Higgs Binoculars for Dark Matter Searches

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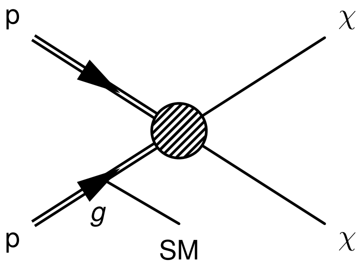
Monika Blanke, **Simon Kast**, Jennifer Thompson, Susanne Westhoff, Jose Zurita

HEIKA - HEIDELBERG KARLSRUHE RESEARCH PARTNERSHIP

The Hunt for the Dark Matter Particles

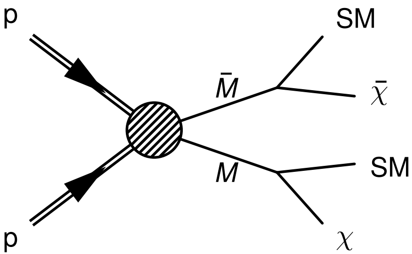
At LHC: Mono-X versus Di-X Signature

Initial state radiation:



$$\sim \sigma\,(pp \to \chi\bar{\chi}) \times g^2$$

Production via mediator:



$$\sim \sigma\left(pp \to M\bar{M}\right) \times BR\,(M \to SM\chi)^2$$

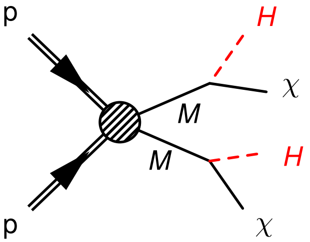
A Novel Signature: Di-Higgs + Missing Energy

Dedicated searches so far:

- Di-jet + MET
- Top-quark pairs + MET
- Di-lepton + MET
- ...

$\Rightarrow$ What about the Higgs?

- Di-Higgs + MET for gravitino DM studied by CMS/ATLAS
  [CMS-SUS-16-044 (1709.043896)]
  [ATLAS (1806.04030)]
- Z' model with $b\bar{b}\gamma\gamma$ in final state [Chen, Lin, Wu, Yue '18]



Our goals:

- Explore viable models and their phenomenology
- Establish simplified models for LHC searches
- Discover dark matter at LHC

Dirac Doublet-Singlet Model

Simplified model which produces the desired signature

e.g. [Mahbubani, Senatore '05], [Freitas, Westhoff, Zupan '15]

$$\mathcal{L}_m \supset -m_D \bar{\chi}_D \chi_D - m_S \bar{\chi}_S \chi_S - (y \bar{\chi}_D \chi_S H + h.c.)$$

EWSB $\rightarrow$ physical particles χ_h and χ_l (DM candidate)

$$\chi_h = \cos\theta \; \chi_S + \sin\theta \; \chi_D, \qquad \chi_l = -\sin\theta \; \chi_S + \cos\theta \; \chi_D$$

with masses

$$m_{h,l} = \frac{1}{2}\left(m_D + m_S \pm \Delta m\right)$$

with

$$\sin^2\theta = \frac{1}{2}\left(1 + \frac{m_D - m_S}{\Delta m}\right), \qquad (\Delta m)^2 = (m_D - m_S)^2 + 2\,(yv)^2$$

Relevant Interactions of χ_h and χ_l

Coupling to the Higgs:

$$\mathcal{L} \supset -\frac{y}{\sqrt{2}}\Big[\sin(2\theta)\left(\bar{\chi}_h\chi_h - \bar{\chi}_l\chi_l\right) + \cos(2\theta)\left(\bar{\chi}_h\chi_l + \bar{\chi}_l\chi_h\right)\Big] h$$

Coupling to the Z:

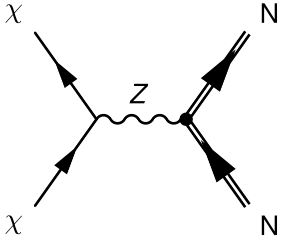
$$\mathcal{L} \supset -\frac{g}{2c_W}\Big[\cos^2\theta\,\bar{\chi}_l\gamma^\mu\chi_l + \sin^2\theta\,\bar{\chi}_h\gamma^\mu\chi_h + \frac{1}{2}\sin(2\theta)\left(\bar{\chi}_h\gamma^\mu\chi_l + \bar{\chi}_l\gamma^\mu\chi_h\right)\Big] Z_\mu$$

Interactions relevant for production of mediator, decay to DM and direct detection cross section.

Avoiding Direct Detection Bounds

DM state χ_l has contribution from neutral component of doublet χ_D through mixing

$\rightarrow$ inherits coupling both to Higgs and Z (dangerous!)

