Spotting hidden sectors with Higgs binoculars

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Lots of evidence for dark matter

Standard Model (SM) can only account for < 5% of the energy in the universe
How to discover dark matter

Dark matter (DM) interacts with SM particles

- **direct detection experiments**
  detect DM particles scattering off nuclei in e.g. liquid Xenon detectors

- **indirect detection experiments**
  observe radiation emitted from DM annihilation in the cosmos

- **DM production at colliders**
  produce DM particles in high-energy collisions
Dark particles at the LHC

**Dark particles**
- electrically neutral
- no QCD colour charge
- stable (at detector scales)
  - leave no trace in particle detector

**How to see the invisible?**
Missing transverse energy and mono-\(X+\not{E}_T\)

- observation of dark particles at the LHC by their recoil against visible SM matter
  - apparent non-conservation of momentum

- hadron collider: initial state parton momenta are unknown, only conservation of transverse momentum can be tested
  - dark particles \(\triangleq \) “missing transverse energy” \(\not{E}_T\)

- traditional signature from initial state radiation: mono-jet+\(\not{E}_T\)

- more recently: mono-\(X+\not{E}_T\) with \(X=t, W, Z, h, \gamma \ldots\)
Complementary channel: $\text{di-}X + \not{E}_T$

- complementary signature

$\text{di-}X + \not{E}_T$

is sometimes more constraining

- relevant e.g. in models with $t$-channel mediators

Papucci, Vichi, Zurek (2014)

- widely studied (c.f. SUSY searches):
  \[
  \text{di-jet} + \not{E}_T, \ t\bar{t} + \not{E}_T, \ \text{di-lepton} + \not{E}_T, \ldots
  \]

What about $\text{di-Higgs} + \not{E}_T$?
The di-Higgs+ $\not{E}_T$ signature

di-Higgs+ $\not{E}_T$ predicted in a variety of BSM scenarios

- Goldstino pair production in models with gauge mediated SUSY breaking
  Giudice, Rattazzi (1999); Matchev, Thomas (1999)

- decay of electroweakinos into Higgs bosons and neutralinos
  Kang, Ko, Li (2015); Bernreuther, Horak, Plehn, Butter (2018); Titterton et al (2018)

- pseudoscalar portal to dark sector
  No (2015): Arganda et al (2017)

- axion-like particles
  Brivio, Gavela, Merlo, Mimasu, No, del rRey, Sanz (2017)

- massive right-handed neutrinos
  Kang, Ko, Li (2015)

- $Z'$ decay in Little Higgs scenarios
  Kang, Ko, Li (2015); Chen, Lin, Wu, Yue (2018)

▶ systematic study of di-Higgs+ $\not{E}_T$ signature required!
The di-Higgs$+\vec{E}_T$ hunting team

MB, S. Kast, J. M. Thompson, S. Westhoff, J. Zurita
JHEP 04 (2019) 160 [arXiv:1901.07558]
Goals of our di-Higgs+ $E_T$ analysis

1. construct **simplified models** that cover relevant final state topologies
2. develop **search strategy** to be used at the (HL-)LHC
3. analyse reach and demonstrate **discovery potential**
Simplified models of a hidden scalar sector

**Final state topologies for $hh\chi\chi$**

**Symmetric ($S$)**

Pair production of heavy scalar $A$ with subsequent symmetric decay $A \rightarrow h\chi$

$$pp \rightarrow AA \rightarrow (h\chi)(h\chi)$$

**Resonant ($R$)**

Pair production of $A$ with asymmetric decays $A \rightarrow hh$, $A \rightarrow \chi\chi$ \(\Rightarrow\) di-Higgs resonance

$$pp \rightarrow AA \rightarrow (hh)(\chi\chi)$$
Ingredients of the simplified models: commonalities

- three new real scalar fields $B$, $A$, $\chi$ — all singlets under the SM gauge group
- dark particle $\chi$ is stable and leaves detector without trace $\Rightarrow \not{\mathcal{E}}_T = p_T(\chi \chi)$
- resonant $s$-channel production of $B$ by gluon fusion
  $$\frac{C_{Bgg}}{\Lambda} B G^a_{\mu\nu} G^{\mu\nu} a$$
  effective dimension-5 operator with scale $\Lambda$
- on-shell decay into $AA$ pair by triple scalar coupling
  $$\frac{m_{BAA}}{2} BAA$$
Ingredients of the simplified models: model-specifics

**symmetric topology**

- both $A$ and $\chi$ belong to dark sector
- coupling that induces $A \to h\chi$ decay

\[
\lambda_{A\chi HH} A\chi H^\dagger H
\]

$H$: SM Higgs doublet

- mixing between $A$ and $\chi$ dialed by independent parameter, can hence be neglected
  - $\text{BR}(A \to h\chi) = 100\%$
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  - $\text{BR}(A \to h\chi) = 100\%$

