Dark Matter Signals at the LHC from a 3HDM

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SCALARS 2017
Warsaw, Poland, 02.12.2017

based on
work in progress
with V. Keus, S. F. King, S. Moretti,
J. Hernandez-Sanchez, D. Rojas

The Standard Model

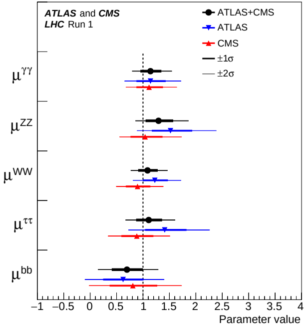
A rigorously tested Theory of Fundamental Interactions

From the LHC:

- a Higgs particle found in 2012
- no significant deviation from the SM
- no sign of New Physics

But no explanation for:

- Dark Matter
- neutrino masses
- baryon asymmetry and baryogenesis
- extra source of CP violation
- vacuum stability
- ...



JHEP 08 (2016) 045

3HDMs

Three-Higgs Doublet Models:

- three scalar doublets, **active** ($\langle\phi_i\rangle \neq 0$) or **inert** ($\langle\phi_i\rangle = 0$)
- room for the SM-like doublet

  $\Rightarrow$ SM-like Higgs, agreement with current data
- different symmetries and different vacuum alignments
- rich phenomenology
- conserved discrete symmetry $\Rightarrow$ DM candidate:

  here Z_2-symmetric I(2+1)HDM: 1 active, 2 inert doublets

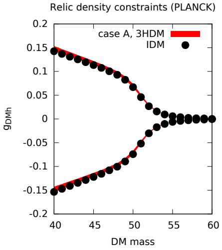
I(2+1)HDM

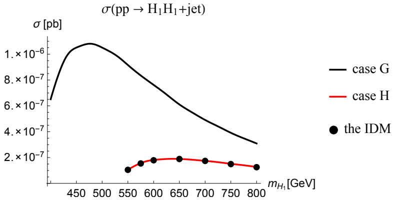
$$\mathbf{Z_2}: \phi_1 \to -\phi_1,\ \phi_2 \to -\phi_2, \quad \phi_3 \to \phi_3,\ \text{SM fields} \to \text{SM fields}$$

$$\langle\phi_1\rangle = 0, \quad \langle\phi_2\rangle = 0, \quad \langle\phi_3\rangle = v$$

LHC & DM phenomenology of I(2+1)HDM studied in:
JHEP 1411 (2014) 016, JHEP 1511 (2015) 003, JHEP 1612 (2016) 014

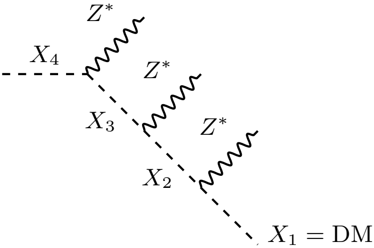
- good DM candidate
- testable at the LHC: $\text{Br}(h_{SM} \to \text{inv}), h_{SM}\gamma\gamma,$ monojets
- testable at DM experiments
- Problem: how to distinguish between models?





Cascade decays in multi-scalar models

$$m_{X_4} > m_{X_3} > m_{X_2} > m_{X_1}, \quad X_1 \text{ stable}$$



- signature: $\not{E}_T + n \times (l^+ l^-)$
- depends on the **particle spectrum**:
  $\to$ number of X_i, masses, couplings
- different processes in different models
- maybe different signals?

The model

Z_2-symmetry in I(2+1)HDM:

$$\phi_1 \to -\phi_1,\ \phi_2 \to -\phi_2, \quad \phi_3 \to \phi_3, \text{ SM fields} \to \text{SM fields}$$