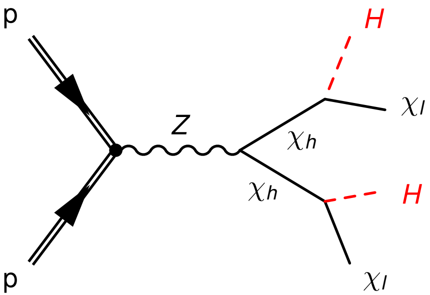


$$\sim \frac{g}{2c_W}\left[\cos^2\theta\,\bar{\chi}_l\gamma^\mu\chi_l\right]Z_\mu$$

Coupling is proportional to mixing angle $\theta \rightarrow$ need to suppress y

$\Rightarrow$ Benchmark choice for further analysis: $y = 10^{-3}$

Signatures at the LHC



- χ_l only appearing as Missing Energy
- Higgs primarily decays to $b\bar{b} \rightarrow$ choose as signal benchmark

$\Rightarrow$ Signal at parton level: 4 b-quarks plus MET

Relevant Backgrounds

Several SM processes can produce identical/similar signature (with Neutrinos resulting in Missing Energy):

Reducible Backgrounds

- $t\bar{t}$
- $Wjjjj$
- $Wbbjj$
- $Wbbbb$
- $Zjjjj$
- $Zbbjj$

Irreducible Backgrounds

- $Zbbbb$
- (ZZZ)
- (ZZh)
- (Zhh)
- (hhh)

Gaining Discrimination Power

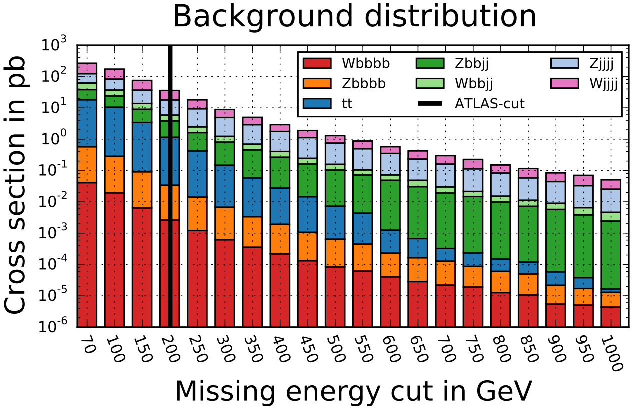
Huge number of background events expected

Reducing the background vs. the signal by applying the following selection criteria:

- Lepton rejection (no isolated electrons/muons with $p_\perp > 7\,\mathrm{GeV}$ within $-2.4 \leq \eta \leq 2.4$)
- Minimum Missing Transverse Energy (MET)
- B-Tagging
- Jet-substructure Analysis

$\Rightarrow$ Optimizing significance and potential for discovery at LHC

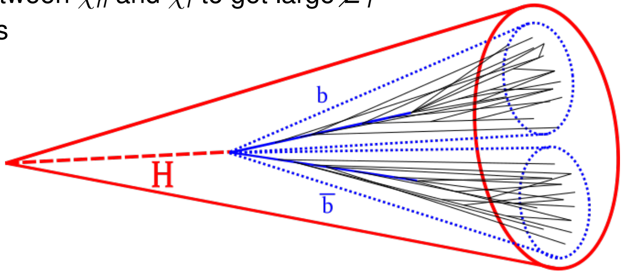
Missing Transverse Energy Trigger



$\Rightarrow$ Favours a scenario with sizeable mass-splitting between χ_h and χ_l

Substructure Analysis

Mass-splitting between χ_h and χ_l to get large $\not{E}_T$
$\rightarrow$ Boosted Higgs

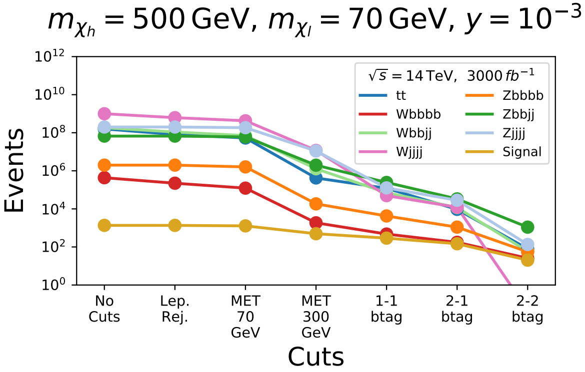


Cluster $b\bar{b}$ in fatjet, use BDRS jet-substructure analysis to identify Higgs
[Butterworth, Davison, Rubin, Salam '08]

$\Rightarrow$ Use our own implementation of BDRS, including detector simulation with Delphes ($R = 1.2$)

B-Tagging of the Subjets

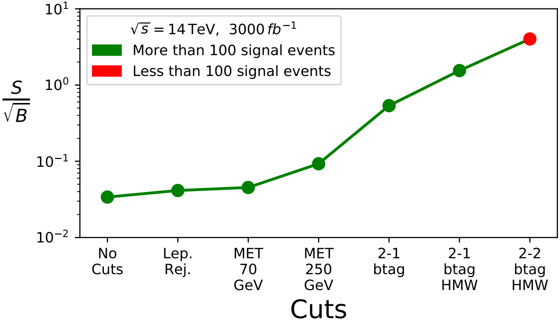
- We have two Higgs $\to$ two fatjets with two *b*-quarks in each
- Discrimination power vs. signal event reduction



Optimizing the Discrimination Procedure

HEiKA Heidelberg Karlsruhe Research Partnership

$m_{\chi_h} = 500\,\text{GeV},\ m_{\chi_l} = 70\,\text{GeV},\ y = 10^{-3}$



$\Rightarrow$ To do: perform a multivariate analysis

Conclusion and Outlook

- Di-Higgs plus Missing Energy is an interesting new signature
- Discovery potential at High Luminosity LHC
- Substructure analysis as powerful tool for Higgs identification
  $\rightarrow$ essential for background discrimination
- Next: Multivariate analysis as final step
- Study other event topologies in different simplified models