**resonant topology**

- only $\chi$ belongs to dark sector
- couplings that induce $A \to hh$ and $A \to \chi\chi$ decays
  $$m_{AHH} A H^\dagger H + \frac{m_{A\chi\chi}}{2} A\chi\chi$$
- $m_{AHH}$ induces $A - h$ mixing
  - $\text{BR}(A \to \chi\chi) = x$
  - $\text{BR}(A \to hh) \approx \text{BR}(A \to ZZ)$
  - $\approx \frac{1}{2} \text{BR}(A \to WW) = \frac{1}{4}(1 - x)$

- $\sigma_S(pp \to hh + E_T) \gtrsim 8 \sigma_R(pp \to hh + E_T)$
Signal & background

Signal

- Higgs boson $h$ decays further into $b\bar{b}$ ($\sim 60\%$), $WW^*$ ($\sim 20\%$), $gg$ ($\sim 8\%$), $\tau\bar{\tau}$ ($\sim 6\%$), $c\bar{c}$ ($\sim 3\%$), $ZZ^*$ ($\sim 3\%$), $\gamma\gamma$ ($\sim 0.2\%$)...

  ➡️ to maximise event rate, consider $h \rightarrow b\bar{b}$ decay channel

  final state signature: $b\bar{b} b\bar{b} + \mathbb{E}_T$

- at parton level, each $b\bar{b}$ pair reconstructs a Higgs boson: $m_{b\bar{b}} = \sqrt{(p_b + p_{\bar{b}})^2} = m_h$

Background

- dominant background processes

  \[ Z(\rightarrow \nu\bar{\nu})/W(\rightarrow \ell\nu) + jjjj/jjbb/bbbb \quad \text{t}(\rightarrow bjj)\bar{t}(\rightarrow b\ell\nu) \quad \text{multi-jet} \]

  ➡️ suppress background by imposing cuts
Understanding the di-Higgs+ $\not{E}_T$ signature

Understanding the signal kinematics: $\not{E}_T$ distribution

- significantly harder $\not{E}_T$ distribution for resonant topology
  - collimated $\chi\chi$ pair from $A$ decay
- position of $\not{E}_T$ peak depends on mass spectrum ($B$-$A$ hierarchy)
  - boost of $A$ contributes to $\not{E}_T$
- hard cut $\not{E}_T > 200$ GeV largely reduces background
Understanding the signal kinematics: Collinearity of $b$-jets

$\Delta R_{bb}^{\text{min}}$: minimum distance between any pair of $b$-jets

- $\Delta R_{bb}^{\text{min}}$ significantly smaller for resonant topology
  - $HH$ pair collimated

- $\Delta R_{bb}^{\text{min}} < 0.4$ for significant number of events in the latter case
  - less than 4 ($b$-)jets in a large number of events

![Histograms showing the distribution of $\Delta R_{bb}^{\text{min}}$ for parton and shower simulations.](image)
### Basic cuts

- **trigger level** (basic event selection): $\mathcal{E}_T > 200$ GeV, isolated lepton veto

- $b\bar{b}$ from boosted Higgs: collimated
  - “fat-jet” with two $b$-subjets
    - require two fat-jets with at least one $b$-tagged subjet each

- **Higgs mass window (HMW)**: $100$ GeV $< M_J < 150$ GeV

**Strategy:**

test various combinations of required number of $b$-tags and HMW on Monte Carlo event sample to optimise cut-and-count analysis
with realistic assumption for systematic uncertainty ($\beta \gtrsim 5\%$): 
no discovery reach even at the HL-LHC ($L = 3 \text{ ab}^{-1}$)
Cutflow: resonant topology

- Situation even worse than for symmetric topology due to lower event rates
Lessons from simple cut-and-count analysis

**useful tools to discriminate signal from background**

- $E_T$ cut and lepton veto
- jet substructure analysis for fat-jets
- $b$-tagging subjets
- Higgs mass window requirement for fat-jet
- ...?

yet, naive cut-and-count approach turned out unsuccessful
Lessons from simple cut-and-count analysis

**useful tools to discriminate signal from background**

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**We need to do something smarter to optimise our search**

> multivariate analysis (MVA)
MVA basics

Cut-and-count analysis
- based on a number of one-dimensional cuts
- not fully optimised
- cannot capture correlations between different variables

Overcome these issues by **multivariate analysis (MVA)**
- optimises multi-dimensional cuts with machine-learning methods
- correlations become visible
- higher signal-background separating power in particular for many variables
Step 1: Basic event selection