Z_2-invariant potential:

$$V = \sum_{i}^{3} \left[-|\mu_i^2|(\phi_i^\dagger \phi_i) + \lambda_{ii}(\phi_i^\dagger \phi_i)^2 \right] + \sum_{ij}^{3} \left[\lambda_{ij}(\phi_i^\dagger \phi_i)(\phi_j^\dagger \phi_j) + \lambda'_{ij}(\phi_i^\dagger \phi_j)(\phi_j^\dagger \phi_i) \right]$$
$$+ \left(-\mu_{12}^2(\phi_1^\dagger \phi_2) + \lambda_1(\phi_1^\dagger \phi_2)^2 + \lambda_2(\phi_2^\dagger \phi_3)^2 + \lambda_3(\phi_3^\dagger \phi_1)^2 + h.c. \right)$$
$$+ \Big(\lambda_4(\phi_3^\dagger \phi_1)(\phi_2^\dagger \phi_3) + \lambda_5(\phi_1^\dagger \phi_2)(\phi_3^\dagger \phi_3) + \lambda_6(\phi_1^\dagger \phi_2)(\phi_1^\dagger \phi_1)$$
$$+ \lambda_7(\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_2) + \lambda_8(\phi_3^\dagger \phi_1)(\phi_3^\dagger \phi_2) + h.c. \Big)$$

- 21 parameters in $V \to 6$ important for collider pheno
- all parameters real
- Yukawa interaction: "Model I"-type (only ϕ_3 couples to fermions)
- explicit Z_2-symmetry

Physical Basis

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{H_1^0 + i A_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{H_2^0 + i A_2^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v + h + i G^0}{\sqrt{2}} \end{pmatrix},$$

Physical states:

- SM-like Higgs h
- 4 neutral ($H_{1,2}, A_{1,2}$) and 4 charged ($H^{\pm}_{1,2}$) scalars

$$H_1 = \cos\theta_h H_1^0 + \sin\theta_h H_2^0, \quad H_2 = \cos\theta_h H_2^0 - \sin\theta_h H_1^0$$

(equivalent rotations for $A, H^{\pm}$ with θ_a, θ_c)

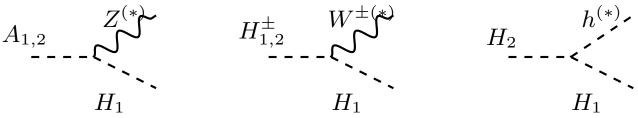
- no complex parameters in V: $H_{1,2}$ and $A_{1,2}$ have opposite parities

Physical parameters:

$$m_{H_1}, m_{H_2}, g_{H_1 H_1 h}, \theta_a, \theta_c, \theta_h$$

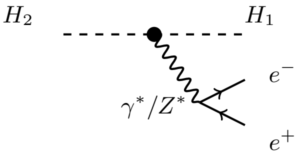
Decays of heavy inert states

- **tree-level decays**



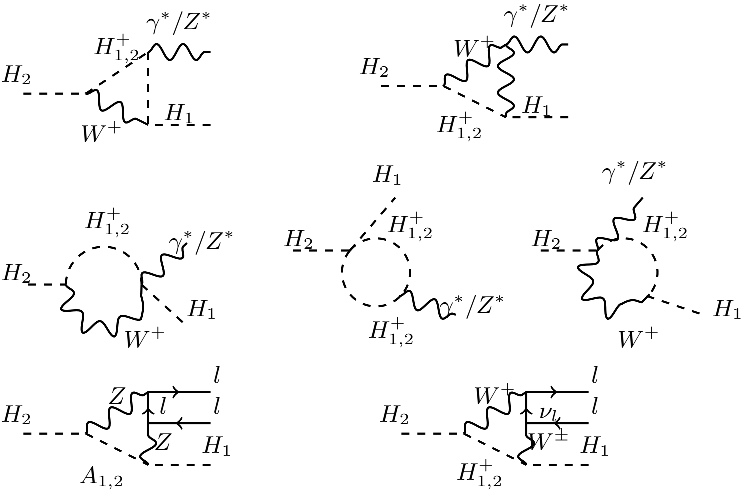
(A) (B) (C)

  - dominant if there is a **large mass splitting** between H_1 and $A_{1,2}, H^{\pm}_{1,2}$
- **loop-induced decay**



  - important if there is a **small mass splitting** between H_1 and H_2

Structure of the loop decay



Loop calculation

$$H_2(p_3) \to H_1(p_2)\gamma^*(p_3 - p_2) \to H_1(p_2) f(k_1) \bar{f}(k_2)$$

General structure of the amplitude:

$$\mathcal{M} = ie\bar{v}(k_1)\gamma^\nu u(k_2) \frac{ig_{\mu\nu}}{(p_3 - p_2)^2} [A(p_3 + p_2)^\mu]$$

