → γγχχ)**

\[ pp \rightarrow H \rightarrow h(γγ) + χχ, \text{Heavy scalar model} \]
\[ m_χ = 60 \text{ GeV}, B(H \rightarrow hχχ) = 100\% \]
Mono-Higgs($\rightarrow bb$)

- Resolved: two b-tagged track-jets + intermediate MET
- Merged: one large-R jet with two b-tagged tracks + large MET

- Background:
  - two main backgrounds: W/Z+jets (15~65%); ttbar (45~80%)
  - control regions are defined with 1-/2-lepton events

**Figure 12:** An event display of a signal event in the merged signal region. This event is characterized by $E_\text{miss} = 694$ GeV and a large-R jet with $m_J = 106$ GeV and two b-tagged track jets.

**Figure 13:** An event display of a signal event in the merged signal region. This event is characterized by $E_\text{miss} = 213$ GeV and two b-tagged small-R calorimeter jets that form a dijet system with $m_{jj} = 120$ GeV.
Mono-Higgs($\rightarrow bb$)

- **Simultaneous fit of the signal region and the control regions has been performed**
  - main backgrounds are normalized to data in CRs
- main uncertainties impact on result
  - **MC statistics (6-60%)**, b-tagging (2-18% in ATLAS, 6-15% in CMS), V+jets modelling (5-8% in ATLAS, 5% in CMS)

No significant BSM excess is observed!
Mono-Higgs($\gamma\gamma, bb$)

- Upper limit is set on the signal strength as a function of $m_A$ and $m_{Z'}$ for $Z'-2$HDM scenario
  - ATLAS: separated $bb$ and $\gamma\gamma$ @36.1 fb$^{-1}$
  - CMS: combined $bb$ and $\gamma\gamma$ @2.3 fb$^{-1}$, (improve for low MET regions because of tight MET trigger for $bb$ channel)

![Graph of signal cross sections](image)
Conclusions

- DM searches in **invisible-Higgs** and **mono-Higgs** signature from ATLAS & CMS at 13 TeV are summarized - direct, indirect constraints from visible channels, and combination are performed

- Consistent with Direct and Indirect searches, no DM candidate has been seen at the LHC yet!

- The upper limits of production cross section times branching fraction is re-interpreted as upper bounds of DM-nucleon cross section, **LHC is very competitive at small DM mass**

- “**We're out of kindergarten, but only in about third grade.**” —Vera Rubin (1928-2016)