**Trigger level**
- $\not{E}_T > 200$ GeV
- isolated lepton veto

**Kinematic selection cuts**
- at least two Cambridge-Aachen fat jets $J_{1,2}$ with radius $R = 1.2$ ($R = 0.6$) for symmetric (resonant) topology
- $p_T(J_i) > 20$ GeV
- each $J_{1,2}$ contains at least two subjets $j_{1,2}^k$
- at least one subjet is $b$-tagged for each fat jet
Step 2: Training boosted decision tree (BDT)

Variables used to discriminate signal from background
- **global variables** – $E_T$, $H_T$, $N_J$, $N_{Jb}$, $N_{jb}$
- **single fat-jet variables** – $p_T(J_i)$, $\eta(J_i)$, $m_{J_i}$, $\Delta \phi(J_i, E_T)$
- **two fat-jet variables** – $\Delta R(J_1, J_2)$, $m_{J_1J_2}$, $\max(m_{J_i}/m_J)$
- **subjet variables** – $p_T(j_{1k}^{i})$, $\eta(j_{1k}^{i})$, $\Delta R(j_{1k}^{i}, j_{1l}^{i})$

Strategy
- divide Monte Carlo events into two sets
- **train BDT** on one set (80%) to correctly **classify** signal and background events
- **test** on other set to avoid overfitting
**BDT performance: symmetric topology**

- BDT works equally well on test set – no overfitting of training set
- large significances possible
HL-LHC discovery reach: symmetric topology

Cross-sections down to the few fb level can be discovered at the HL-LHC ($\mathcal{L} = 3 \text{ ab}^{-1}$)
Discovery luminosity: symmetric topology

assuming simple TeV-scale UV-completion for $Bgg$ coupling, this can be translated into the integrated luminosity required for discovery

\[ \sqrt{s} = 14 \text{ TeV} \]
\[ m_B = 500 \text{ GeV}, \text{ Symmetric} \]
\[ 5\% \text{ systematics} \]

\[ \text{discovery luminosity \, [fb^{-1}]} \]

\[ \text{m}_X \, [\text{GeV}] \]
\[ m_A \, [\text{GeV}] \]

\[ \text{discovery luminosity \, [fb^{-1}]} \]

\[ \text{m}_X \, [\text{GeV}] \]
\[ m_A \, [\text{GeV}] \]
BDT performance: resonant topology

- good BDT performance also for resonant topology
- smaller significances reached
HL-LHC discovery reach: resonant topology

- lower cross-sections can be probed than for symmetric topology
- however discovery challenged by lower event rates

[recall factor $1/8$ for equal $\sigma(pp \rightarrow AA)$]

$\sqrt{s} = 14$ TeV, $L = 3$ ab$^{-1}$
Resonant 5% systematics

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Conclusions

Systematic study of the di-Higgs+ $\not{E}_T$ signature

- construction of simplified models covering possible final state topologies
- understanding of di-Higgs+ $\not{E}_T$ phenomenology
- implementation of multi-variate analysis
- investigation of HL-LHC discovery reach

 dbHelper icon

Higgs binoculars are a sensitive probe of hidden sectors!
UV-completing the $Bgg$ vertex

- introduce heavy vectorlike quark $Q$ with mass $m_Q \sim \text{TeV}$ and Yukawa coupling to $B$

  $$-y_Q B \bar{Q} Q$$

- integrate out $Q$ to generate effective coupling $Bgg$

  $$\frac{C_{Bgg}}{\Lambda} = \frac{g_s^2 y_Q}{48\pi^2 m_Q}$$

- with $m_Q = \Lambda = 1 \text{ TeV}$ and $y_Q = 1$, this yields

  $$C_{Bgg} \simeq 2.1 \cdot 10^{-3}$$
Dark matter interpretation for $\chi$

$\chi$ stable due to discrete $\mathbb{Z}_2$ symmetry ➔ dark matter candidate?

- null results from direct detection experiments can be accommodated in both topologies without affecting the di-Higgs+$E_T$ pheno, but choosing appropriate coupling values
- sufficient DM annihilation cross sections to avoid overclosing universe can be obtained in several scenarios:
  - $m_\chi > m_h$: $\chi\chi \rightarrow hh$ via $t$-channel $A$ exchange (symm. top.)
  - $2m_\chi \approx m_h$: $\chi\chi \rightarrow h \rightarrow b\bar{b}$ (Higgs resonance region)
- additional freedom if we add couplings and/or states beyond the simplified model
Event generation and analysis details

Signal event generation

- MG5_aMC@NLO 2.6.1 ➢ Pythia 8.2 ➢ Delphes 3.3.3 (ATLAS default)
- CheckMATE2 to verify validity of benchmarks in presence of current and future complementary (HL-)LHC searches

Background simulation

- Sherpa 2.2.1

Analysis tools

- ROOT
- jet substructure with SoftDrop, augmented by modules to access $b$-tags of subjets
- MVA: scikit-learn implementation of AdaBoost, employing SAMME.R algorithm