General structure of the loop vertex:

$$A(p_3 + p_2)^\mu = M_{\mu,T} = \sum_i M_\mu^{(i)}$$

contains contributions from different diagrams

→ information about masses, couplings, vertices

$$M_\mu^{(1)}(m_{H_i^\pm}, m_W, m_{12}, m_{H_i}) = \frac{eg^2}{4} A_i^\pm m_\mu^{(1)}(m_{H_i^\pm}, m_W, m_{12}, m_{H_i})$$

$$m_\mu^{(1)} = \frac{1}{16\pi^2} \int \frac{d^n k}{(2\pi)^n} \frac{(k+2p_3)_\alpha (2k+p_3+p_2)_\mu (k+2p_2)_\beta [g^{\alpha\beta} - \frac{k^\alpha k^\beta}{m_W^2}]}{[(k+p_3)^2 - m_{H_i^\pm}^2][(k+p_2)^2 - m_{H_i^\pm}^2][k^2 - m_W^2]}$$

$$A_1^\pm = -(\cos\theta_c \cos\theta_h + \sin\theta_h \sin\theta_c)(\cos\theta_c \sin\theta_h - \cos\theta_h \sin\theta_c)$$

→ calculation gives us $\Gamma(H_2 \to H_1\gamma^* \to H_1 f \bar{f})$

Effective potential

- We add an effective term $H_2 \to H_1 f\bar{f}$:

$$L_{\text{eff}} = L_{\text{I(2+1)HDM}} + iK_f(H_1\partial_\mu H_2 - H_2\partial_\mu H_1)\bar{f}\gamma^\mu f$$

- Amplitude:

$$M = iK_f\bar{v}(k_1)\gamma^\mu(p_3 + p_2)_\mu u(k_2) \Rightarrow |M^2| \sim K_f^2$$

- Compare that with previous calculation and

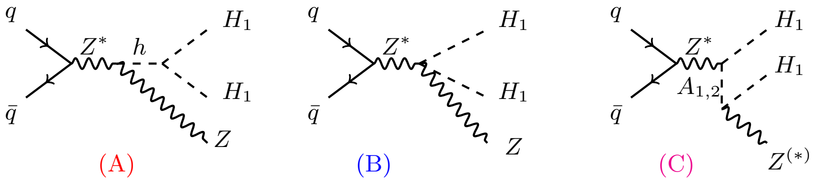
$$K_f^2 = \frac{16\pi^3 m_{H_2}^3 \Gamma(H_2 \to H_1 f\bar{f})}{I_3}$$

  - $\Gamma(H_2 \to H_1 f\bar{f})$ – partial decay width
  - I_3 – phase space integral

- we can use L_{eff} for numerical scans in CalcHEP

Cascade decays @ LHC

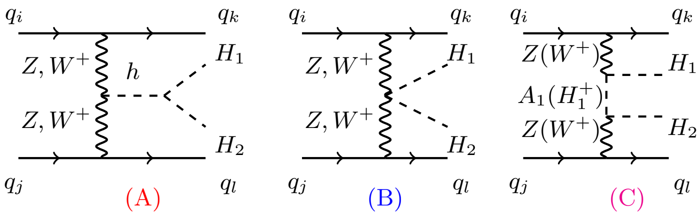
$pp \to ... \to H_1 H_1 f \bar{f}$



- (A) depends on $g_{H_1 H_1 h}$
- (B) depends on $g_{H_1 H_1 Z Z}$ – fixed gauge coupling
- (C) depends on $g_{H_1 A_1 Z}$ – **possible differences w/r IDM** we may learn something about A_i

Cascade decays @ LHC

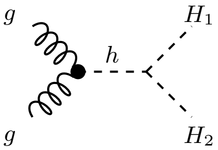
$pp \to ... \to H_1 H_1 f \bar{f} +$ jets



- loop calculation enters $H_2 \to H_1 f \bar{f}$
- (A) depends on $g_{H_1 H_2 h}$
- (B) depends on $g_{H_1 H_2 ZZ}$ – fixed gauge
- (C) depends on $g_{H_1 A_1 Z}$

Cascade decays @ LHC

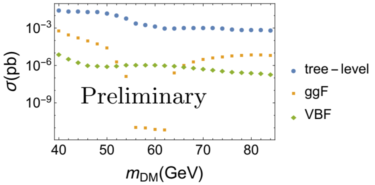
$pp \to ... \to H_1 H_1 f \bar{f}$

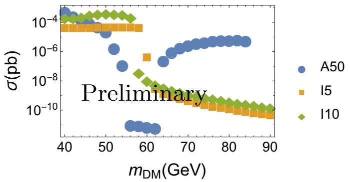


- loop decay of $H_2 \to H_1 \gamma^* / Z^*$
- other mode – $H_2 \to h H_1$ (suppressed)
- should be promising if other decays suppressed and $m_{H_1} + m_{H_2} \approx m_h$

Results

$$\sigma(pp \to H_1 H_1 l^+ l^-)$$





- different benchmarks: $m_{H_2} - m_{H_1} = 5, 10, 50\,\text{GeV}$
- we see the phase space structure
- we see the impact of $g_{H_1 H_1 h}$
- "bad" scenario A50 – large tree-level contribution
  $\to$ loop-process contribute up to 10%
- that is promising for scenarios with small $m_{H_2} - m_{H_1}$

Summary and Outlook

- **Cascade decays – present in all multi-scalar models**

  → if DM candidate has heavier (unstable) partners
- Depend on particle spectrum and couplings

  → maybe a way to distinguish between models?
- Tree-level and loop-induced decays

  → can lead to different results
- What is done:
  - **full loop calculation** of $H_2 \to H_1 \gamma^* \to H_1 f \bar{f}$
  - first benchmarks are under investigation – results soon!
- What should be done:
  - detailed analysis of benchmarks and surrounding points
  - comparison with the IDM and the SM background
  - predictions for the LHC and future colliders (High Luminosity needed)
  - something we didn't think of?

More results to come

BACKUP SLIDES

Parameters of V

- $\mu_3^2 = v^2\lambda_{33} = m_h^2/2$ fixed from extremum conditions
- "dark hierarchy": $\mu_1^2 = n\mu_2^2,\ \lambda_{13} = n\lambda_{23},\ \lambda'_{13} = n\lambda'_{23},\ \lambda_3 = n\lambda_2$
- $\left(\lambda_4(\phi_3^\dagger\phi_1)(\phi_2^\dagger\phi_3) + \lambda_5(\phi_1^\dagger\phi_2)(\phi_3^\dagger\phi_3) + ...\right)$: no new phenomenology

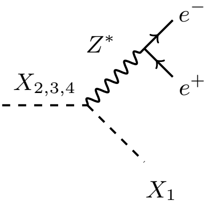
  $\Rightarrow \lambda_{4-8} = 0$
- $\lambda_1, \lambda_{11,22,12}, \lambda'_{12}$ – self-interactions of inert doublets

21 parameters → 6 relevant parameters

- μ_2^2 – mass scale of inert particles
- μ_{12}^2, λ_2 – mass splittings
- n – dark hierarchy parameter
- $\lambda_2, \lambda_{23}, \lambda'_{23}$ – DM-Higgs coupling

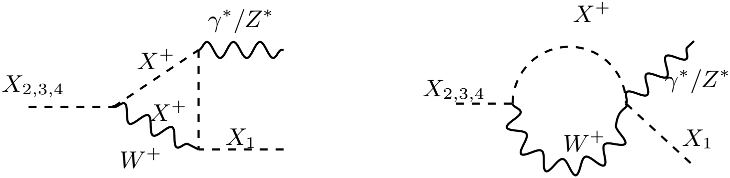
Inert cascade decays at the LHC

$$pp \to Z \to X_{2,3,4} X_1 \to X_1 X_1 Z^* \to X_1 X_1 e^+ e^-$$



- signature: $\not{E}_T$ and dilepton pair
- dominant if there is a **large mass splitting** between DM and other inert particles
- process present in all $SU(2)$ DM models (e.g. the IDM: HAZ vertex)
- possible differences due to varying strength of $X_1 X_j Z$ coupling

$$pp \to h \to X_{2,3,4}X_1 \to X_1X_1\gamma^*/Z^* \to X_1X_1e^+e^-$$



- signature: $\not{E}_T$ and dilepton pair
- γ^* loop – important if there is a **small mass splitting** between DM and other inert particles